EXERGY ASSESSMENT FOR A TYPICAL MULTI-EFFECT THERMAL VAPOR COMPRESSION DESALINATION UNIT (MED-TVC)

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الملخص

تهدف هذه الورقة إلى تقييم الأداء الديناميكي الحراري للوحدة الأولى في محطة التحلية بمدينة الزاوية التي تم توريدها من قبل شركة سيدم الفرنسية وقامت شركة انكا- تيكنيكا التركية بتركيبها حيث بدأت المحطة بإنتاج مياه الشرب في سنة 2010. تتكون المحطة المبنية على نظرية التحلية متعددة المراحل مع الضغط الحراري للبخار من أربع مراحل بسعة إجمالية قدرها 80,000 متر مكعب في اليوم. تم تبني البيانات التصميمية والحقيقية لغرض التحليل ومقارنة النتائج حيث وُجد أن أكبر تحطيم في الاكسيرجي يحدث أثناء ضغط البخار حراريا بنسبة 45.76% من الاكسيرجي المستهلكة في تشغيل الوحدة، بينما الفقد في الاكسيرجي مع التدفق الخارج من وحدة التحلية يسهم بما نسبته 22.25% من الاكسيرجي المستهلكة. بيّنت النتائج أيضاً أن المؤثرات والمسخنات والمكثف النهائي يسهم كل منها بما نسبته 16.13%، 7.84% و 8.02% من الاكسيرجي المستهلكة بالترتيب.

ABSTRACT

The aim of this paper is devoted to assess the thermodynamics performance of unit one of Zawia city desalination plant. The plant was supplied by French company SIDEM and constructed by Turkish ENKA TEKNIK Company started producing distillate water in July 2010. The plant is based on multiple-effect distillation with thermal vapor compression technology and consists of four units with total capacity of 80,000 m^3/day. Design and real time data in summer and winter sessions are adopted for the analysis. The analysis reveals that the thermal vapor compression and the effects are the main source of exergy destruction. The major exergy destruction takes place during the thermal vapor compression processes, which contribute to an average value of 45.76%% of the consumed exergy. Losses contribute to about 22.25% of the consumed exergy. Effects, pre-heaters and final condenser contribute on average to 16.13%, 7.84%, and 8.02% of the consumed exergy, respectively.

KEYWORDS: Desalination; Exergy; Irreversibility; Thermal Vapor Compression; Effectiveness.

INTRODUCTION

Exergy concept is adopted to assess the thermodynamic performance of a typical multi-effect thermal vapor compression desalination unit (MED-TVC). The purpose is to quantify the amount of exergy destroyed in each component of the plant which reflects the cost of the product. To improve the thermodynamics performance of seawater desalination plants, irreversibilities within the plant's components should be understood and reduced [1]. Several studies have been published since the early of 1990's concerning Multi-Effect-Thermal Vapor Compression (ME-TVC) desalination plants.

Exergy analysis was performed for conventional Multi Effect Boiling (MEB), Mechanical Vapor Compression (MVC) and MED-TVC desalination plants by Zamamiri, et al. [2]. Results showed that MED-TVC desalination plant restrained good thermodynamic effectiveness.

Al-Najem et al. [3] presented energy and exergy analysis for the individual components for single and multi effect thermo-vapor compression systems. Results showed that the steam ejector and the evaporator were the main source of exergy destruction.

Alasfour et al. [4] developed mathematical models for three configurations of a MED-TVC desalination system using energy and exergy analysis. A parametric study was also performed to investigate the impacts of different parameters on the system performance. Results showed that the first effect was responsible for about 50 % of the total effect exergy destruction. The parametric study also showed that the decrease in exergy destruction was more pronounced than the decrease in the gain output ratio at lower values of motive steam pressure. It was found lowering the temperature difference across the effects, by increasing the surface area, would decrease the specific heat consumption. On the other hand, exergy losses were small at low temperature difference and low top brine temperature.

Choi et al. [5] presented an exergy analysis for MED-TVC pilot plant units, which were developed by Hyundai Heavy Industries Company. Exergy analysis showed that most of the specific exergy losses were in thermal vapor compressor and the effects.

Wang & Lior [6] presented the performance analysis of a combined humidified gas turbine (HGT) plant with MED-TVC desalination systems using second law of thermodynamics. The analysis was performed to improve the understanding of the combined steam injection gas turbine power and water desalination process and ways to improve and optimize it. Results showed that the dual purpose systems had good fuel utilization and design flexibility.

Sayyaadi & Saffari [7] developed thermo-economic optimization model of a MED-TVC desalination system. The model was based on energy and exergy analysis. A genetic algorithm was used to minimize the water product cost.

Exergy analysis for Zuara desalination plant in Libya was introduced by A. Muftah and G. Fellah [8]. Zuara desalination plant is based on Multi-Effect Desalination Technology (MED), and consists of three units with total capacity of 40000 m^3 per day. A thermodynamic analysis was developed to find the contribution of unit's components to total exergy destruction. The analysis showed that the unit effectiveness was about 16% during the performance test (full load); however, for half load performance the effectiveness decreased severely to 4.651%. By using different operating data for the analysis, the results showed that the unit operation was more efficient at full load than half load, and summer session operation was more effective than winter session.

New Trend in the Development of MED-TVC Desalination System was given by Anwar Bin Amer [9]. Exergy analysis showed that the specific exergy destruction in ALBA unit (94.65 kJ/kg) was almost twice that in Umm Al-Nar and Al-Jubail units of 54.24 kJ/kg and 41.16 kJ/kg respectively, this because a high motive pressure of 21 bars was used in ALBA compared to low motive pressure of 2.8 bars in other units. The analysis indicated that thermo-compressor and the effects were the main sources of exergy destruction in these units. On the other hand, the first effect of this unit was found to be responsible for about 31% of the total effects exergy destruction compared to 46% in ALBA and 36% in Umm Al-Nar. It was claimed that, the specific exergy destruction could be reduced by increasing the number of effects as well as working at lower top brine temperatures.

MODELING OF UNIT ONE OF ZAWIA DESALINATION PLANT

The plant is located on the north-west of Libyan coast on the Mediterranean Sea, at Zawia city (32^{o} N 12^{o} E). The plant was supplied by French company SIDEM and constructed by ENKA TEKNIK Company, near Zawia electrical power station. It started producing distillate water in July 2010.

The plant consists of four 20,000 m^3/day (4.4 MIGD-Million Imperial Gallon per Day-) MED-TVC units with total capacity of 80,000 m^3/day (17.6 MIGD). A schematic diagram for Zawia desalination plant (MED-TVC) system is shown in Figure (1). Each unit consists of two separate rows of effects cell1A, cell2A, cell3A and cell1B, cell2B, cell3B, each packed into one circular vessel along with a thermo-compressor. Both vessels are connected parallel with a third vessel in the middle, which contains two effects cell4 and cell5 along with a final condenser. The incoming seawater is first preheated in a distillate cooler and then heated in a final condenser. A fraction of seawater is rejected to surroundings when necessary, and the remaining seawater flows uniformly to each effect. Seawater spreads as a thin film over the evaporator's horizontal tubes. A small fraction of the saturated steam from the boiler flows to a vacuum ejector and the remaining steam to a thermo-compressor as a motive steam. The flow of motive steam leaving the nozzle creates a vacuum to withdraw the vapor, which is generated in the third 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 leaves the first effect then returns to the boiler loop, and some of the condensate is sprayed into the TVC to control the steam temperature. The vapor, which is generated in the first effect, flows to the tube side of the next effect, where the same process of condensation and evaporation is repeated. The brine, which is produced in one effect, cascades down to the next effect for flashing. The seawater from the last effect is discharged as rejected brine. The collected condensate from all effects flows to a distillate cooler, where it serves to preheat the incoming seawater, and then pumped to a storage tank.

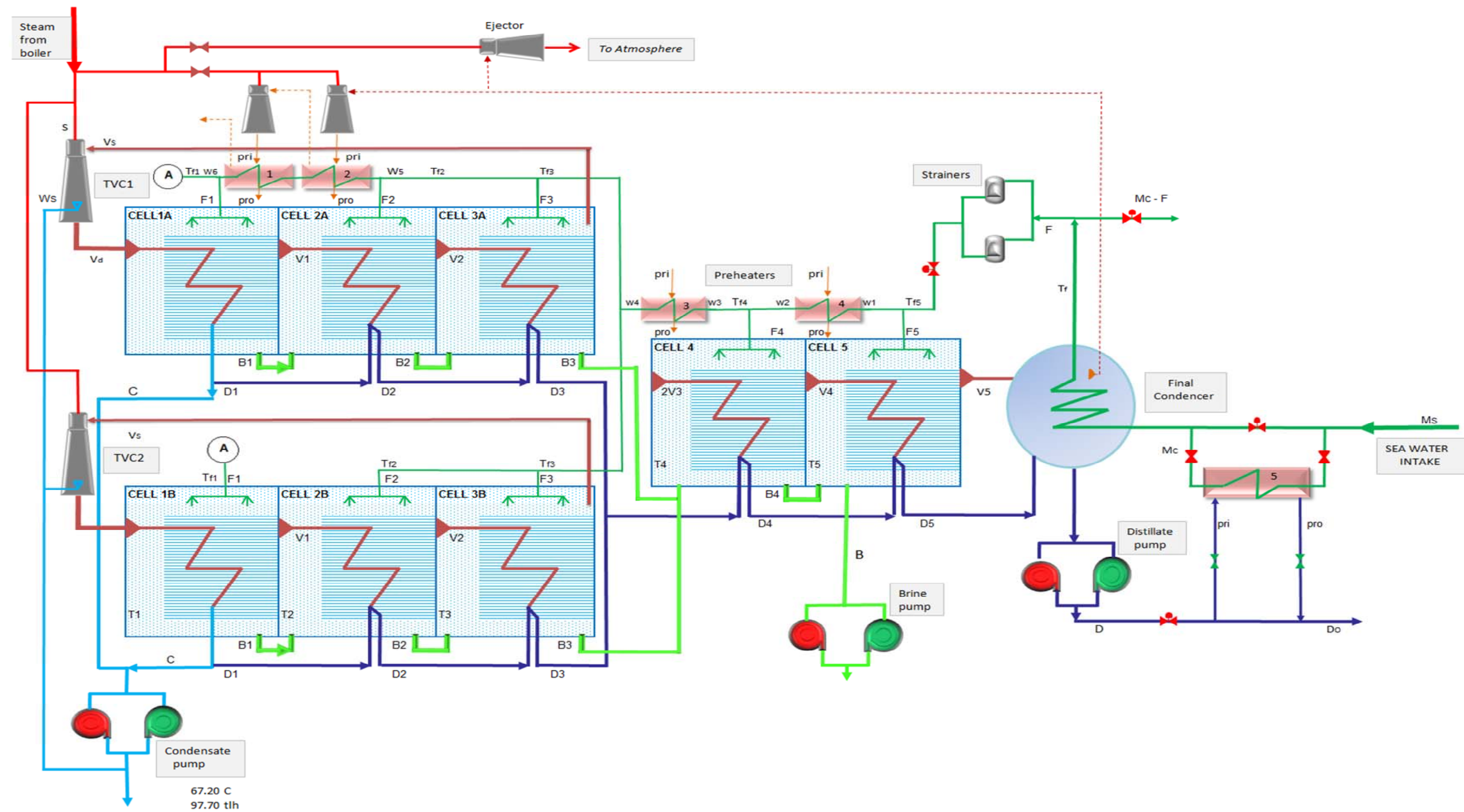


Figure 1: Schematic diagram for unit one of Zawia desalination plant

Assumption

The following assumptions are adopted for the analysis:

- For seawater only Sodium Chloride (NaCl) with a mass fraction (x_s) of 4.2 % (42,000 ppm) is considered.
- The water-NaCl solution is an ideal solution.
- All processes are steady-state and steady-flow with negligible potential and kinetic energy effects.
- The contribution of chemical exergy to total exergy is small and neglected.
- The salinity of the incoming raw water is constant.
- The system components are insulated and hence the heat loss is neglected.
- The restricted reference state is at 25°C and 1.013 bar.

Mass and Energy Balance Equations

The mass balance for a steady-state, steady-flow process is:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

$\dot{m}_{in}$ and $\dot{m}_{out}$ are mass flow rates entering and leaving the control region respectively. Steady-state, steady-flow energy equation without work and heat terms is written as:

$$\sum \dot{m}_{in} h_{in} = \sum \dot{m}_{out} h_{out} \tag{2}$$

h_{in} and h_{out} are the enthalpies of streams entering and leaving the control region respectively.

Exergy Balance Equations

For steady-state, steady-flow process, the destroyed exergy (Irreversibility, $\dot{I}$) is:

$$\dot{I} = \sum \dot{\Psi}_{in} - \sum \dot{\Psi}_{out} \tag{3}$$

Where: $\dot{\Psi} = \dot{m}\left[\left(h - h_o\right) - T_o\left(s - s_o\right)\right]$ (4)

Where h and h_o are the enthalpies at the given state and at the restricted dead state respectively, and s and s_o are the entropies at the given state and at the restricted dead state respectively.

Seawater Enthalpy Equation

The enthalpy of seawater is [10]:

$$h = \left\{ \begin{array}{l} 4.2045016T - 0.0678226CT + 1.47532 \times 10^{-3} C^2 T \\ - \left[\left(6.8002552 - 3.095114C + 0.1624438C^2\right) \times 10^{-4} T^2\right] \\ + \left[\left(5.3015464 - 1.6853152C + 0.0853674C^2\right) \times 10^{-6} T^3\right] \\ - 0.04881 \end{array} \right\} \times 1000 \tag{5}$$

T: is seawater temperature in °C, and C: is the seawater salinity in %.

Seawater Entropy Equation

The specific entropy of sea salt in seawater is [10]:

$$s_s = XC + YC^{1.5} + ZC^2 \tag{6}$$

$$X = 1.421815 \times 10^{-3} + 3.1337 \times 10^{-7} T + 4.2446 \times 10^{-9} T^2 \tag{7}$$

$$Y = -2.1762\times10^{-4} + 4.1426\times10^{-7}T - 1.6285\times10^{-9}T^2 \tag{8}$$

$$Z = 1.0201\times10^{-5} + 1.5903\times10^{-8}T - 2.3525\times10^{-10}T^2 \tag{9}$$

T is seawater temperature in ºC, and C is seawater salinity in ppm. Saline water can be considered as an ideal solution, the entropy can be found by:

$$S = m_s s_s + m_w s_w \tag{10}$$

s_s and s_w are the specific entropies of sea salt and pure water, respectively.

Gain Output Ratio "GOR"

The gain output ratio is used to evaluate the performance of thermal desalination processes. It is defined as the ratio of total produced distilled water ($m_{\text{distillate}}$) to the motive steam supplied (m_{steam}).

$$GOR = \frac{m_{\text{distillate}}}{m_{\text{steam}}} \tag{11}$$

Specific Heat Consumption "Q_d"

This is one of the most important characteristics of thermal desalination systems. It is defined as the thermal energy consumed by the system to produce one kilogram of distilled water.

$$Q_d = \frac{m_{\text{steam}}}{m_{\text{distillate}}} L \tag{12}$$

Where L is the motive steam latent heat in kJ/kg.

Specific Exergy Consumption "ΔΨc"

The specific exergy consumption is one of the best methods used to evaluate the performance of the ME-TVC. It is defined as the exergy consumed by the motive steam to produce one kilogram of distillate. Steam enters as saturated vapor and returns to boiler as saturated liquid at lower temperature and pressure, hence:

$$\Delta\Psi_c = \frac{\dot{m}_{\text{steam}}}{\dot{m}_{\text{distillate}}}\left[\left(h_{\text{steam}} - h_{\text{condensate}}\right) - T_o\left(s_{\text{steam}} - s_{\text{condensate}}\right)\right] \tag{13}$$

Specific Exergy Destruction

The specific exergy destroyed per unit distillate (Irreversibility per unit distillate, I) is the algebraic summation of the rate of exergy change across unit's components divided by the mass flow rate of the distillate water, and can be expressed as:

$$\dot{I}/\dot{m}_{\text{distillate}} = \frac{\sum\Delta\dot{\Psi}}{\dot{m}_{\text{distillate}}} \tag{14}$$

The main design and real time data (Table (1)) are obtained from the records of the General Company of Electricity (GECOL), the owner of the Zawia Desalination Plant.

Table 1: Main design and real time data

	Design data		Real time data	
	Winter	Summer	Winter	Summer
Steam temperature (^oC)	224	224	222	222.2
Steam pressure (bar)	25	25	22	22.4
Steam mass flow rate perTVC (t/h)	46.6	46.6	45	45
Condensate temperature (^oC)	70	70	70	70
Distillate water temperature (^oC)	21	41	21.46	41
Distillate water mass flow rate (t/h)	831.14	835.55	831.89	836.03
Sea water temperature (^oC)	17.5	27	19.5	26
Sea water mass flow rate (t/h)	2750	2750	2756.20	2758.8
GOR	8.92	8.97	9.24	9.29

RESULTS AND DISCUSSION

Thermodynamic analysis is performed for unit one of Zawia desalination plant. The plant produces 20,000 m^3/day (833.33 t/h, 4.4 MIGD) of distilled water. Design and real time data (full load) for winter and summer sessions are adopted for the analysis.

The specific heat consumption is calculated and plotted in Figure (2), where values between 37.57 and 39.94 kWh/m^3 are obtained. Deviation of specific heat consumption by using real time and design data is no more than 3.5%. For 4.4 MIGD, specific heat consumption of 29.1 kWh/m^3 was reported [5].

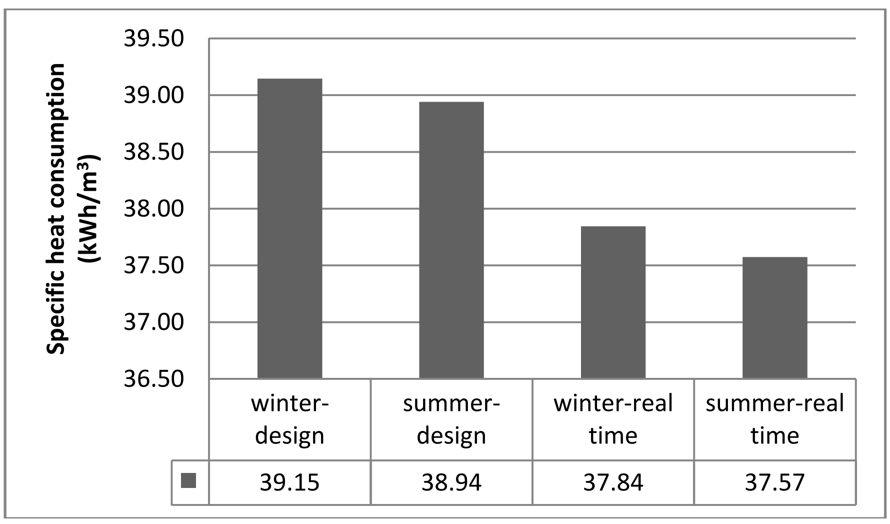


Figure 2: Specific heat consumption

Specific exergy consumption is an indicator for the thermodynamic performance of the desalination unit. Exergy consumption is the difference between the inlet steam and condensate exergies. The results are plotted in Figure (3). Since the flow rates and the temperatures of the steam and the condensate are almost close values (Table (1)), the specific exergy consumptions are almost identical for design and real time with value of about 23 kWh/m^3.

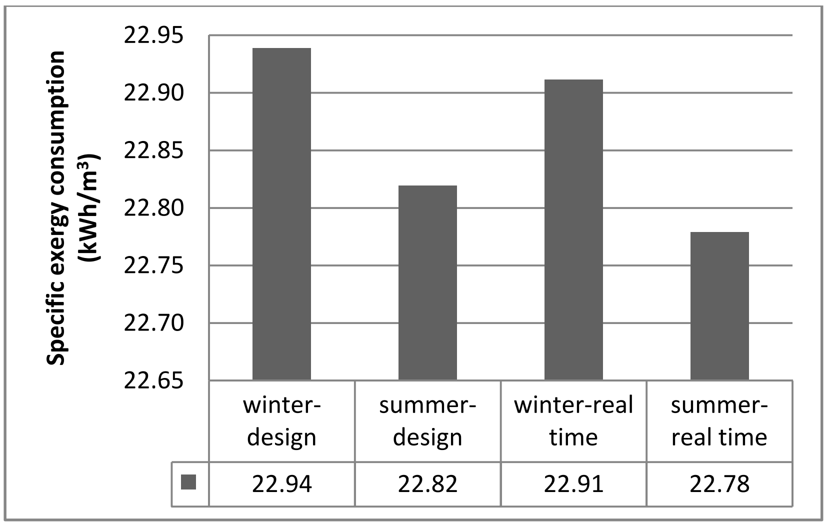


Figure 3: Specific exergy consumption

Specific exergy destruction is a relevant tool for performance evaluation. The specific exergy destruction is plotted in Figure (4), where values between 21.24 and 23.71 kWh/m^3 are obtained. Typical value of 28.15 kWh/m^3 for 4.4 MIGD was reported [5]. Values between 14 and 24kWh/m^3 were also found in the literature [8]. Differences are due to deviation of design data and system configuration.

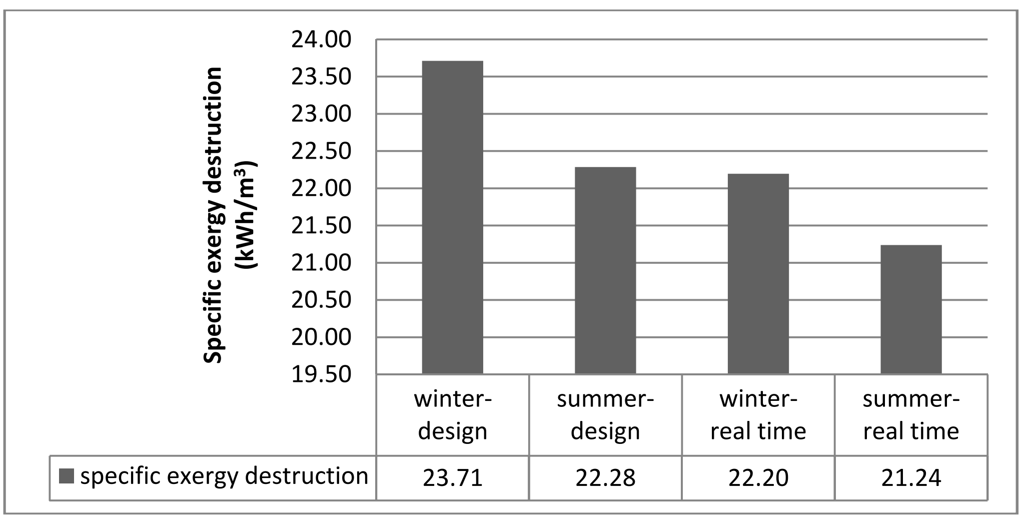
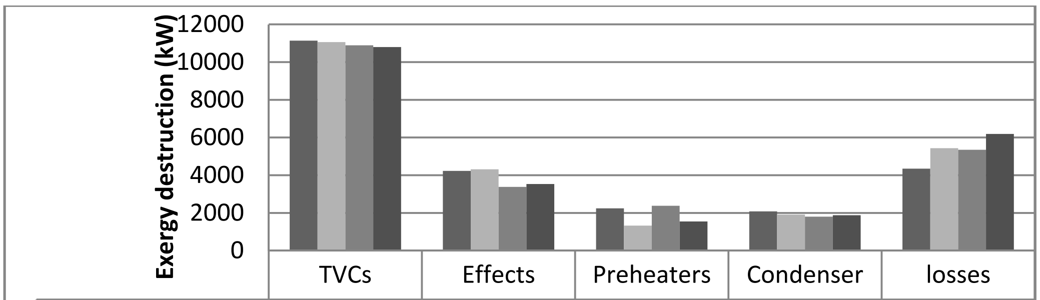


Figure 4: Specific exergy destruction (kWh/m^3)

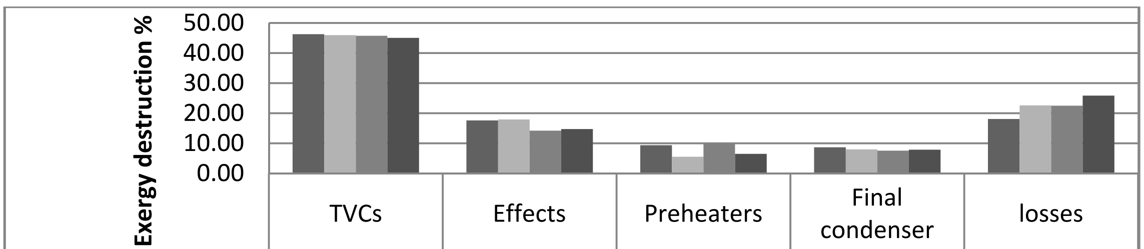
The contribution of unit's components to the destructed exergy is shown in Figure (5), and its percentage relative to total consumed exergy is shown in Figure (6). The major exergy destruction occurs in the thermal vapor compressors (ejectors). Around 45.5% of the consumed exergy is destroyed during thermal compression process.

To reduce irreversibility, another source of steam at lower temperature and pressure is recommended. Losses include exergy content of out flow streams (brine and distillate water) contribute to about 18.07 to 25.85% of the consumed exergy. The results are consistent with that given in the literature [5].



	TVCs	Effects	Preheaters	Condenser	losses
winter-design	11132	4235	2251	2090	4347.79
summer-design	11056	4317	1329	1917	5436.79
winter- real time	10891	3383	2384	1805	5354.66
summer-real time	10792	3533	1548	1882	6191.07

Figure 5: Rate of Exergy destruction for different operating conditions



	TVCs	Effects	Preheaters	Final condenser	losses
winter-design	46.28	17.60	9.36	8.69	18.07
summer-design	45.96	17.95	5.52	7.97	22.60
winter-real time	45.72	14.20	10.01	7.58	22.48
summer-real time	45.07	14.75	6.46	7.86	25.85

Figure 6: Exergy destruction percentage for different operating conditions

CONCLUSIONS AND RECOMMENDATIONS

- Exergy analysis is performed for unit one of Zawia MED-TVC desalination plant.
- Only physical exergy is considered for the analysis. So as a future task, chemical exergy may be considered.
- Specific heat consumption, specific exergy consumption and specific exergy destruction are calculated and plotted. The results are consistent with that given in the literature.
- Results show that the TVC is the main source of exergy destruction.
- Results for design and real time data are close.
- Instead of using separate boiler to produce steam for heating and evaporating seawater, it is recommended, to have the steam from the low pressure steam turbine of Zawia power station. That might reduce the specific exergy destruction, and improve the overall performance.

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