Exergy Analysis of Large ME-TVC Desalination System

Anwar O. Binamer

Water & Energy Program\Research Directorate
Kuwait Foundation for the Advancement of Sciences (KFAS)

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Outlines

- Introduction
- Process description
- Thermal analysis
- System performance and model validity
- Sensitivity analysis
- Conclusions.

Introduction

* Several ME-TVC desalination units have been installed recently in most of the GCC countries .

* The total installed capacity has increased up to 500 MIGD in the last decade.

Table1: Several projects of ME-TVC in GCC

Year	Location	Country	Total capacity, MIGD
1991	Jabal Dhana	UAE	4
2000	Umm Al-Nar	UAE	7
2001	Layyah	UAE	10
2002	Al-Taweelah A_1	UAE	52
2005	Sharjah	UAE	16
2006	Al-Hidd	Bahrain	60
2007	Al-Jubail	Saudi Arabia	176
2008	Fujairah	UAE	100
2010	Ras Laffan	Qatar	63

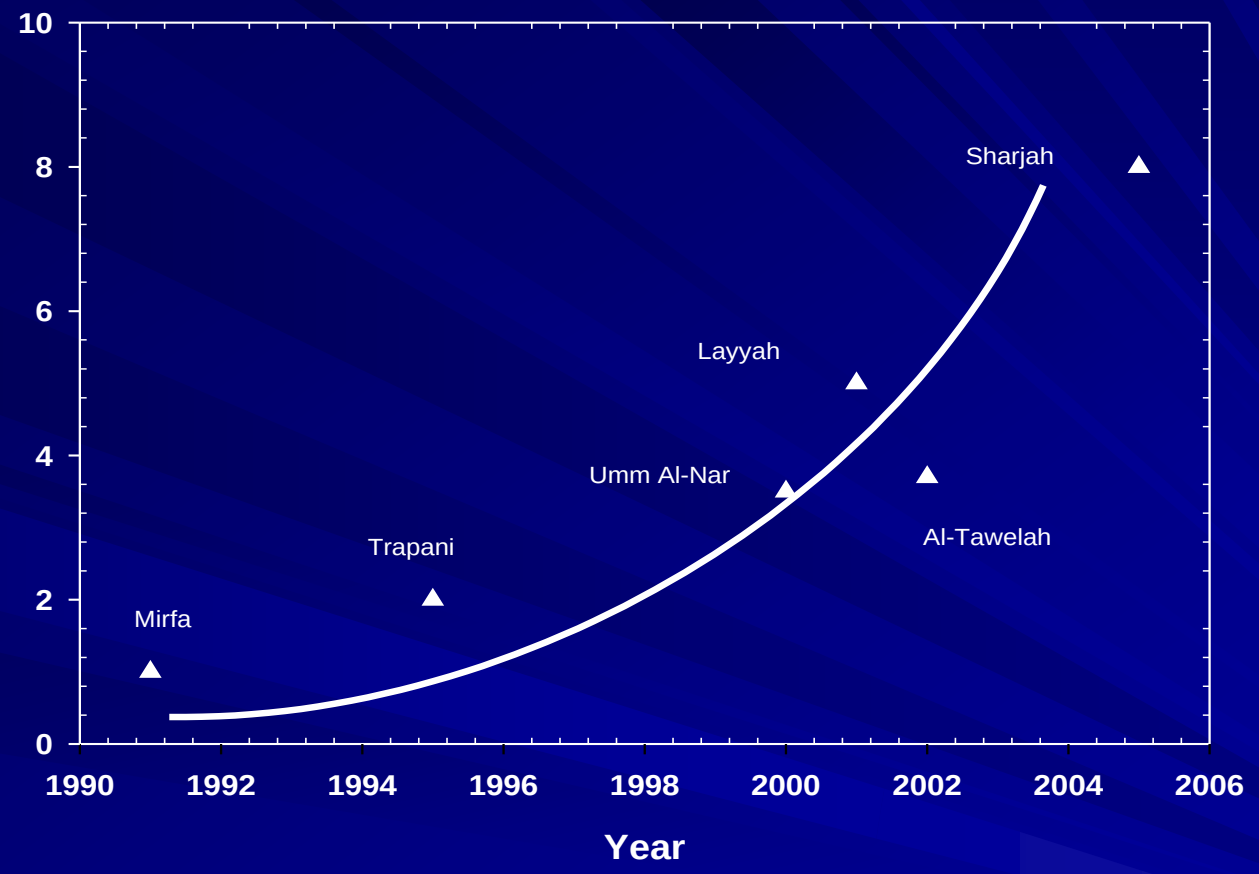
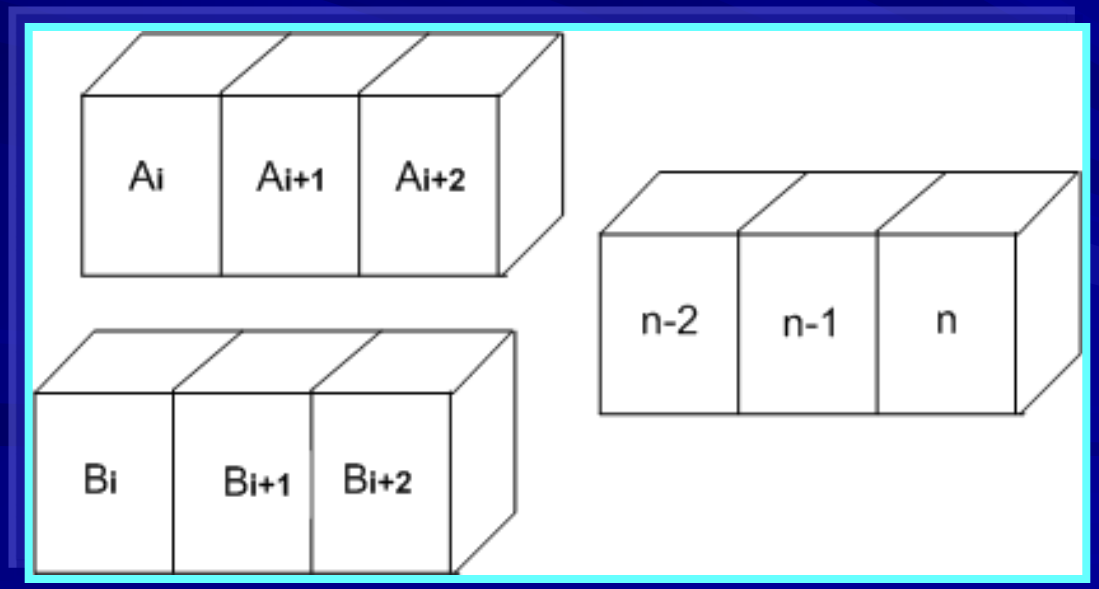


Fig. 1 The unit size capacities of these units were increased exponentially from 1 to 8.5 MIGD in a very short period.

* The unit size capacity is available at 10 MIGD, and it is expected to increase up to 15 MIGD in the near future.

* The new trend of combining ME-TVC with conventional multi-effect unit led to this increase in the unit size.



* Limited studies were carried out ME-TVC from exergy point of view since the mid of nighties, but it has been published in several works recently.

* A mathematical model of ME-TVC is developed in this study, using EES Software.

* This model is used to evaluate the system performance of some new commercial units having capacities of 2.4, 3.5 and 6.5 MIGD.

Process Description

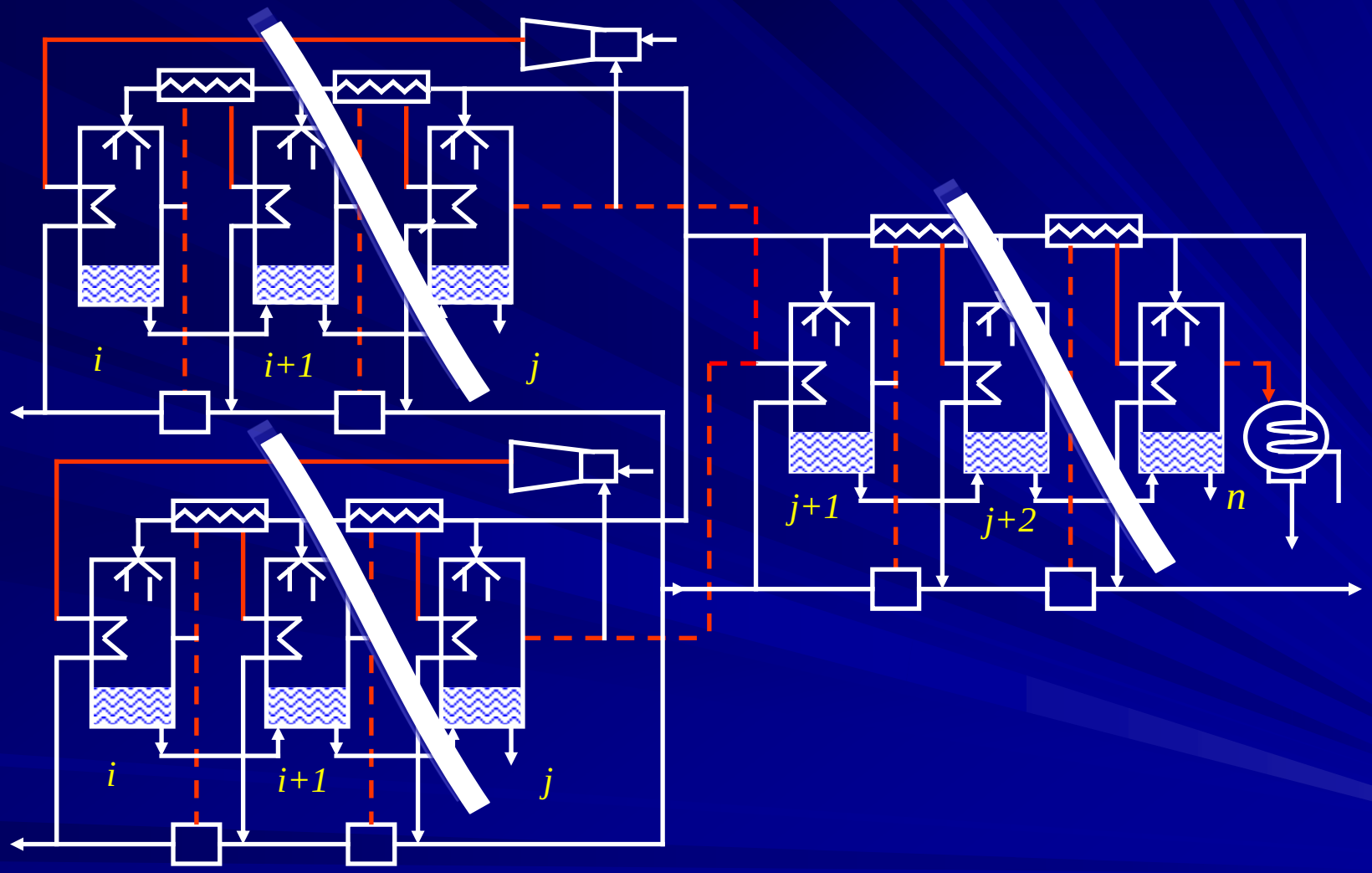


Fig. 2 Two identical ME-TVC units are combined with a single ME unit.

Thermal analysis

* First and Second Laws analyses are used to develop a mathematical model of the system.

* Mass, energy and exergy balance is applied to the thermo-compressors, evaporators, feed heaters and end condenser.

* Assumptions:

- Steady state operation,
- Negligible heat losses to the surrounding,
- Equal temperature difference across effects & feed heaters,
- The variations of *Cp* & *BPE* with the *T* and salinity are negligible.

* Energy balance is applied to each evaporator in ME-TVC units, in order to find:

$$D_1 = \frac{(D_s + D_r)\cdot(h_d - h_{fd})}{L_1} - F_1 \cdot C \cdot \left(\frac{T_1 - T_{f1}}{L_1}\right) \qquad 1$$

$$D_2 = (D_1 + D_r \cdot y - F_1 \cdot y)\cdot \frac{L_1}{L_2} + B_1 \cdot \frac{C \cdot \Delta T}{L_2} - F_2 \cdot C \cdot \frac{(T_2 - T_{f2})}{L_2} \qquad 2$$

$$D_j = [(D_{j-1} + \sum_{i=1}^{j-2}(D_i + D_r)\cdot y - (j-1)\cdot F_j \cdot y)]\cdot \frac{L_{j-1}}{L_j} + B_{j-1} \cdot \frac{C \cdot \Delta T}{L_j} - F_j \cdot C \cdot \frac{(T_j - T_{fj})}{L_j} \qquad 3$$

* Energy balance is applied to each evaporator in MED unit, in order to find:

$$D_{j+1} = 2 \cdot D_f \cdot \frac{L_j}{L_{j+1}} + 2 \cdot B_j \cdot \frac{C \cdot \Delta T}{L_{j+1}} - F_{j+1} \cdot C \cdot \frac{(T_{j+1} - T_{fj+1})}{L_{j+1}} \qquad 4$$

$$D_{j+2} = \left(D_{j+1} + \sum_{i=1}^{j} (D_i + D_r) \cdot y - (j+n) \cdot F_{j+2} \cdot y \right) \cdot \frac{L_{j+1}}{L_{j+2}} + 2 \cdot B_{j+1} \cdot \frac{C \cdot \Delta T}{L_{j+2}} - F_{j+2} \cdot C \cdot \frac{(T_{j+2} - T_{fj+2})}{L_{j+2}} \qquad 5$$

$$D_n = [(D_{n-1} + \sum_{i=1}^{n-2} (D_i + D_r) \cdot y - (j+n-1) \cdot F_i \cdot y)] \cdot \frac{L_{n-1}}{L_n} + 2 \cdot B_{n-1} \cdot \frac{C \cdot \Delta T}{L_n} - F_i \cdot C \cdot \frac{(T_n - T_f)}{L_n} \qquad 6$$

* The total distillate output from all effects is equal to

$$D = 2 \cdot \sum_{i=1}^{j} D_i + \sum_{j+1}^{n} D_{j+1}, \quad i = 1,2,\ldots 3 \qquad 7$$

* Exergy balance is conducted to the thermo-compressors, evaporators, condenser and the leaving streams to find the exergy destruction (I):

$$I = T_o \cdot \Delta S = E_{in} - E_{out} \quad (8)$$

Thermo-compressor

The exergy destruction in the thermo-compressors

$$I_{ej} = D_s \cdot \left[\left(h_s - h_d\right) - T_o \cdot \left(S_s - S_d\right)\right] - D_r \cdot \left[\left(h_d - h_{gj}\right) - T_o \cdot \left(S_d - S_{gj}\right)\right] \quad (9)$$

Effects

The exergy destruction in the first, second and last effect

$$I_{e1} = (D_s + D_r)\cdot\left[(h_d - h_{fd}) - T_o\cdot(S_d - S_{fd})\right] - D_1\cdot L_1\cdot\left(1-\frac{T_o}{T_{v1}}\right) - F_1\cdot C\cdot\left[(T_1 - T_{f1}) - T_o\cdot In\left(\frac{T_1}{T_{f1}}\right)\right] \quad 10$$

$$I_{e2} = (D_1 + D_r y - F_2 y)\cdot L_1\cdot\left(1-\frac{T_o}{T_1}\right) + B_1\cdot C\cdot\left[\Delta T - T_o\cdot In\left(\frac{T_1}{T_2}\right)\right] - D_2\cdot L_2\cdot\left(1-\frac{T_o}{T_2}\right) - F_2\cdot C\cdot\left[(T_2 - T_{f2}) - T_o\cdot In\left(\frac{T_2}{T_{f2}}\right)\right] \quad 11$$

$$I_{en} = \left[D_{n-1} + \sum_{i=1}^{n-2}(D_i + D_r)\cdot y - (j+n-1)F_i\cdot y\right]\cdot L_{n-1}\cdot\left(1-\frac{T_o}{T_{n-1}}\right) + 2\cdot B_{n-1}\cdot C\cdot\left[\Delta T - T_o\cdot In\left(\frac{T_{n-1}}{T_n}\right)\right] - D_n\cdot L_n\cdot\left(1-\frac{T_o}{T_n}\right) - F_i\cdot C\cdot\left[(T_n - T_f) - T_o\cdot \ln\left(\frac{T_n}{T_f}\right)\right] \quad 12$$

Condenser and Leaving Streams

* The exergy destruction in the condenser,

$$I_c = D_n \cdot L_n \cdot \left(1 - \frac{T_o}{T_n}\right) - M_c \cdot C \cdot \left[\left(T_f - T_c\right) - T_o \cdot \ln\left(\frac{T_f}{T_c}\right)\right] \quad (13)$$

* The leaving streams, D_r ,D_f and B_n can be expressed as:

$$I_{Dr} = D_r \cdot C \cdot \left[\left(T_{vj} - T_c\right) - T_o \cdot \ln\left(\frac{T_{vj}}{T_c}\right)\right] \quad (14)$$

$$I_{Df} = D_f \cdot C \cdot \left[\left(T_{vj} - T_c\right) - T_o \cdot \ln\left(\frac{T_{vj}}{T_c}\right)\right] \quad (15)$$

$$I_{Bn} = D_n \cdot C \cdot \left[\left(T_n - T_c\right) - T_o \cdot \ln\left(\frac{T_n}{T_c}\right)\right] \quad (16)$$

* The heat transfer area of each effect can be obtained from the latent heat of condensation (thermal load).

$$Q = U_e \cdot A_e \cdot \Delta T_e \qquad (17)$$

* heat transfer area for the 1st , 2nd and last effect

$$A_{e1} = \frac{(D_s + D_r) \cdot [h_d - h_{fd}]}{U_{e1} \cdot (T_d - T_1)} \qquad (18)$$

$$A_{e2} = \frac{(D_1 + D_r \cdot y - F_1 \cdot y) \cdot L_1}{U_{e2} \cdot (T_{v1} - T_2)} \qquad (19)$$

$$A_n = \frac{[(D_{n-1} + \sum_{i=1}^{n-2} (D_i + D_r) \cdot y - (j + n - 1) \cdot F_i \cdot y] \cdot L_{n-1}}{U_{en} \cdot (T_{vn-1} - T_n)} \qquad (20)$$

System performance

* The system performance of the ME-TVC model can be evaluated in terms of :

Gain output ratio

$$GOR = \frac{D}{D_s} \quad (21)$$

Specific heat consumption

$$Q_d = \frac{D_s \cdot L_s}{D} \quad (22)$$

Specific exergy destruction

$$I_t = \sum \frac{I_i}{D} \quad (23)$$

Specific heat transfer area

$$\frac{At_d}{D} = 2 \cdot \sum_{i=1}^{j} \frac{A_{ei}}{D_i} + \sum_{j+1}^{n} \frac{A_{ei}}{D_i} + \sum_{i=1}^{n-2} \frac{A_{fi}}{D_i} + \frac{A_c}{D} \quad (24)$$

Specific exergy consumption

$$A_d = \frac{D_s}{D} \cdot \left[\left(h_s - h_{fd} \right) - T_o \cdot \left(S_s - S_{fd} \right) \right] \quad (25)$$

Model Validity

* The validity of the model was tested against some available data of commercial units having different capacities:

- ALBA in Bahrain 2.4 MIGD,
- Umm Al-Nar in UAE 3.5 MIGD
- Al-Jubail in KSA 6.5 MIGD.

* The results showed good agreements

Table 2: Model results against the actual data.

Desalination Plant	Alba		Umm Al-Nar		Al-Jubail	
Number of effects	**4**		**6**		**8**	
Unit capacity, MIGD	**2.4**		**3.5**		**6.5**	
Oper. & Desi. Parameters	M	A	M	A	M	A
Motive pressure, bar	21	21	2.8	2.8	2.7	2.7
Top brine temperature, ^{o}C	63	63	63	62	63	NA
Minimum brine temperature, ^{o}C	48	48	44	43	42	NA
Motive steam flow rate, kg/s	17	16.8	22	21.3	31	NA
Temperature drop per effect, ^{o}C	5	5	3.8	3.8	3	NA
System Performance						
Gain output ratio	7.23	7.5	8.37	8.6	10.9	NA
Specific heat consumption, kJ/kg	348	NA	292	287	223	NA
Specific exergy consumption, kJ/kg	127	NA	74	NA	56	NA
Specific heat transfer area, m^2/kg/s	244	NA	335	310	452	NA
Specific exergy destruction, kJ/kg/s	94	NA	54	NA	41	NA

Sensitivity analysis

* A sensitivity analysis is carried out to investigate the system performance variations of Al-Jubail unit.

* This project belongs to Marafiq Company and it is currently considered as the largest ME-TVC plants in the world, **(176 MIGD).**

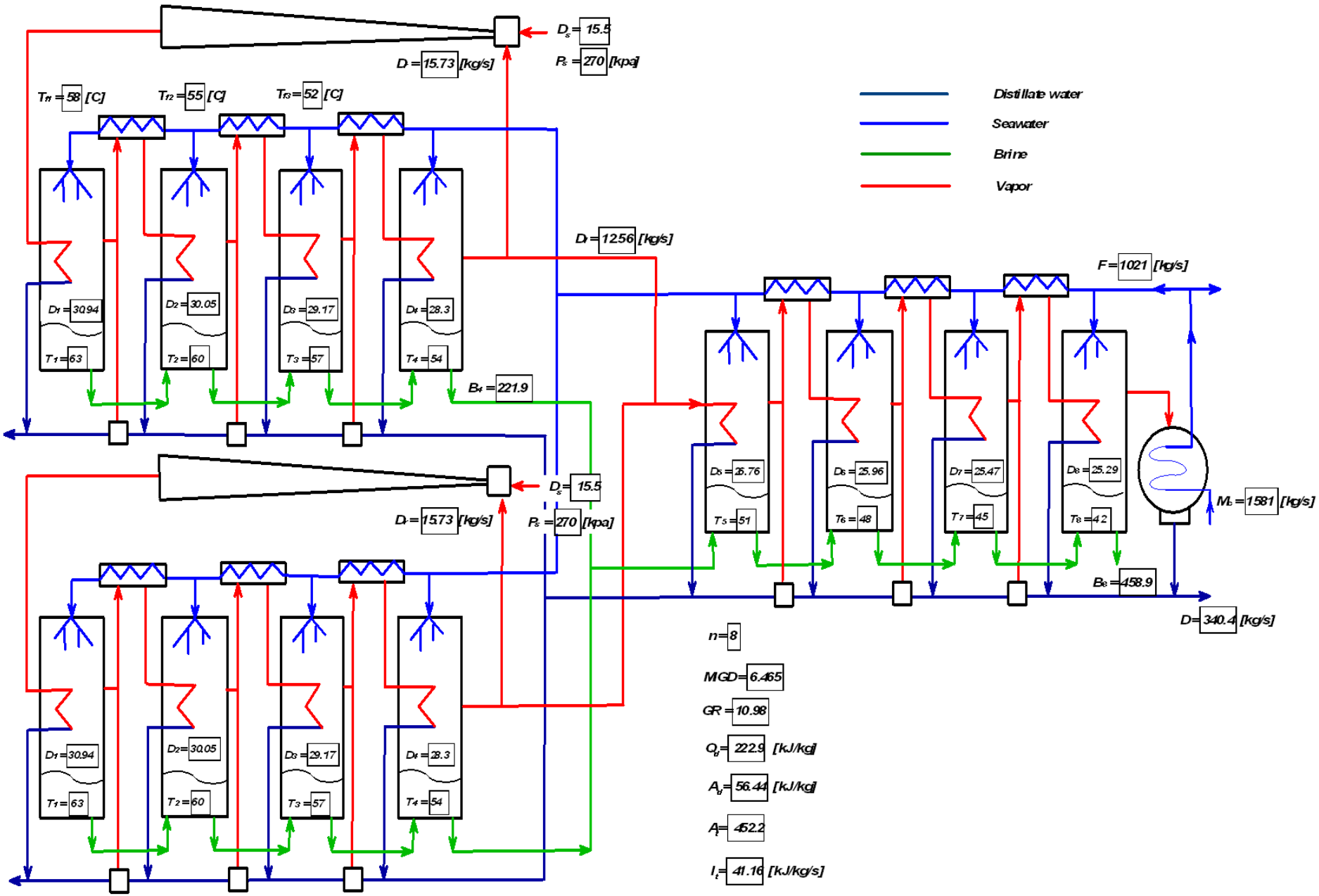


Fig. 3 Schematic Diagram of Al-Jubail ME-TVC unit

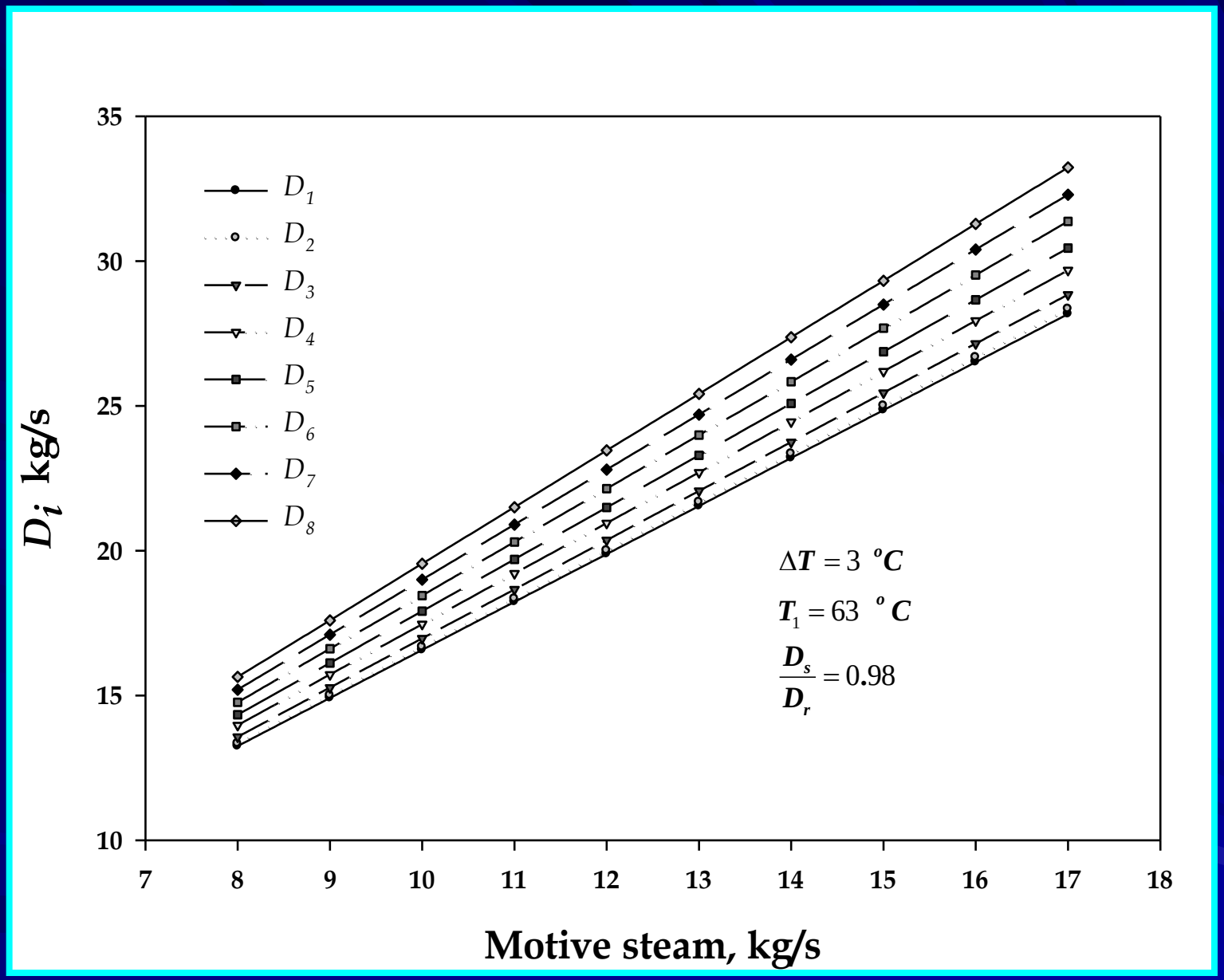


Fig. 4 The effect of motive steam on the distillate production from the effects.

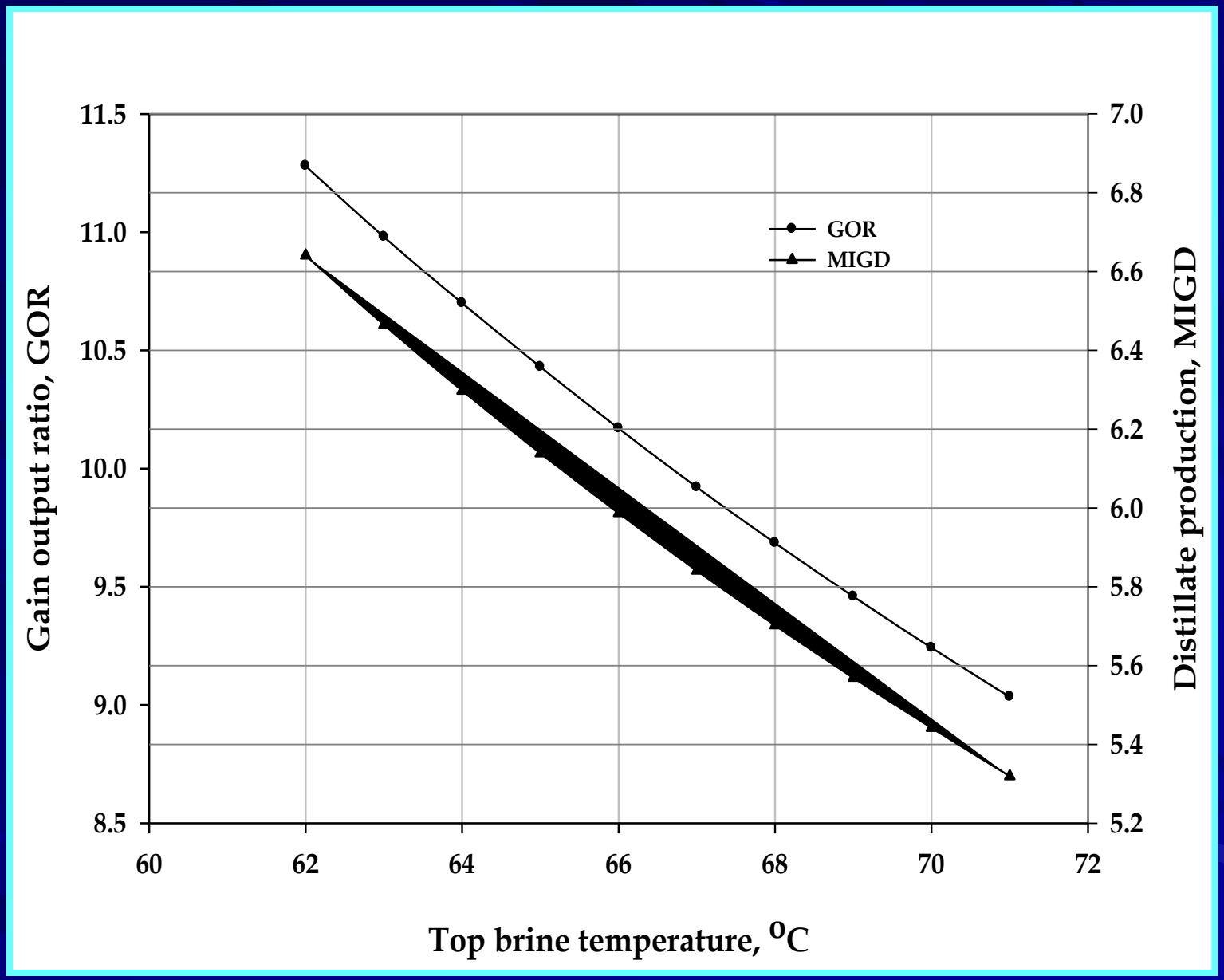


Fig.5 The effect of T_1 on the distillate production and gain ratio.

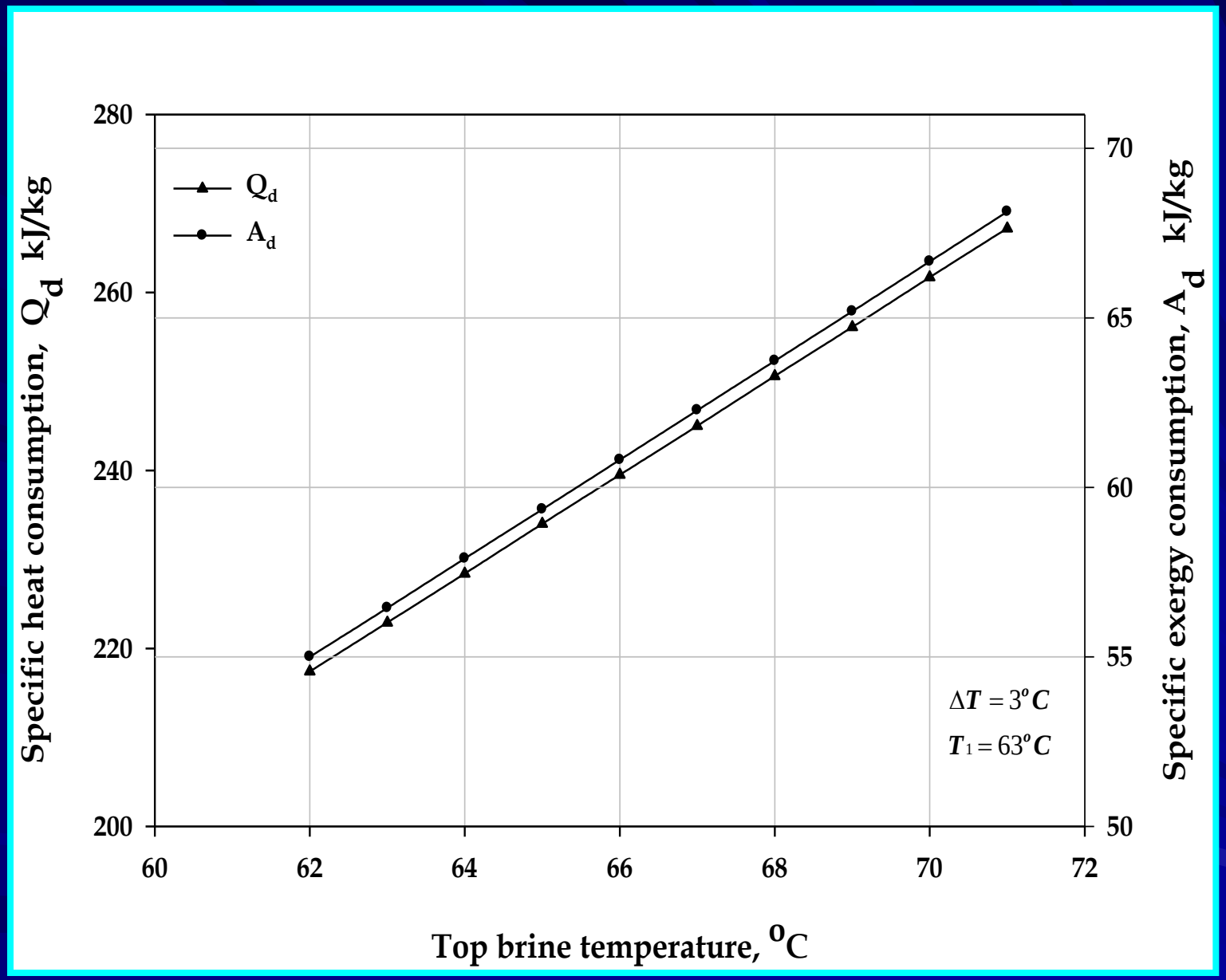


Fig.6 The effect of T_1 on the specific heat and specific exergy consumption.

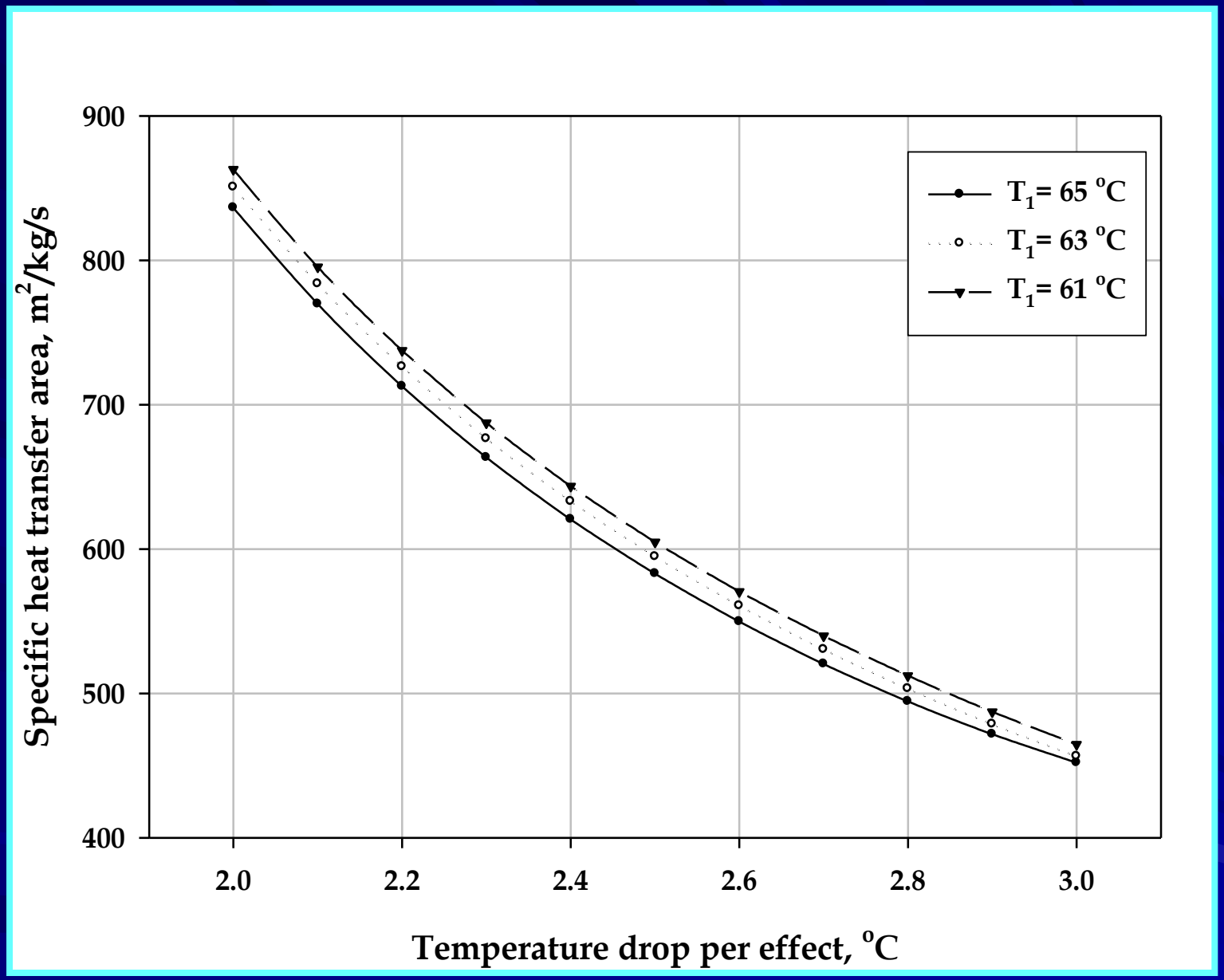


Fig.7 The effect of ΔT on the specific heat transfer area at different T_1

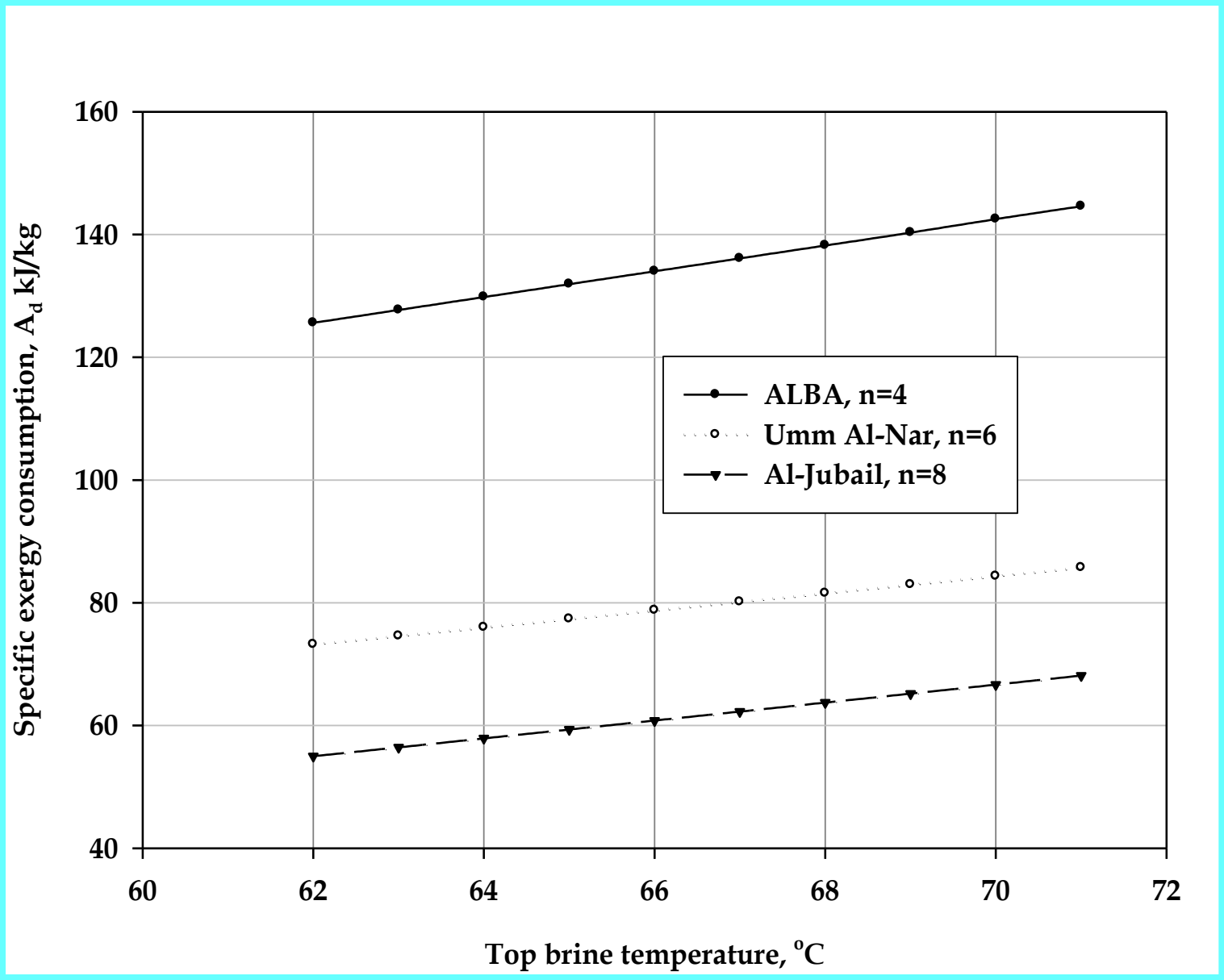


Fig.8 The effect of T_1 on the specific exergy destruction for different units

AL-Jubail, 6.5 MIGD

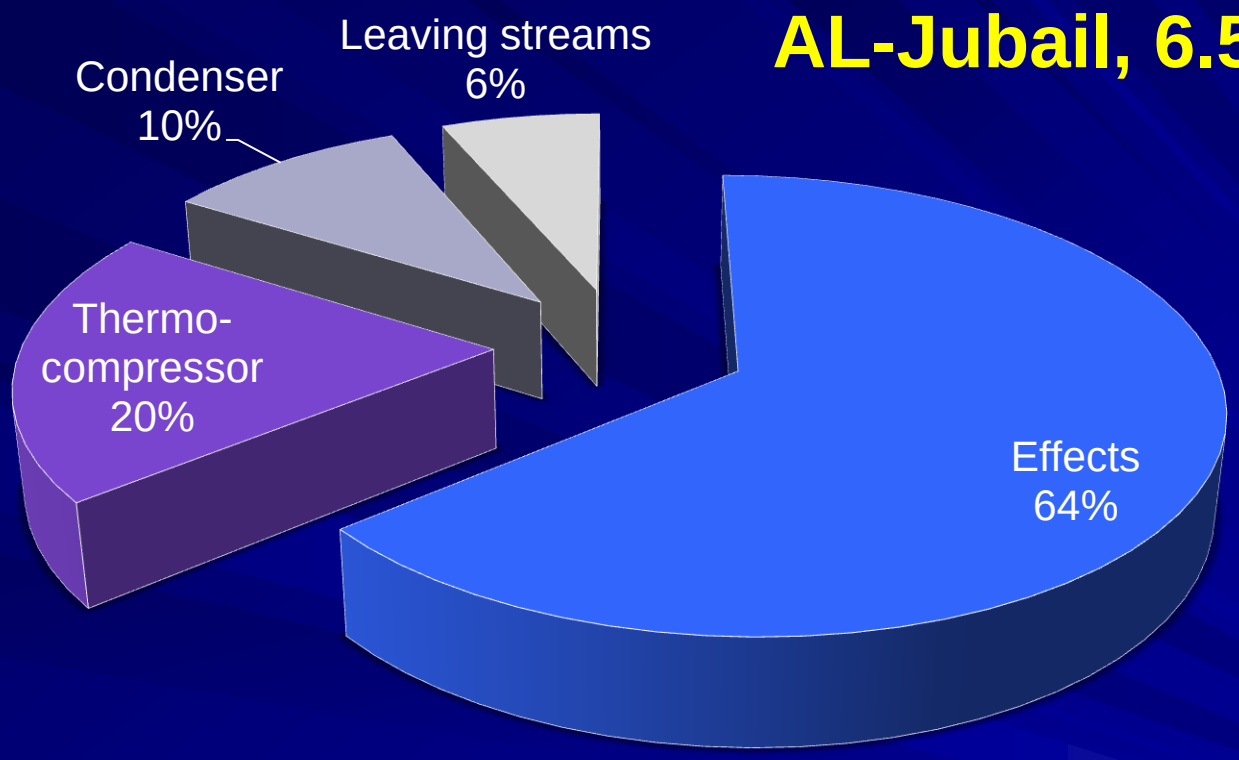


Fig.9 The main exergy destructions in Al-Jubail Unit.

Thermo-compressors and effects are the main sources of exergy destruction

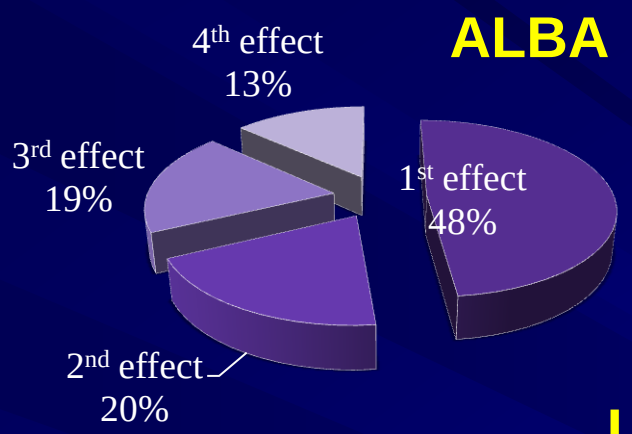
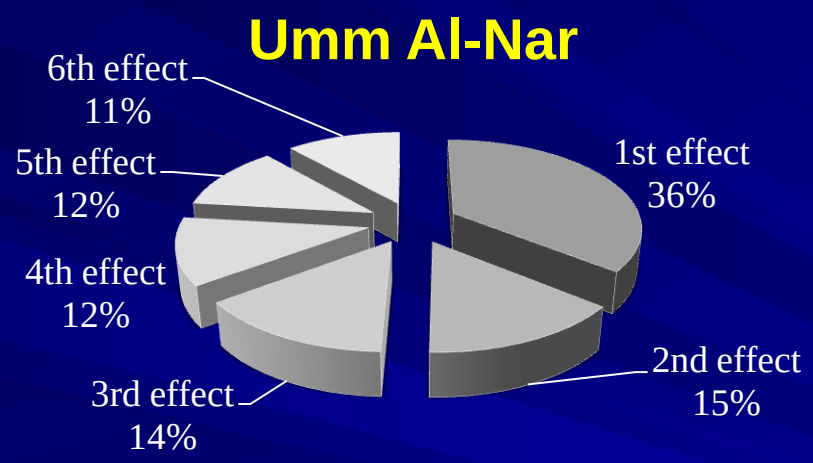
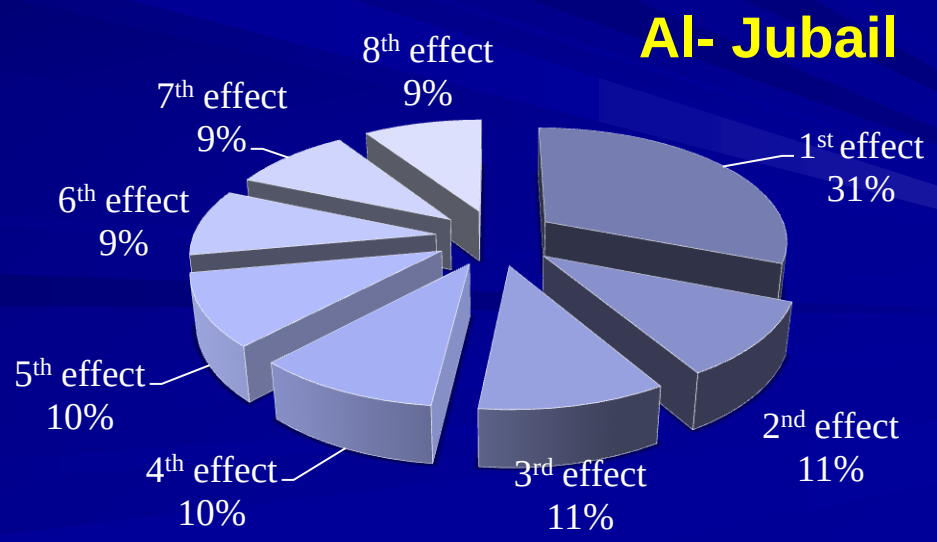


Fig. 10 The exergy destruction distribution in the effects.





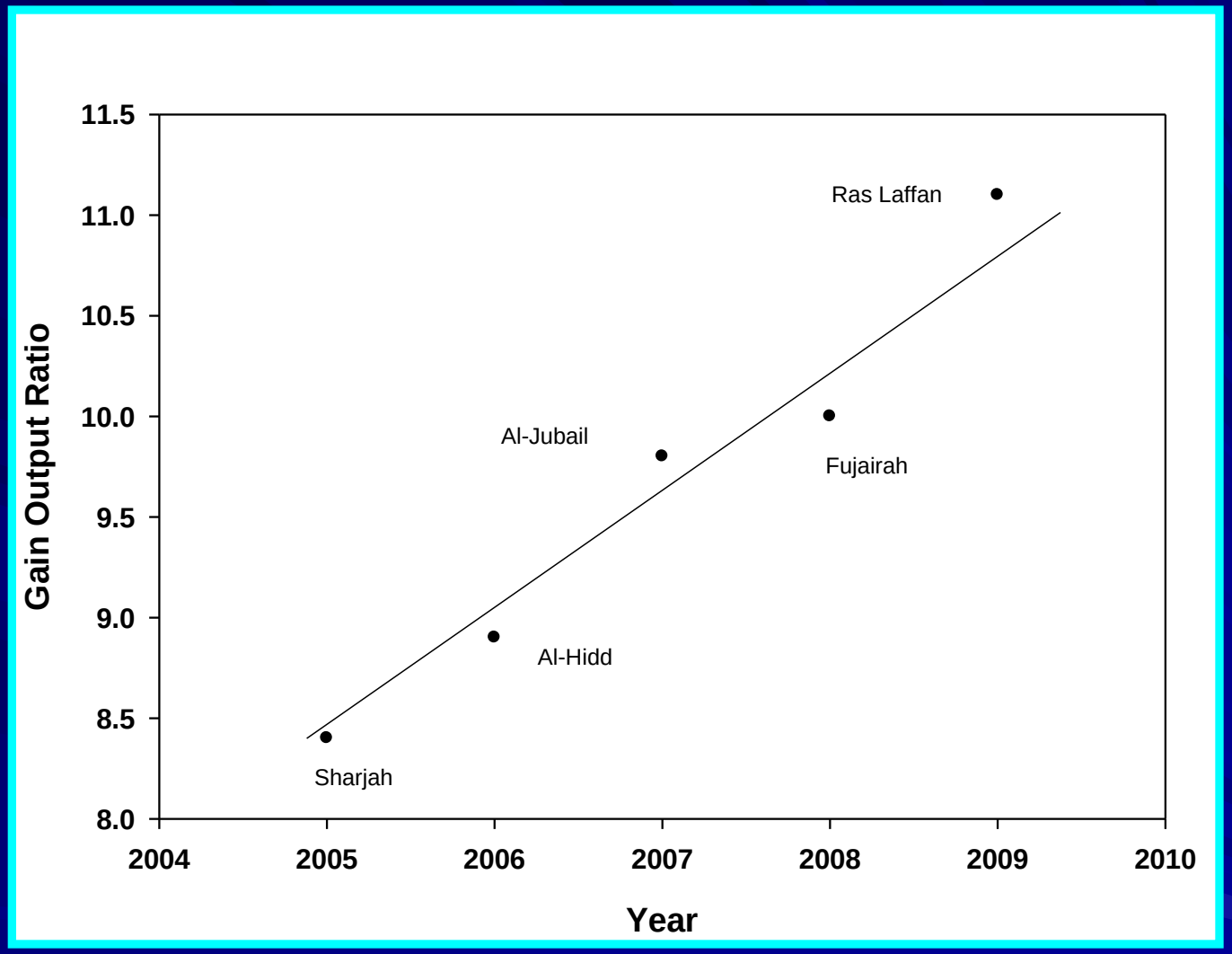


Fig. 11 The increase of gain ratios in the new projects.

Table 3. Most ME-TVC units operated by CCPP in the new projects.

Plant	ALBA	Umm Al-NAR	Al-JUBAIL	Al-Fujairah
Country	Bahrain	UAE	KSA	**UAE**
Year of commission	1999	2000	2007	**2008**
Source of steam	Boiler	CG-ST/HRSG	CG-ST/HRSG	**CG-ST/HRSG**
Type of fuel	Diesel oil	Natural gas	Natural gas	**Natural gas**
Power Capacity, MW	-	1700	2700	**2000**
Desalination	ME-TVC	ME-TVC	ME-TVC	**ME-TVC/RO**
Unit capacity, MIGD	2.4	3.5	6.5	**8.5/RO**
Number of units	4	2	27	**12/RO**
Total capacity, MIGD	9.6	7	176	**100+30**
Number of effects	4	6	8	**10**
Water cost, US $/m^3	NA	NA	0.827	**0.60**

Hybrid desalination system is introduced in Al-Fujairah project

(large ME-TVC units of 8.5 MIGD with RO).

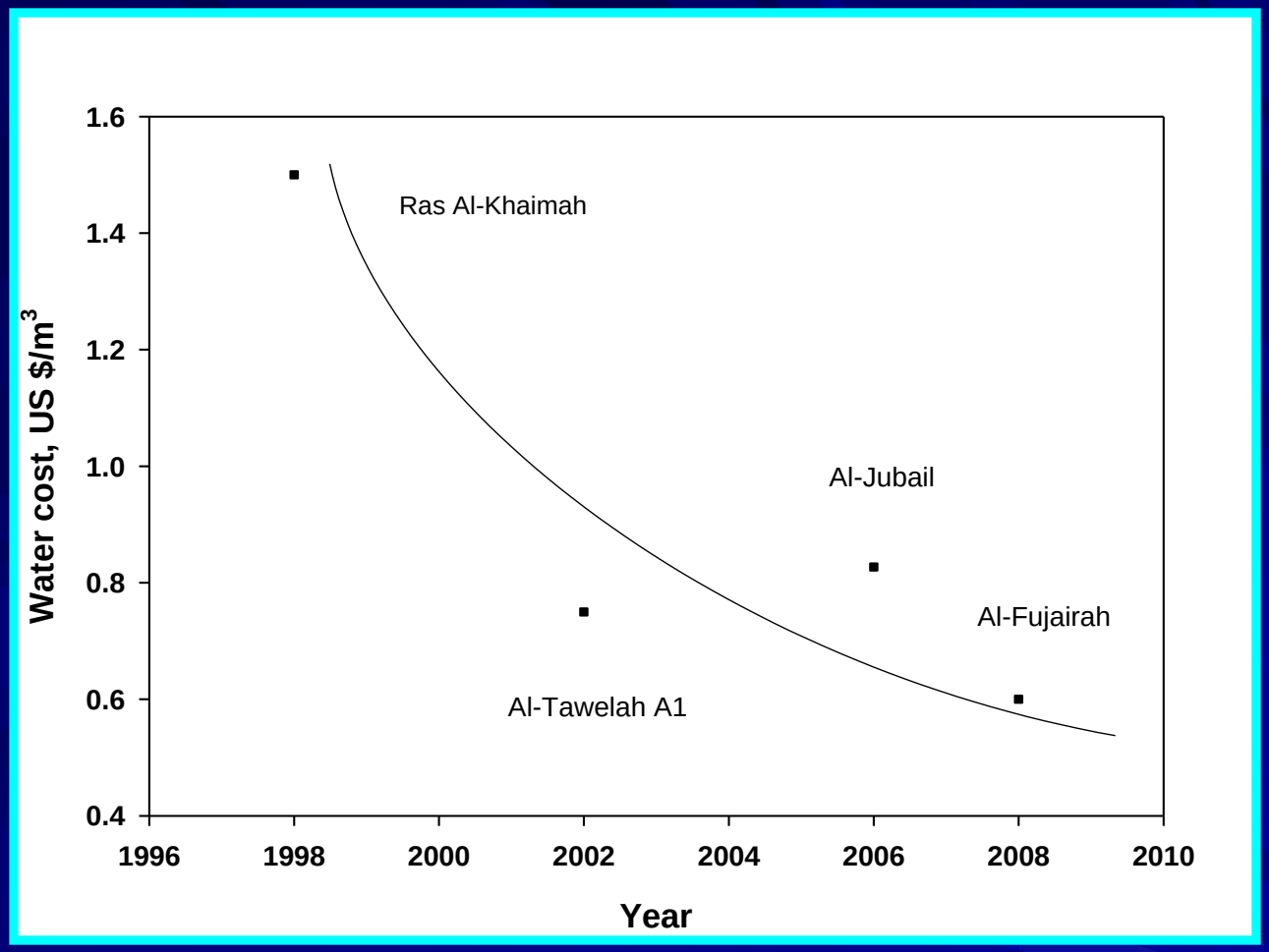


Fig. 12 The decrease in the water cost in the last decade (ME-TVC).

Conclusions

* The new trend of combining ME-TVC unit with a conventional MED unit has been used lately in several large projects. This trend provides an approach to increase the unit capacity with a more compact design.

* Exergy analysis shows that the specific exergy destruction in ALBA unit is almost twice that in Umm Al-Nar and Al-Jubail units because high motive pressure is used in ALBA compared to low motive pressure in other units.

* The analysis indicates that thermo-compressors and the effects are the main sources of exergy destruction in these units.

* The first effect of Al-Jubail was found to be responsible for about 31% of the total effects exergy destruction compared to 48% in ALBA and 36% in Umm Al-Nar.

* The specific exergy destruction can be reduced by increasing the number of effects as well as working at lower top brine temperatures.

* The manufacturer tried to increase the number of effects gradually (4, 6, 8, etc.) in order to increase the size of the units in a compact design

* Most of the new ME-TVC units are commonly operated with large combined cycle power plants in order to reduce the power and water cost.

THANK YOU