THERMOECONOMIC APPROACH FOR EVALUATING THE PERFORMANCE OF MULTI-EFFECT- MECHANICAL VAPOR COMPRESSION DESALINATION UNIT

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الملخص

يستخدم مفهوم الإكسيرجي كطريقة تقليدية لتقييم أداء منظومات الطاقة من منظور الديناميكا الحرارية، حيث يتم حساب تحطيم الإكسيرجي (اللا إنعكاسية) لتقييم عدم كفاءة مكوناتها. الا ان تكلفة عدم الكفاءة لا يمكن ايجادها الا باستخدام التحليل الديناميكي- الحراري. يهدف هذا العمل إلى محاكاة آداء وحدة تحلية بضغط البخار- متعددة المراحل من المنظور الحراري-الإقتصادي حيث تم استخدام طريقة التكلفة النوعية للإكسيرجي للمحاكاة. بيّنت النتائج أن الحد الأدنى للتكلفة النوعية للمياه المنتجة يمكن الحصول عليه لوحدة تحلية من ثلاث مراحل، وهذه النتيجة في اتفاق تام مع تلك التي أعطيت في الأدبيات. أظهرت النتائج أن الحد الأدنى للتكلفة النوعية للمياه المنتجة يتوافق مع ضاغط بخار كفاءته 91٪ لوحدة تحلية من مرحلة واحدة و 82٪ للمراحل المتعددة. النتائج بيّنت ايضا أنه بخفض نسبة ضغط البخار في وحدة المراحل الثلاث من 2.15 إلى 1.6، يمكن تقليل الأستهلاك النوعي للطاقة بنسبة 40.5 ٪، والتكلفة النوعية للماء المنتج بنسبة 2.75٪.

ABSTRACT

Exergy analysis is the traditional approach to evaluate the performance of thermal systems from thermodynamic point of view, where exergy destruction (irreversibility) is determined to assess the deficiency of the plant's components. However, the costs of those deficiencies can be determined only through thermoeconomic analysis. The aim of this work is to simulate the performance of multi-stage desalination unit from thermoeconomic point of view. The Specific Exergy Costing (SPECO) method is adopted for simulation.

The results show that the minimum unit cost of the product water is obtained for the three stages unit, the obtained result is in good agreement with that given in the literature. The minimum unit cost is found at compressor efficiency of 91% for the single-stage and at 82% for the multi-stages. It is found that, by reducing the pressure ratio of the compressor in the three-stage system from 2.15 to 1.6, the specific power consumption can be reduced by 40.5%., and the unit product cost by 2.75%.

KEYWORDS: Desalination; Multi-Effect Evaporation (MEE); Mechanical Vapor Compression (MVC); Exergy Destruction; Thermo-Economics; Unit Product Cost.

INTRODUCTION

People, particularly in the arid zones, are more conscious for the scarcity of fresh water for mankind consumptions. Water supply has become more challenging with rapidly increasing population and low rainfall. Desalination of seawater offers a practical approach to resolve the problem of water scarcities [1].

Fresh water consumption has been continuously increasing along the last decades, due to different factors such as population growth, improvement of living standards and economic development, and it is expected that the situation will be getting worse in the coming few years with the increase in human consumption of clean water [2].

In the current work, Mechanical Vapor Compression (MVC) system is selected for the analysis. The MVC system is compact, confined, and does not require external heating source. The system is driven by electric power; therefore, it is suitable for remote population areas with access to power gridlines. Another advantage of the MVC system is the absence of the down condenser and the cooling water requirements [3].

Dividing the plant's cost by its capacity is the classical approach to estimate the product unit cost, however, this approach does not give details about the contribution of each plant's component to the product unit cost [4].

Thermoeconomic approach is adopted for the analysis of different thermal systems, it combines economic and thermodynamic analysis by applying the concept of cost, which is an economic property, to exergy which is a thermodynamic property and deals with the value of energy within a plant [5].

Thermoeconomic methodology is adopted by many authors, where the production cost is allocated on the component level. High irreversible devices of the desalination plant rise the unit cost of the material streams associated with their production[1].

Thermoeconomic model of Multi-Effect Evaporation, Mechanical Vapour Compression (MEE-MVC) is presented by A. S. Nafey et al. [6]. It is found by using an external steam to initiate the evaporation process, the thermal performance ratio may be reduced by 8%, however, the product unit cost increases by 29%.

The effect of brine recirculation was investigated for a single effect Mechanical Vapour Compression (MVC) desalination unit by M. A. Jamil and S. M. Zubair [4]. The result shows the specific energy consumptions for a single effect of (MVC) system with and without brine recirculation are 13kWh/m^3 and 9.8kWh/m^3, respectively.

A new design for a Multi Stage Flash Mechanical Vapour Compression (MSF-MVC) desalination process was presented by A. A. Nafey et al. [7]. The analysis was based on energy, exergy and thermoeconomic methodologies. It was found that the last stage had the highest value of sum of capital, operation, maintenance, and exergy destruction cost.

To avoid excessive deterioration in the performance the desalination unit with the increase in the number of stages, it is so significant, to realize the effect of the size of the plant on the thermoeconomic performance of the MEE-MVC unit. In this work the effect of the number of stages on the unit cost of the exergy destruction and on the unit cost of different streams are determined.

PROCESS DESCRIPTION

A schematic diagram for multi-stage, vapor compression desalination unit (4 stages) is shown in Figure (1). The intake sea water is split into two streams, one stream enters the distillate heat exchanger, and the other stream enters the brine heat exchanger, where they exchange heat with the distillate and brine streams, respectively.

Both streams, after leaving the heat exchangers are mixed and fed to the evaporators. In the evaporator, part of the feed water is evaporated, and the rest is rejected as a brine water.

The evaporated water in evaporator 1 is used as a source of heat to evaporate the feed water in evaporators 2, 3, and 4. The brine stream exits one evaporator and cascades to the next one.

As can be shown, the evaporated water which is leaving the last evaporator (evaporator 4), is recycled and flows into the compressor, where both pressure and temperature are raised, and water becomes a superheated steam.

Part of the distillate water at the outlet of the first evaporator flows into the de-superheater to mix with the superheated steam to decrease its temperature to the saturation one.

The condensate water from all evaporators is mixed and used as heating stream in the distillate heat exchanger. Also, the brine water from all evaporators is mixed and used as heating stream in the brine heat exchanger.

ASSUMPTIONS:

The following assumptions are adopted for the analysis:

- The distillate is salt free.
- Effect of the boiling point elevation is neglected.
- Constant, but not equal, overall heat transfer coefficients for heat-exchangers. $U_b = 3.9\ kW/m^2K$ and $U_d = 2.5\ kW/m^2K$.
- Compressor efficiency 75%.
- Pump efficiency 78%.
- The product and reject are at the same temperature (T_{30}).

THE DESIGN DATA

Table (1), shows the input data which are implemented for the analysis [1], [6] and [4].

Table 1: The input data

X_f	32000 ppm	T_o	21 C^o
$\dot{m}_f$	200 t/h	T_v	65 C^o
U_b	3.9 kW/m^{2}k	ΔT_{Ev}	5 C^o
U_d	2.5 kW/m^{2}K	α	0.5
η_p	78%	i_{ifl}	5%
η_C	75%	i	7%
r_p	35	Availability (β)	0.9
r_c	2.15	Electrical cost	0.007 $/kWh
N	20 years		

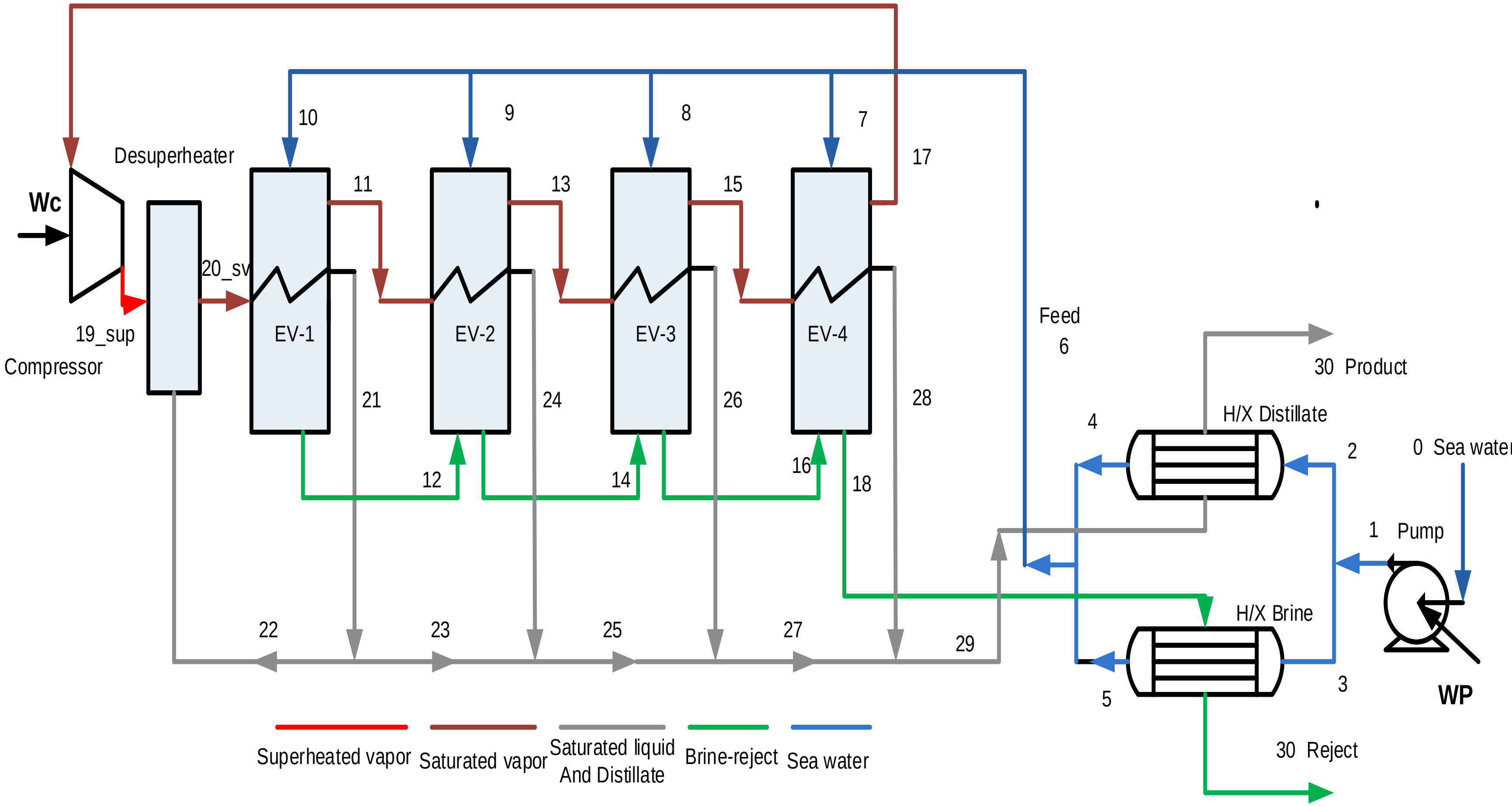


Figure 1: multi-stage mechanical vapor compression desalination unit

THE THERMODYNAMIC MODEL

The continuity equation for steady-state, steady-flow process can be written as:

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{1}$$

In general form for "n" number of stages (effects) we may have:

$$\dot{m}_{b,n} = n \times \dot{m}_d \frac{x_f}{x_b - x_f} \tag{2}$$

$\dot{m}_{b,n}$ is the brine mass flow rate for "n" stages.

The split ratio is defined as:

$$\alpha = \frac{\dot{m}_2}{\dot{m}_1} \tag{3}$$

And hence:

$$\dot{m}_3 = (1 - \alpha)\dot{m}_1 \tag{4}$$

The feed water flow rate for "n" stages can be written as:

$$\dot{m}_f = n \times \dot{m}_d \frac{x_b}{x_b - x_f} \tag{5}$$

Another split ratio can be defined as:

$$\mu = \frac{\dot{m}_{22}}{\dot{m}_{20\_sv}} \tag{6-a}$$

In general, the last equation can be interpreted as:

$$\mu = \frac{\dot{m}_{distillate\ from\ evap.1\ to\ desuperheater}}{\dot{m}_{sat.vapour\ leaving\ the\ desuperheater}} \tag{6-b}$$

The first law equation can be written as:

$$\sum \dot{m}_i h_i + \dot{Q}_k = \sum \dot{m}_e h_e + \dot{W}_k \tag{7}$$

The enthalpy of feed water can be deduced as:

$$h_6 = \frac{x_f}{x_b} h_{18} + \frac{x_b - x_f}{2\, x_b}\left(h_{17} + \frac{\mu}{1-\mu} h_{22} + 2\, h_{29} - \frac{1}{1-\mu} h_{20\_sv}\right) \tag{8-a}$$

For "n" number of effects, the foregoing equation can be written as:

$$h_f = \frac{x_f}{x_b} h_b + \frac{x_b - x_f}{n\, x_b}\left(h_{vn} + \frac{\mu}{1-\mu} h_{sl} + n\, h_d - \frac{1}{1-\mu} h_{sv}\right) \tag{8-b}$$

$f,\ d,\ b,\ vn,\ sv$ and sl , are feed, distillated, brine, generated vapor from evaporator "n", saturated vapour, and saturated liquid out from the first effect respectively.

The general form of the enthalpy of the product for any number of effects is deduced as:

$$h_{Product} = h_b + h_{intke} - h_f + \frac{x_b - x_f}{x_b}(h_d - h_b) \tag{9}$$

Exergy balance can be given by:

$$\sum \left(1 - \frac{T_0}{T}\right)\dot{Q}_k + \sum \dot{\Psi}_{i,k} = \sum \dot{\Psi}_{e,k} + \dot{W}_k + \dot{I}_k \tag{10}$$

Where:

$$\dot{\Psi} = \dot{m}[(h - h_0) - T_0(s - s_0)] \tag{11}$$

The isentropic efficiency of the compressor and pump is given by:

$$\eta_{isentropic} = \frac{\dot{W}_{isntropic}}{\dot{W}_{actual}} \tag{12}$$

The effectiveness is given by:

$$\varepsilon = \frac{Rate\ of\ Exergy\ out}{Rate\ of\ Exergy\ in} \tag{13}$$

The fundamental equations of enthalpy and entropy of the saline water are given as presented by M. H. Sharqawy et al. [8]:

Seawater enthalpy equation is:

$$h_{sw} = h_{pw} - S(a_1 + a_2S + a_3S^2 + a_4S^3 + a_5T + a_6T^2 + a_7T^3 + a_8ST + a_9S^2T + a_{10}ST^2) \quad (14)$$

Where h_{sw} and h_{pw} the enthalpy of seawater and pure water, T and S are temperature and salinity of intake seawater, respectively, and $a_1 = -2.2348 \times 10^4$, $a_2 = 3.152 \times 10^5$, $a_3 = 2.803 \times 10^6$, $a_4 = -1.446 \times 10^7$, $a_5 = 7.826 \times 10^3$, $a_6 = -4.417 \times 10^1$, $a_7 = 2.139 \times 10^{-1}$, $a_8 = -1.991 \times 10^4$, $a_9 = 2.778 \times 10^4$, $a_{10} = 9.728 \times 10^1$.

And seawater entropy equation is:

$$s_{sw} = s_{pw} - S(b_1 + b_2S + b_3S^2 + b_4S^3 + b_5T + b_6T^2 + b_7T^3 + b_8ST + b_9S^2T + b_{10}ST^2) \quad (15)$$

Where: $b_1 = -4.231 \times 10^2$, $b_2 = 1.463 \times 10^4$, $b_3 = -9.88 \times 10^4$, $b_4 = 3.095 \times 10^5$, $b_5 = 2.562 \times 10^1$, $b_6 = -1.443 \times 10^{-1}$, $b_7 = 5.879 \times 10^{-4}$, $b_8 = -6.111 \times 10^1$, $b_9 = 8.041 \times 10^1$, $b_{10} = 3.035 \times 10^{-1}$.

PERFORMANCE PARAMETERS

The performance of the MVC is determined in terms of the following variables:

- The specific power consumption, kWhr/m^3 which is given by:

$$W = \frac{\dot{W}_C + \dot{W}_P}{\dot{V}_d} \quad (16)$$

Where W is specific power consumption, $\dot{V}_d$ is the distilled volume flow rate.

- The specific heat transfer surface area sA, which is given by:

$$sA = \frac{A_{Ev} + A_d + A_b}{\dot{m}_d} \quad (17)$$

The parameter sA is used to evaluate and compare the size and hence the cost of the heat exchangers for different desalination plants.

Where A_{Ev} is the evaporator area, and is given by?

$$A_{Ev} = \frac{\dot{m}_s(h_s - h_d)}{U_{Ev}(T_s - T_d)} \quad (18)$$

The heat transfer coefficient can be estimated as given by F. N. Alasfour and H. K. Abdulrahim [9]:

$$U_{Ev} = 3 + 0.05(T_b - 60) \quad (19)$$

A_d, A_b are the distillated and brine preheaters areas respectively, which are given by:

$$A_d = \frac{\dot{m}_{29}c_P(T_{29} - T_{30})}{U_d(LMTD)_d} \quad (20)$$

$$A_b = \frac{\dot{m}_{18}c_P(T_{18} - T_{30})}{U_b(LMTD)_b} \quad (21)$$

Where:

$$(LMTD)_d = \frac{(T_{29} - T_4) - (T_{30} - T_2)}{\ln\left(\frac{T_{29} - T_4}{T_{30} - T_2}\right)} \quad (22)$$

$$(LMTD)_b = \frac{(T_{18} - T_5) - (T_{30} - T_3)}{\ln\left(\frac{T_{18} - T_5}{T_{30} - T_3}\right)} \quad (23)$$

THE THERMOECONOMIC MODEL

The Specific Exergy Costing (SPECO) method was developed by A. Lazzaretto and G. Tsatsaronis [5]. In this method, the cost rates of the exergy streams entering the component plus the cost rates associated with purchasing, maintaining, and operating the same component equal to cost rates of exergy streams leaving the component. In mathematical form, the cost balance equation for any component (k) can be written as:

$$\sum_i \left(c_i \dot{\Psi}_i\right)_k + \dot{Z}_k + c_{q,k}\dot{\Psi}_{q,k} = \sum_e \left(c_e \dot{\Psi}_e\right)_k + c_{W,k}\dot{W}_k \quad (24)$$

Where, c_i, c_e, c_q and c_w are the unit costs (costs per unit exergy). And $\dot{Z}_k$ is the capital investment, operating and maintenance expenses for component "k" in $/h. The capital cost rate can be written:

$$\dot{Z}_k = \frac{\emptyset_k \times \dot{C}_k}{j \times \beta} \quad \left(\frac{\$}{hr}\right) \quad (25)$$

Where j is the operating hours, β is the plant availability factor, the factor ϕ = 1.06 considers the maintenance cost, $\dot{C}_k$ is annualized equipment cost and can be written:

$$\dot{C}_k = (PEC)_k \times CRF \quad \left(\frac{\$}{year}\right) \quad (26)$$

Where, PEC is the equipment purchasing cost. The capital recovery factor (CRF) is given by:

$$CRF = \frac{i}{1 - (1 + i)^{-N}} \quad (27)$$

Here N is the lifetime of the equipment in years and i is the effective interest rate, given as:

$$i = \left(1 + i_{inf}\right)(1 - i_{real}) - 1 \quad (28)$$

Where, i_{inf} is the inflation rate and i_{real} is the real or desired interest rate.

Table (2) summarizes various correlations used for the calculation of capital cost of different components of the system as given by G. Fellah [1].

To obtain the unit exergy cost for each exergy stream, several equations equal to the number of streams must be formulated and solved simultaneously. Since the number of streams is larger than the plant's components, a set of auxiliary equations must be formulated based on F-P rules [5], such that the total number of equations must equal to the number of unknowns.

Table 2: Cost equations

Component	Equation	Range of Applicability
Heat Exchangers	$1000(12.86 + A^{0.8})$	
Evaporator	$250Q\Delta T_m^{-1}\Delta P_t^{-0.01}\Delta P_{sh}^{-0.1}$	$150 \le Q \le 800$ $2 \le \Delta T_m^{-1} \le 22$ $0.06 \le \Delta P_t \le 0.35$ $0.03 \le \Delta P_{sh} \le 0.06$
Compressor	$7364\dot{m}_v r_c \left(\frac{\eta_C}{1-\eta_C}\right)^{0.7}$	$10 \le \dot{m}_v \le 455$ $1.1 \le r_c \le 2$ $2.3 \le \frac{\eta_C}{1-\eta_C} \le 11.5$
Pump	$13.92\dot{m}_w \Delta P^{0.55}\left(\frac{\eta_P}{1-\eta_P}\right)^{1.05}$	$2 \le \dot{m}_w \le 32$ $100 \le \Delta P \le 6200$ $1.0 \le \frac{\eta_P}{1-\eta_P} \le 9$

A (m^2); Q (kW); T (ºC), P (kPa); $\dot{m}$ (kg/s)

RESULTS AND DISCUSSION

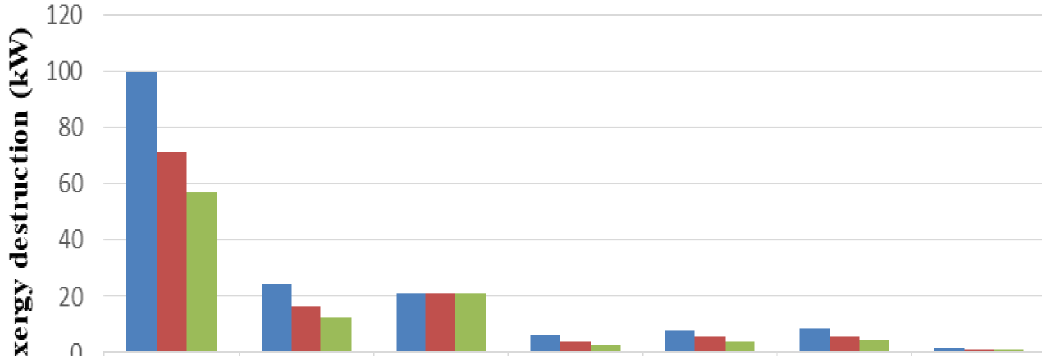
By using the specified design data (Table (1)), the thermodynamic results of the single and multi-stage units are calculated and tabulated as shown in Table (3).

Table 3 Thermodynamic results of single and multi-stage MVC

	1-Eff	*2-Eff*	*3-Eff*	*4-Eff*
T_f (℃)	55.4	55.4	53.1	49.9
$T_{heated\ steam}$ (℃)	152.2	149.86	143.77	137.66
$T_{rejected}$ (℃)	39.1	32.94	29.9	28.44
Distillate Product (m^3/hr)	71.5	81.1	81.14	81.66
Distillated Heat Exchanger Area (m^2)	112.8	217.67	333.41	444.68
Brine Heat Exchanger Area (m^2)	27.88	94.36	126.65	138.04
Evaporators Area (m^2)	751.83	2347.37	3215	5973.03
Specific heat area ($m^2/kg/s$)	44.94	118	163	289
Exergy Input (MW)	3.94	2.4	1.76	1.45
Exergy Distraction (MW)	0.27	0.17	0.13	0.104
Compressor Work (MW)	3.45	1.92	1.27	0.96
Specific Power Consumption (kWh/m^3)	43.16	23.7	15.7	11.77
Exergatic Efficiency	6.9	7.9	8.9	9.9

As can be shown, the distillate volume flow rate increases from 71.5 m^3/h for the single stage unit to 81.66 m^3/h for the four stages unit. Also, the recycled steam to compressor decreases with the increase in the number of stages, and hence both the compressor power and the specific power consumption are decreasing as well with the increase in the number of stages. A remarkable improvement in the exergatic efficiency is obtained by using multi-stage unit over the single-stage unit.

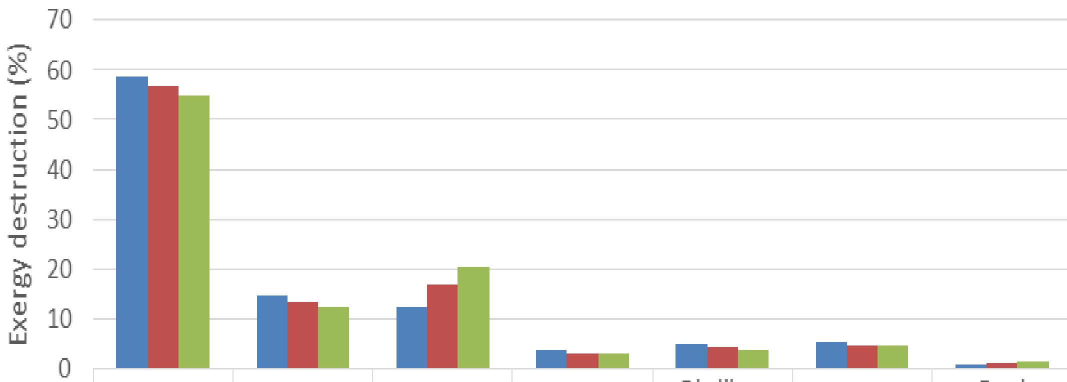
The exergy destructions in kilowatt and in percentage are shown in Figure (2) and Figure (3), respectively. As can be shown, the exergy destruction in the evaporator is dominant, where it contributes from 58.69% (two effects) to 54.87% (four effects) of the total exergy destruction.



	Evaporators	Compressor	Pump	Brine Heat Exchanger	Distillate Heat Exchanger	De-Superheater	Feed Seawater Mixer
2-Eff	99.97	24.66	21.19	6.25	8.2	8.63	1.43
3-Eff	71.54	16.77	21.19	3.87	5.54	5.95	1.24
4-Eff	57.02	12.77	21.19	3.1	3.86	4.59	1.39

Figure 2: Exergy destruction (kW)

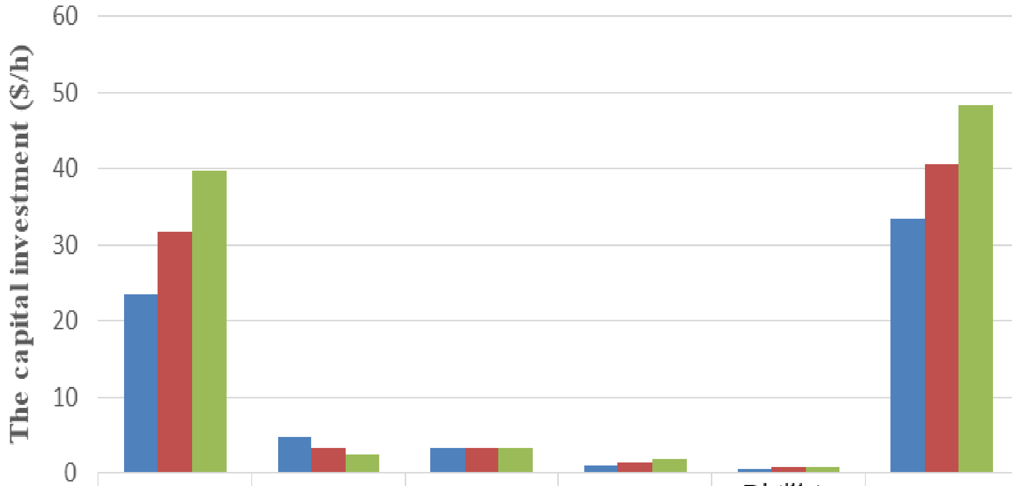
The second contributor to total exergy destruction is the compressor, where the percentage decreases from 14.48 % (two effects) to 12.29% (four effects) of the total exergy destruction, the reduction is due to the reduction in the recycled steam to compressor.



	Evaporators	Compressor	Pump	Brine Heat Exchanger	Distillate Heat Exchanger	De-Super.	Feed Seawater Mixer
2-Eff	58.69	14.48	12.44	3.67	4.81	5.07	0.84
3-Eff	56.73	13.3	16.79	3.06	4.39	4.71	0.98
4-Eff	54.87	12.29	20.39	2.98	3.72	4.42	1.33

Figure 3: Exergy destruction (%)

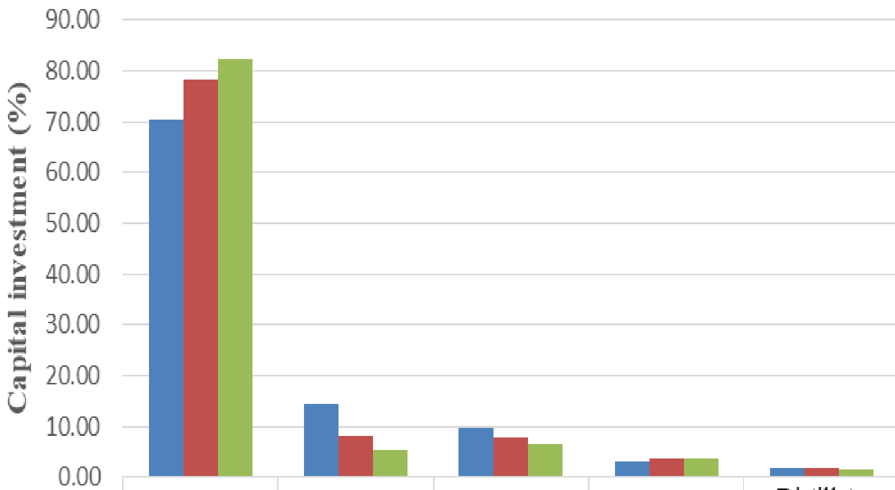
The capital investment cost for each component in $/h and in percentage of the total investment cost are shown in Figure (4) and Figure (5) respectively. As can be shown, the capital investment cost of the evaporator is dominant due to the large surface area.



	Evaporator	Compressor	Pump	Brine H/X	Distillate H/X	Total
2-Eff	23.65	4.86	3.27	1.1	0.65	33.53
3-Eff	31.86	3.32	3.27	1.5	0.76	40.71
4-Eff	39.87	2.58	3.27	1.81	0.78	48.31

Figure 4: The components investment cost of the (MEE-MVC) systems.

The evaporator cost contributes from 70.53% to 82.53 % of the total capital investment cost.



	Evaporator	Compressor	Pump	Brine H/X	Distillate H/X
% 2-eff	70.53	14.49	9.75	3.28	1.94
% 3 eff	78.26	8.16	8.03	3.68	1.87
% 4 eff	82.53	5.34	6.77	3.75	1.61

Figure 5: The components investment cost in percentage of the (MEE-MVC) systems.

Figure (6) shows a comparison of the unit product cost for the single-stage, two stages, three stages and four stages unit. As can be shown the three-stage system possess the lowest unit product cost, beyond the three-stage unit, the unit product cost increases due to the increases in the components' capital cost, the result in good agreement with that reported by A. S. Nafey et al. [6].

By reducing the pressure ratio of the vapour compressor in three stages system from 2.15 to 1.6, the capital cost of the compressor is reduced by 25.3%, and the specific power consumption is also reduced by 40.5%. Sequentially, the unit product cost is reduced from 1.005 to 0.977 $\$/m^3$ (2.75% reduction).

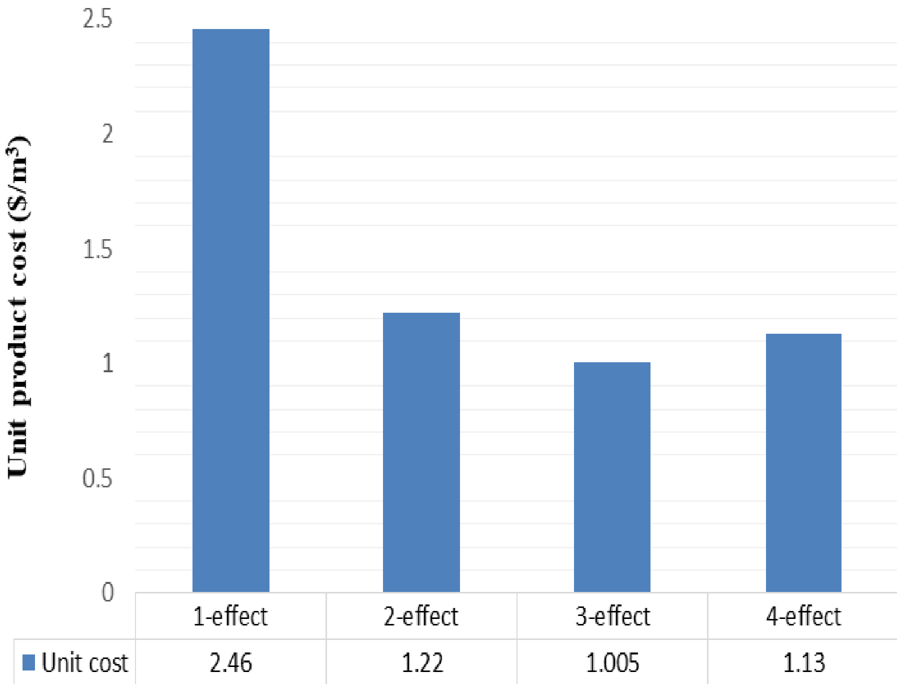


Figure 6: The unit product cost

Figure (7) shows the effect of the compressor efficiency on the product unit cost for the three-stage system. As can be shown with the rise in compressor efficiency the compressor work and exergy destruction are reduced on the expense of the purchase cost of the compressor, and it has a beneficial effect on the production unit cost. The unit cost of production continues to decrease as the compressor's efficiency reaches up to 82% which is the best value, giving an insignificant reduction of production cost by 0.2%, while the compressor's purchase value increases by 25.5%. Any rise in the compressor's efficiency higher than 82% turns the compressor's purchase cost into a dominant factor leading to an increase in production cost. And the compressor efficiency affects the specific energy consumption, which can reduce approximately 8.4% the energy consumption.

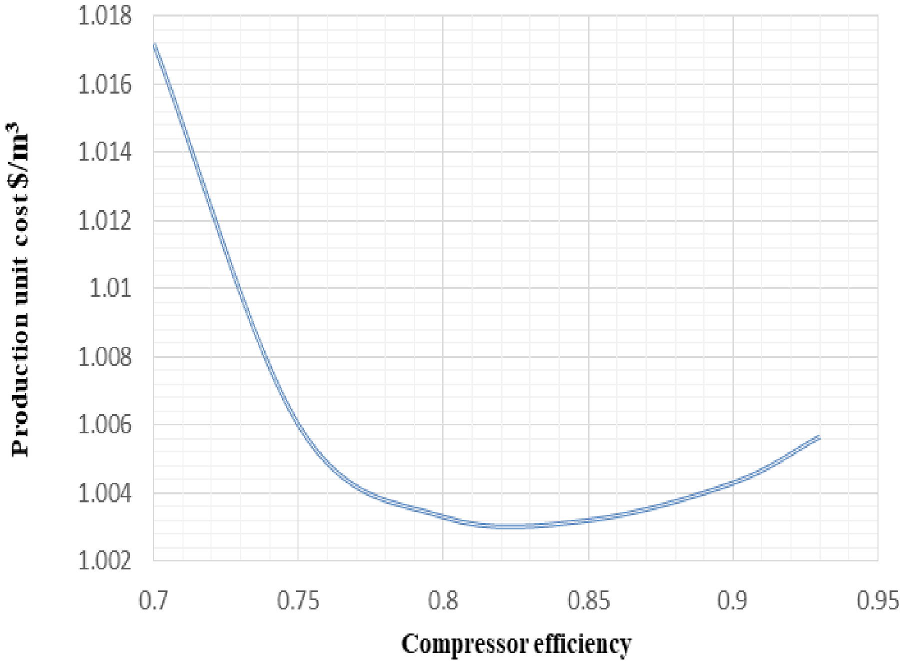


Figure 7: The effect of compressor efficiency on the product unit cost for three-stages MEE-MVC system.

CONCLUSIONS

Thermoeconomic analysis of the single-stage and multi-stage systems is carried out to estimate the energy consumption, exergy destruction, exergatic efficiency, capital investment cost, and the unit product cost. Using the design data for the MEE–MVC plants, the following points are highlighted:

- Specific Exergy Costing (SPECO) method is employed to estimate the unit cost of all streams.
- Using the design condition of the considered MEE–MVC desalination plant, thermoeconomic results show that the minimum unit product cost is obtained at three evaporators.
- ·The unit cost of the product water is found equal to 2.46 $\$/m^3$ for single effect, and 1.005 $\$/m^3$ for three evaporators, which is in good agreement with that given in the literatures.[6]
- The analysis shows that the compressor's efficiency affects substantially the specific energy consumption.
- There is an optimum point for the compressor efficiency at which the product unit cost is a minimum.

NOMENCLATURE

Symbol			Subscript	
A	area	m^2	d	distillate
$\dot{C}$	cost rate	\$/h	f	feed
c	specific cost	\$/kWh	b	brine
CRF	capital recovery factor		p	pump
i	interest rate		c	compressor
$\dot{I}$	irreversibility	kW	0	ambient
j	operating time	hours	v	vapor
LMTD	logarithmic mean temperature difference	^{o} C	inf	inflation
$\dot{m}$	mass flow rate	kg/s	i	inlet
n	stage number		e	exit
N	period of time	years	sl	saturated liquid
P	pressure	kPa		
PEC	purchasing cost		sv	saturated vapor
$\dot{Q}$	rate of heat transfer	kW	k	component
r	pressure ratio		sw	seawater
S	salinity	kg/kg	w	water
s	specific entropy	kJ/kg	ev	evaporator
T	temperature	^{o} C	pw	Pure water
U	overall heat transfer coefficient	$kW/m^2.^oC$	t	tube
$\dot{V}$	volume flow rate	m^3/h	sh	shell
$\dot{W}$	power	kW	s	steam
x	salinity	ppm		
$\dot{Z}$	cost rate	\$/h		
Greek letters				
η	efficiency			
ε	effectiveness			
α	mass ratio			
μ	mass ratio			
Ψ	exergy rate	kW		
β	availability factor			
ϕ	factor			

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