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Desalting fuel energy cost in Kuwait in view of $75/barrel oil price

M.A. Darwish
Mechanical Engineering Department, Kuwait University, POB 5969, Safat 13060, Kuwait
Tel. +965 481-1188, ext. 5789; Fax: +965 484-7131; email: darwish@kuc01.kuniv.edu.kw

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Abstract

Desalination is an energy intensive process. All seawater desalting processes, multi-stage flash (MSF), multi-effect boiling (MEB), and seawater reverse osmosis (SWRO) consume significant amounts of energy. In view of the rising fuel costs, US$75 per barrel of oil, the amount and cost of fuel consumed to desalt seawater becomes one of the main factors determining the final desalted water cost. This in turn becomes a major factor in choosing the method to be used. Some desalting systems (MSF and MEB) are usually combined with power plants in what is called co-generation power desalting plants, or CPDP. Fuel is supplied to the CPDP to produce both desalted water D and power W, and the fuel cost is to be allocated between the two products D and W. Exergy analysis and equivalent work are among the methods used to determine the fuel energy charged to each product. When a desalting system, such as SWRO, is not combined with a power plant, the fuel energy can be directly determined. In this paper the fuel energy consumed for desalting water in the most used arrangements are calculated based on exergy analysis. These arrangements include: (1) Seawater reverse osmosis, SWRO, desalting units supplied with a) electric energy from steam power plant of typical η_c = 0.388, and b) combined gas/steam power cycle of typical η_c = 0.54. The SWRO is assumed to consume typical 5 kWh/m^3 electric energy. (2) MSF units such as the units operating in Kuwait CPDP, which consumes thermal energy of value 258 kJ/kg by steam supplied to the brine heater and 16 kJ/kg by steam supplied to steam ejectors, and mechanical energy of 4 kWh/m^3 for pumping. The MSF can be operated by: (a) steam extracted from steam turbines as in cogeneration power desalting plants, CPDP, using extracting/condensing steam turbines as in Kuwait and most Arab Gulf countries, called later case 1; (b) Steam supplied directly from boilers having boiler efficiency = 0.9 as in single purpose desalting plants, such as Al Shuwaikh desalting plant in Kuwait, case 3b or in winter time when no steam turbines are available in the CPDP to supply steam to the desalting units, case 3a. (3) Low temperature multi effect boiling, LT-MEB, desalting units that consume the same thermal energy 258 kJ/kg as the MSF units, by steam extracted from turbine, but at a lower pressure supplied to the first effect of the MEB, plus 16 kJ/kg by steam supplied to steam ejectors and mechanical energy of 2 kWh/m^3 for pumping, case 2. The MEB can be operated by steam coming from the same sources.

Keywords: MSF multi stage flash; Reverse osmosis; Consumed thermal energy; Equivalent consumed work; Cogeneration power desalting plants CPDP

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1. Introduction

Kuwait and some of the other Arab Gulf countries have a water problem [1] due to very limited water resources; combining desalting units with steam turbines in power plants of limited water to power production ratio; lack of timely response to match the increase of water demand with installed desalting capacity; high potable water consumption per capita; lack of measures and public incentives to conserve water; unrealistically low pricing of water and power; lack of awareness of the value of water in homes and public buildings such as mosques and schools, high desalting water cost, and other aspects. The only method used to desalt seawater in Kuwait is the multi stage flash (MSF) method, which is known by its high energy consumption, approximately 20 kWh/m^3 as specific equivalent work, compared with reverse osmosis SWRO and multi effect boiling desalting methods.

The continuous increase of fuel prices urged the power plants and desalination industry to develop more energy efficient systems. The power plants efficiency increased up to 55% for gas/steam turbines combined cycles CC. The consumed specific mechanical energy decreases to less than 5 kWh/m^3 for SWRO system, and equivalent work of 12 kWh/m^3 for both mechanical vapor compression, MVC, and low temperature multi effect boiling, LT-MEB, desalting systems. The high fuel cost, where the oil price per barrel reached $75, requires serious reviewing of the fuel energy consumed by different desalting methods and their cost. The SWRO desalting units do not combine with power plants, consume only mechanical energy, and its consumed fuel energy can be easily determined. Meanwhile the commonly used MSF and MEB desalting methods are usually combined with power plants of steam, gas, and gas/steam turbine CC types, and the plants become co-generation power-desalting plants CPDP. The CPDP fuel energy is used to produce both desalted water D and power W, and this fuel is allocated between D and W by different allocation methods. These methods include availability (exergy) based on the second law of thermodynamics and equivalent work.

Different cases of most used desalting systems combined with steam CPDP are presented in this paper to evaluate the real fuel energy consumed to desalt water in MJ/m^3, its cost in \$/m^3. An existing steam CPDP is used as reference plant to calculate the fuel energy when this plant supplies steam to MSF, and MEB or power to SWRO system.

2. Reference CPDP plant

A modern example of a co-generation power desalting plant, CPDP, is Azzour plant operating in Kuwait, which is chosen here as a reference CPDP plant. The exergy concept, based on the second law of thermodynamics analysis, is used to evaluate its performance. The exergy analysis gives the real value of the thermal energy used in terms of the potential of this energy to produce work called exergy or availability; and is used to allocate the fuel charged to the desalting and power production processes.

The Azzour plant (Fig. 1) [2] has a nominal power capacity W = 300 MW at generator terminal, capable of supplying a Q_d = 196 MW heat to the brine heaters BH of two MSF desalting units of 7.2 MIGD each, and gives nominal power to heat ratio W/Q_d =1.53 MW/MIGD. The plant power output range is 80–300 MW, and Q_d ranges from zero (no MSF unit in operation) to 98 (or 196) MW one (or two) MSF unit(s) in operation. The turbine has a tandem arrangement with HPT, IPT, and LPT cylinders along with the generator are mounted on single shaft. The steam is extracted to the MSF units from cross tube connecting the IPT and LPT cylinders. The cycle uses regenerative feed heaters (5 closed and one open) and reheating. The flow sheet and state numbers are given in Fig. 1.

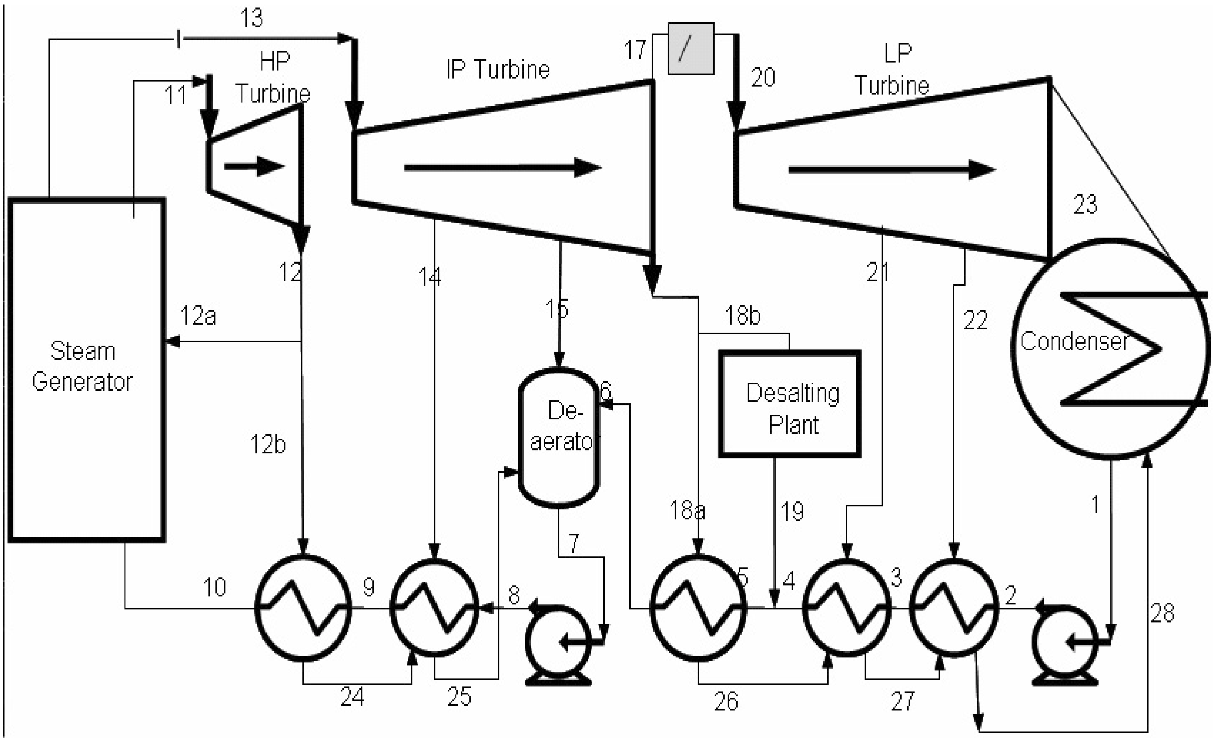


Fig. 1. Azzour cogeneration power desalting plant [2].

The main plant data with and without steam supply to the MSF units at different loads are given in Tables 1 and 2. The exergy analysis for the plant at full power load with and without steam supply to the MSF units is given in Tables 3 and 4 [3]. The steam turbine line presentation on the h-s chart is shown in Fig. 2.

Each of the two used MSF desalting unit produces 7.2 MIGD (distillate flow rate D = 379 kg/s), operates with 110°C top brine temperature supplied with steam at 115°C saturation temperature, has re-circulation to distillate flow rates ratio R/D = 9.2, and guaranteed gain ratio $GR = D/S_d = 9$ where S_d is the steam flow to the desalters. The specific thermal energies of heat given to brine heater Q_d/D is 258 kJ/kg, and to steam ejector is 16 kJ/kg; and the specific pumping (mechanical) energy is 14.4 kJ/kg. At the steam extraction point, the temperature and pressure are higher than that allowed at the entry to the MSF units. So, the steam is de-superheated and throttled between the cross tube and desalting units.

2.1. Case 1: MSF desalting units supplied with steam extracted from turbine

Case 1 is for MSF supplied with heat Q_d by steam extracted from the steam turbine to its BH in the reference CPDP in Kuwait. The plant performance, including MSF units, is based on the first law of thermodynamics and is given by:

- $GR = D/S_d$ is used to rate the MSF units.
- The power plant efficiency $\eta_p = W/Q_{fw}$ where W is the work output, and Q_{fw} is the fuel energy added to produce W.
- The utilization factor, $UF = (W + Q_d)/Q_f$, is used to rate the CPDP where Q_f is the fuel energy added to produce both Q_d and W.
- The rating of the MSF units by GR is not

Table 1
Main data for the cogeneration plant (with desalting)

% of nominal capacity	27	50	75	100
Fuel flow rate, (kg/s)	8.74	11.9	15.67	20.13
Excess air (%)	15	15	15	15
Air flow rate (kg/s)	152.04	207	272.7	350.27
Output steam flow rate (kg/s)	118.88	162.48	222.81	297.6
Throttle pressure (bar)	139	139	139	139
Throttle temperature (C)	510	535	535	535
Reheat pressure (bar)	14.85	22.7	30.7	38.4
Reheat temperature (C)	485	535	535	535
Final feed temperature (C)	198.9	220.2	236.5	246.4
Condenser pressure (bar)	0.0438	0.0479	0.0526	0.0637
Extracted steam flow rate to desalting unit (kg/s)	77	75	77.22	76.72
Extracted steam pressure (bar)	3.5	3.5	3.5	4.74
Extracted steam temperature (C)	289.5	276	239.3	249.5
Enthalpy of steam inlet to desalting unit (kJ/kg)	3047	3019.5	2944.2	2960.9
Enthalpy of condensate leaving the desalting unit (kJ/kg)	406.1	406.1	406.1	406.1
Heat flow rate (kJ/s)	203,349	196,002	196,000	195,997

Table 2
Main data for the cogeneration plant (without desalting)

% of nominal capacity	27	50	75	100
Fuel flow rate (kg/s)	5.48	9.28	13.5	17.86
Excess air (%)	15	15	15	15
Air flow rate (kg/s)	152.04	207	272.7	350.27
Output steam flow rate (kg/s)	74.36	124.55	188.87	261.037
Throttle pressure (bar)	139	139	139	139
Throttle temperature (C)	500	535	535	535
Reheat pressure (bar)	9.46	17.76	26.7	36.7
Reheat temperature (C)	535	535	535	485
Final feed temperature (C)	178.5	207.6	228.7	246.1
Condenser pressure (bar)	0.0504	0.0552	0.068	0.0851

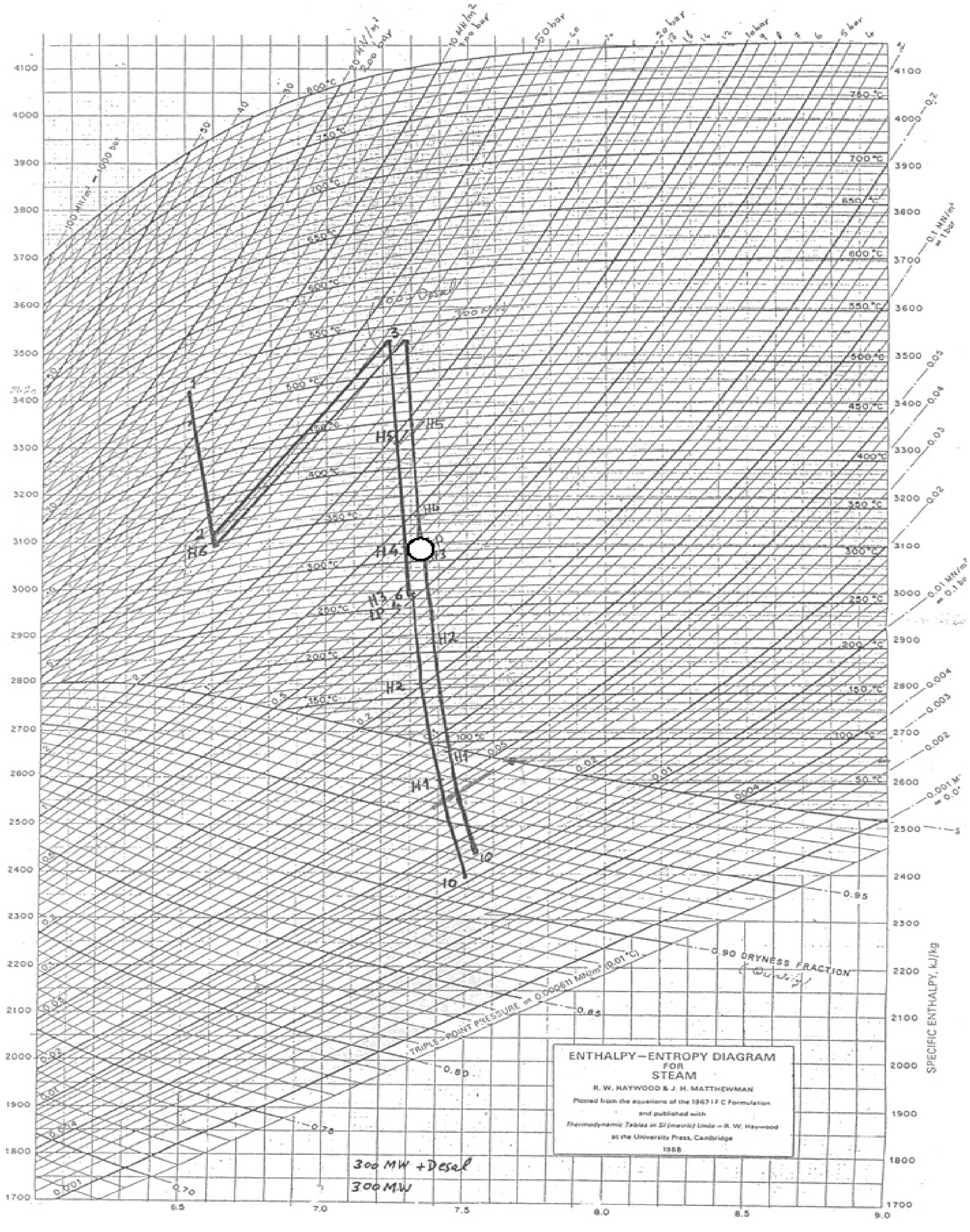
realistic as the direct relation between the additional fuel energy added to the steam generator SG in CPDP when steam is extracted to the MSF units and Q_d (actual heat added to BH) is not known. Moreover, this rating does not account for heat added to steam ejectors and the pumping energy consumed by desalters. The rating of the CPDP by the UF is also unrealistic as it adds Q_d (low quality energy) to work (high quality energy). What is needed is to express the real con-sumed fuel energy Q_{fd}/D to the SG to produce 1 m^3 of desalted water and fuel energy to produce kWh work, or heat rate, HR. This is done by the present exergy analysis.

Table 3
Second Law Analysis of major components in a power plant at full load and full steam supply to desalting units [2]

Item description of component	*E* input (MW)	*E* output (MW)	*E* loss	Effectiveness (%)
Steam generator	899.22	422.41	476.81	46.98
Combustion	899.22	704.77	194.46	78.38
Heat transfer	634.29	422.41	211.88	66.6
HP turbine	98.6	90.77	7.83	92.06
IP turbine	141.84	135.81	6.03	95.75
LP turbine	87.13	77.23	9.9	88.63
Electric generator	303.8	299.24	4.56	98.5
Feed water train				
Heater 1	5.33	3.5	1.82	65.78
Heater 2	4.61	3.92	0.68	85.15
Heater 3	11.1	9.39	1.7	84.64
Heater 4	38.52	36.97	1.55	95.98
Heater 5	—	—	—	—
Heater 6	39.4	34.41	4.99	87.34
Desalting unit	59.72	2.341		

Table 4
Second Law Analysis of major components in power plant without desalting process (full load)

Item description of component	*E* input (MW)	*E* output (MW)	*E* loss	Effectiveness (%)
Steam generator	797.58	373.66	423.92	46.85
Combustion	373.66	172.47	201.19	46.16
Heat transfer	745.43	373.66	371.77	50.13
HP turbine	88.35	80.22	8.12	90.81
IP turbine	104.78	98.6	6.17	94.11
LP turbine	141.57	125.39	16.18	88.57
Electric generator	304.22	299.65	4.56	98.5
Feed water train				
Heater 1	8.91	5.97	2.94	66.96
Heater 2	7.63	6.36	1.27	83.36
Heater 3	10.98	9.5	1.48	86.48
Heater 4	35.34	34.46	0.88	97.51
Heater 5	14.47	12.84	1.62	11.22
Heater 6	16.85	15.77	1.08	93.61
Condenser	20.37	0	20.37	0
Feed water pump	6.33	5.46	0.87	86.18


ENTHALPY—ENTROPY DIAGRAM
FOR
STEAM
R. W. HAYWOOD & J. H. MATTHEWMAN
1968
SPECIFIC ENTHALPY, kJ/kg
DRYNESS FRACTION
TRIPLE-POINT PRESSURE = 0.000611 MN/m² (0.01°C)
300 MW +Desal
300 MW

In a CPDP, the fuel added to the SG of CPDP produces fuel energy $Q_f = M_f$ HHV and availability (exergy) $E_f = M_f\, a_f$. This E_f increases the exergy of the water flowing in the SG by E_b (see Fig. 3). Part of E_b equal to E_d is consumed by the desalting units to produce D, and the balance $E_w = E_b - E_d$ is consumed by the turbines to produce W. The SG second law efficiency is defined by:

$$\varepsilon_b = E_b/E_f$$

where

$$E_b = M_s\,(a_{11}-a_{10}) + M_r\,(a_{13}-a_{12a}) = M_s[(h_{11}-\mathrm{h}_{10}) - T_o(s_{11}-s_{10}) + M_r\,[(h_{13}-h_{12a})-T_o(s_{13}-s_{12a})]$$

The fuel added exergy is $E_f = M_f\, a_f \cong M_f$ HHV $\cong Q_f$.

The first law efficiency of SG is defined by η_b= heat gained by the water Q_b/fuel energy Q_f:

$$Q_b = M_s\,(h_{11}-h_{10}) + Mr\,(h_{13}-h_{12a})$$

By knowing that η_b =0.9, data can be obtained (Table 5).

$$Q_b = 804.871 \text{ MW}, E_f \cong Q_f = 894.3,\quad E_b = 422.412 \text{ MW}, \varepsilon_b = 0.4723$$

The available energy consumed by the desalting process is

$$E_d = S_d\,(a_{si}-a_{we}) = Sd\,[(h_{is}-h_{we}) - T_o\,(s_{si}-s_{we})]$$

The conditions of the heating at the desalting inlet and outlet are given in Table 6. So, the heat given to the desalting plant Q_d and availability E_d are:

$$Q_d = S_d(h_{is}-h_{we}) = 196 \text{ MW, and } E_d = 57.38 \text{ MW}$$

The turbine second law efficiency (effectiveness) is defined by $\varepsilon_w = W/E_w$ where W is the power output, E_w is the exergy consumed for power. The exergy E_d = 57.38 MW is taken out of E_b = 422.412 MW and the balance is E_w = (422.412−57.38) = 364.04 MW. This gives the second law efficiency for the power process (work output/consumed exergy for power):

$$\varepsilon_w = W/E_w = 300/364.04 = 0.8241.$$

So the the equivalent work for desalting

$$W_d = \varepsilon_w\, E_d = 57.38\times0.824 = 47.28 \text{ MW}.$$

The specific exergy consumed by the BH of the MSF units (per unit distillate) is E_d/D = 57380/757.7 = 75.73 kJ/kg or 75.73 MJ/m^3, and its equivalent specific work is 62.4 kJ/kg.

The fuel energy (and cost) added to the steam generator is allocated to power W and desalted water D according to the exergy consumed by each product.

The ratio fuel charged to desalting to the total fuel = (E_d/E_b) = 0.1358; the fuel energy charged to desalination = 0.1358×894.3 = 121.45 MW; and the fuel charged to power = 894.3 – 121.45 = 772.85 MW. Since the desalted water output is D = 757.7 kg/s, the fuel energy charged to desalt 1 m^3 due to Q_d added to the BH is (121,450 kJ/s/ 757.7 kg/s) = 160.3 kJ/kg or 160.3 MJ/m^3. This means that only an additional 121.45 MW of fuel energy is added to the SG to enable the plant to supply the MSF units by 196 MW, and this is the main merit of the CPDP.

Besides the heat supplied to the brine heater, steam is supplied to the ejectors of the MSF units (about 6% of the steam added to the brine heater but at higher pressure (or exergy). This can increase the exergy, equivalent work and fuel charged for all heat energy at least 6% or to 75.73×1.06 = 80.27 MJ/m^3 specific exergy, 169.9 MJ/m^3 specific fuel energy, 66.14 mJ/m^3 specific equivalent work. More work energy is

Fig. 2 (opposite). Enthalpy–entropy diagram for the case of a 300 MW turbine supplying steam to two MSF units of 7.2 MIGD each.

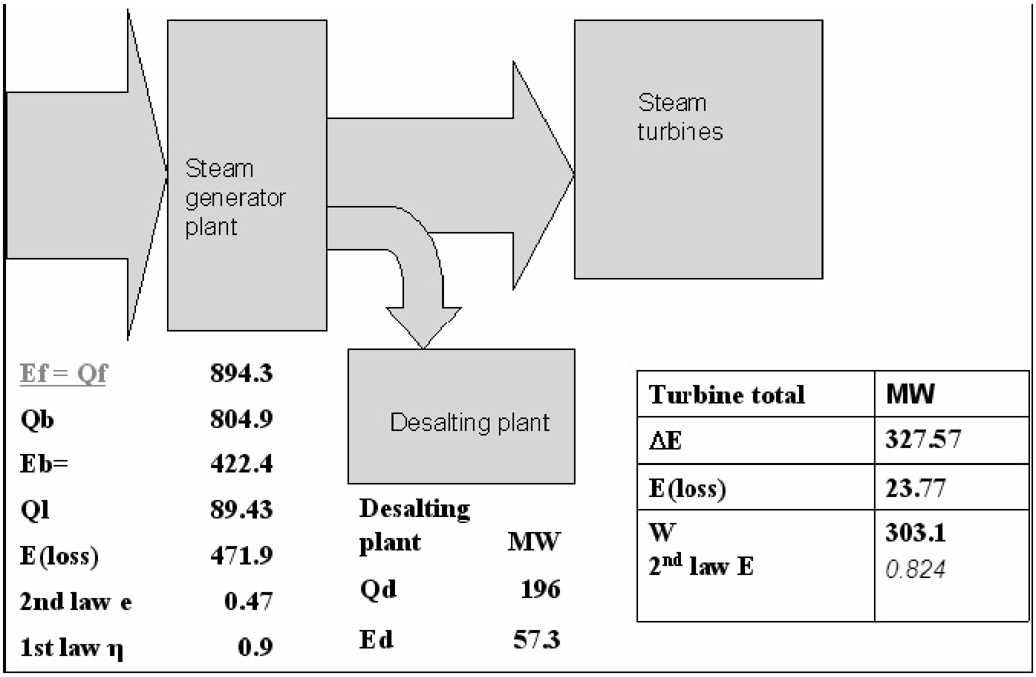


Fig. 3. Exergy distribution in Azzour plant with steam to MSF extracted from turbine, case 1.

Table 5
Mass flow rates, enthalpy, entropy, exergy to and from the steam generator at numbered points as given in Fig. 1

State point	Location at boiler	Mass (kg/s)	Enthalpy (kJ/kg)	Entropy (kJ/kg K)	Exergy A (kJ/kg)
10	Feed water inlet	297.6	1069.4	2.737	256
12a	Cold re-heater	135.6	3110.4	6.605	1140.5
11	Superheated steam outlet	297.6	3419.1	6.517	1475.5
13	Hot re-heater	135.6	3526.1	7.212	1374

Table 6
Mass flow rates, enthalpy, entropy, exergy to and from the MSF desalting units in case 1 at numbered points as in Fig. 1

	Desalting unit	Mass (kg/s)	Enthalpy h, kJ/kg	Entropy s kJ/kg.K	Exergy a, kJ/kg
18	Inlet	76.717	2960.9	7.316	778.4
19	Exit	76.717	406.1	1.2728	30.52

consumed by the MSF pumps at the rate of 14.4 kJ/kg (4 kWh/m^3). If the pumping work is produced by a power plant of 0.36 efficiency, the fuel energy charged for the pumping is 14.4/0.36 = 40 kJ/kg (40 MJ/m^3). So, the fuel energy charged to desalt 1 m^3 is 169.9 + 40 = 209.9 MJ/m^3, and equivalent work charged to desalt 1 m^3 is (66.14+14.4) = 80.54 MJ/m^3 (22.37 kWh/m^3).

So, new terms are used to rate the desalting process including specific consumed exergy due to heat (maximum work that can be obtained from heat) used per m^3 of desalted water (=80.27 MJ/m^3 for case 1 does not include pump work), specific equivalent work (=80.54 MJ/m^3 for case 1 including pump work), and specific consumed fuel energy (209.9 MJ/m^3 for case 1). The exergy term allows the adding of the pump work to it.

This can be used to give a rough estimate for the cost fuel energy consumed to produce 1 m^3 of desalted water. Considering that one barrel of oil produces 5.7 GJ heat, cost of crude oil is $75/ barrel. Then fuel cost to produce 1 m^3 of desalted water is (209.9/5700)(75) = $2.762/$m^3$.

The fuel charged to the power output $Q_f \times [(E_b - E_d)/E_b]$ = 772.85 MW produces 300 MW. This gives power plant efficiency of

$$\eta_p = (300/772.85) = 0.388$$

and heat rate of

$$\text{HR} = 3600/\eta_p = 9274.2 \text{ kJ/kWh}$$

The fuel cost per kWh electric energy is (9.326/5700)(75) = $0.122/kWh.

2.2. Case 2: MEB desalting units supplied with steam extracted from turbine

The MSF desalting units is known by its high consumed energy, and can be substituted by the more energy efficient MEB desalting units in the new Sabbyia power plant to reduce the consumed fuel for desalting. This plant has the same arrangement of the Azzour plant. A modification was suggested to substitute the MSF units with efficient MEB units (although of the same gain ratio), and adding a back pressure steam turbine BPST to increase its power output for the same fuel input to the SG [4]. The suggestion (Fig. 4) is to supply the 76.717 kg/s steam used to feed the two MSF units in case 1 to the BPST at 2960 kJ/kg enthalpy.

The steam exits from the BPST at 2600 kJ/kg enthalpy and 0.6 bar pressure. This allows for little pressure drop from 0.6 bar at turbine exit to 0.35 bar needed for the MEB units. The exit enthalpy from the MEB units is h_f = 316 kJ/kg, (saturated liquid at 75°C). The BPST work is W(BPST) = 76.717 × (2960−2600) = 27,618 kW. So the plant power output increases to W = 300 + 27.618 = 327.618 MW.

The steam discharged from the BPST supplies heat to the MEB first effect at a rate of:

$$Q_d = 76.717(2600-314)/1000 = 175.375 \text{ MW}$$

If the MEB units has the same Q_d/D = 258 kJ/kg of the MSF units, the MEB units output would be 679.75 kg/s (12.92 MIGD), 10.3% less than the D output of case 1, and the MEB gain ratio would be 8.86, which can be easily attained by using MEB of 9 effects.

The exergy consumed by the MEB units E_d for this case, calculated from data given in Table 7, is

$$E_d = S_d\,(a_{si} - a_{we}) = Sd\,[(h_{is} - h_{we}) - T_o\,(s_{si} - {}_{we})]$$
$$= 76.717\,[(2600-314) - 300\,(7.45-1.015)]$$
$$= 27{,}279 \text{ kW} = 27.279 \text{ MW}$$

Table 7
Mass flow rates, enthalpy, entropy, exergy to and from the MEB desalting units in case 2 given in Fig. 4

Desalting unit	Mass kg/s	Enthalpy h, kJ/kg	Entropy s kJ/kg.K	Exergy a, kJ/kg
Inlet	76.717	2600	7.45	778.4
Exit	76.717	314	1.015	30.52

As before Q_b = 804.871 MW, $E_f \cong Q_f$ = 894.3, and E_b = 422.412 MW, and E_d = 27.279 MW, and E_d/D = 40.13 kJ/kg, E_w = 395.133 MW, ε_w = 327.618/395.13 = 0.829. The exergy distribution for this suggested case 2 is given in Fig. 5.

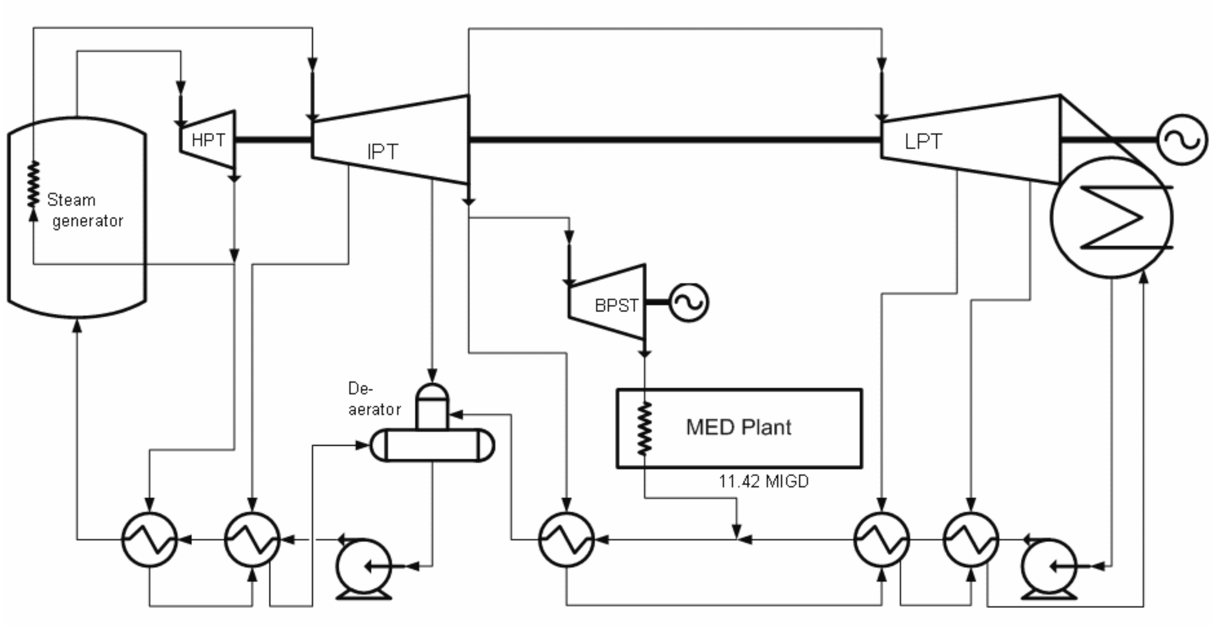


Fig. 4. Suggested modifications: added SWRO and BPST and replacing MSF by MED units [4].

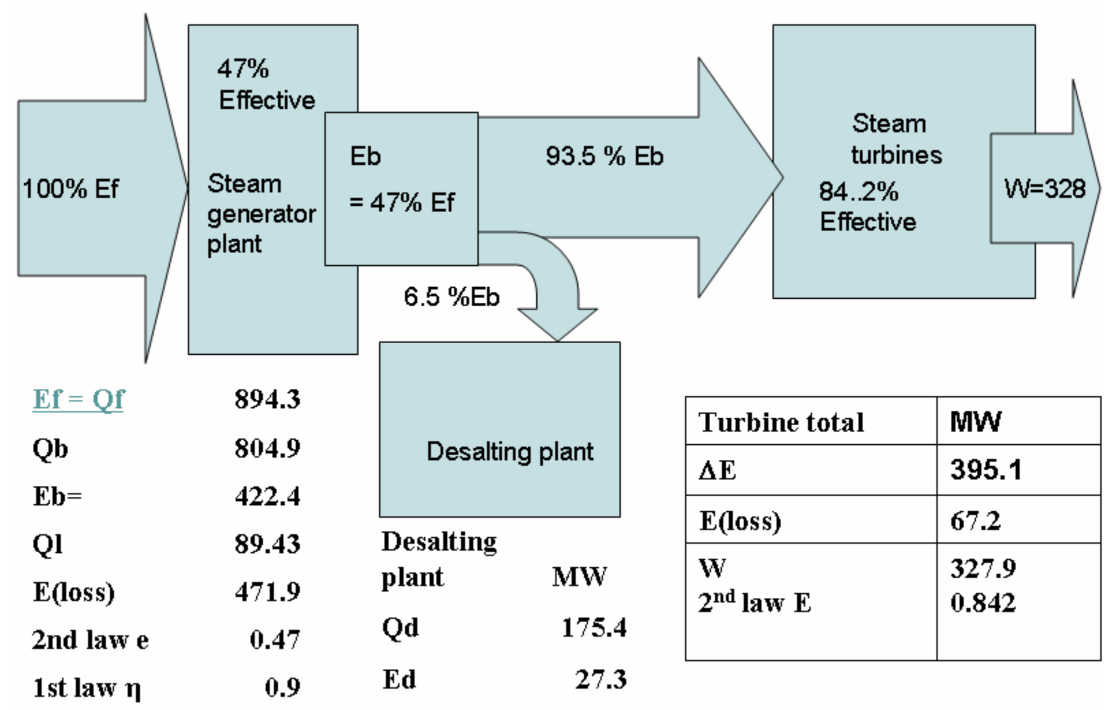


Fig. 5. Exergy distribution in the Azzour plant in case 2 with MEB units substituting the MSF units and addition of BPST.

- Fuel energy charged for desalting = (27.279/422.412) × 894.3= 58.7 MW
- Fuel energy charged for W(=327.618 MW) = (894.3−58.7) = 835.6 MW
- The second law efficiency of the power cycle is 327.618/395.142 = 0.828
- The equivalent work for the MEB units = 27.279×0.828 = 22.587 MW

By adding 6% to count for steam supply to ejectors, the consumed exergy, equivalent work, and fuel energy increase to 28.916 MW, 23.942 MW, 62.22 MW, respectively. The pumping energy for the MEB units is 7.2 kJ/kg (=2 kWh/m^3), and 20 kJ/kg fuel energy is needed to produce this work.

Since the desalted water output is D = 679.75 kg/s, the specific fuel energy (for heat and pumping) = (62220/679.75) + 20 =115.53 kJ/kg or 115.53 MJ/m^3, and the fuel energy cost/m^3 = (115.53/5700)×75 = \$1.4675/m^3 (47% less than case 1).

Specific equivalent work = (23940/679.75) + 20 = 55.22 kJ/kg or (15.34 kWh/m^3). This gives power plant efficiency η_p = (327.421/841.22) = 0.389 compared to 0.386 calculated for combination with MSF units, i.e. almost the same, and heat rate:

$$HR = 3600/\eta_p = 9254.5 \text{ kJ/kWh}$$

The fuel cost per kWh electric energy is (9.2545/5700)(75) = \$0.122/kWh. This is almost the same as case 1.

2.3. Case 3: MSF units with steam directly supplied from steam generator

In the reference CPDP, the flow rate of steam expanded in the turbine decreases as the load demand decreases. In winter, when a turbine operates at low load below a minimum stable load MSL or being out of operation, while the MSF has to operate at its rating capacity, the steam supplied to the MSF comes directly from the SG bypassing the turbine. Fig. 6 shows high pressure HP live steam from the SG passing to two reducing stations. The first is the HP to low pressure LP where the steam is throttled to the pressure required by the BH of the MSF units, and this LP steam is de-superheated before its entrance to the BH. The second is the HP to intermediate pressure IP reducing station where the steam is throttled to IP (in the range of 12–18 bar) required by the steam ejectors of the MSF units to remove non-condensable gases from the stages.

The steam HP/LP and HP/IP reducing stations are fed with spray injection cooling water from boiler feed water pumps for de-superheating. In this case 3a the same amount of steam 76.717 kg/s is taken directly from the SG at 538°C, 150 bar, 3419 kJ/kg enthalpy, 6.517 kJ/(kgK) entropy, and 1475.5 kJ/kg specific exergy, passes through throttling and de-superheating station before being supplied to the MSF units, and leaves the units as condensate at 115°C, 406 kJ/kg enthalpy, 1.273 kJ/kg.K entropy, and 30.52 kJ/kg specific exergy. So, the heat gained by this steam in the SG is

$$Q_b = 76.717(3419-406) = 231.15 \text{ MW}$$

Since Q_d = 196 MW, then 35.15 MW is lost due to de-superheating The fuel energy added to the SG to produce this steam is:

$$Q_f = Q_b/\eta_b = 231.15/0.9 = 256.83 \text{ MW}$$

Since D = 757.7, the specific fuel energy for this case (256,830/757.7) = 338.96 kJ/kg or 338.96 MJ/m^3. When the pumping energy is added, more 40 kJ/kg (40 MJ/m^3) fuel energy is needed, and the total fuel energy/m^3 would be 378.96 MJ/m^3, and its cost is (378.96/5700)75 = \$4.99/m^3.

The exergy distribution for case 3a is given in Fig. 7. Case 3 is not frequently applied, but it is also not an isolated case. In 1999, steam directly

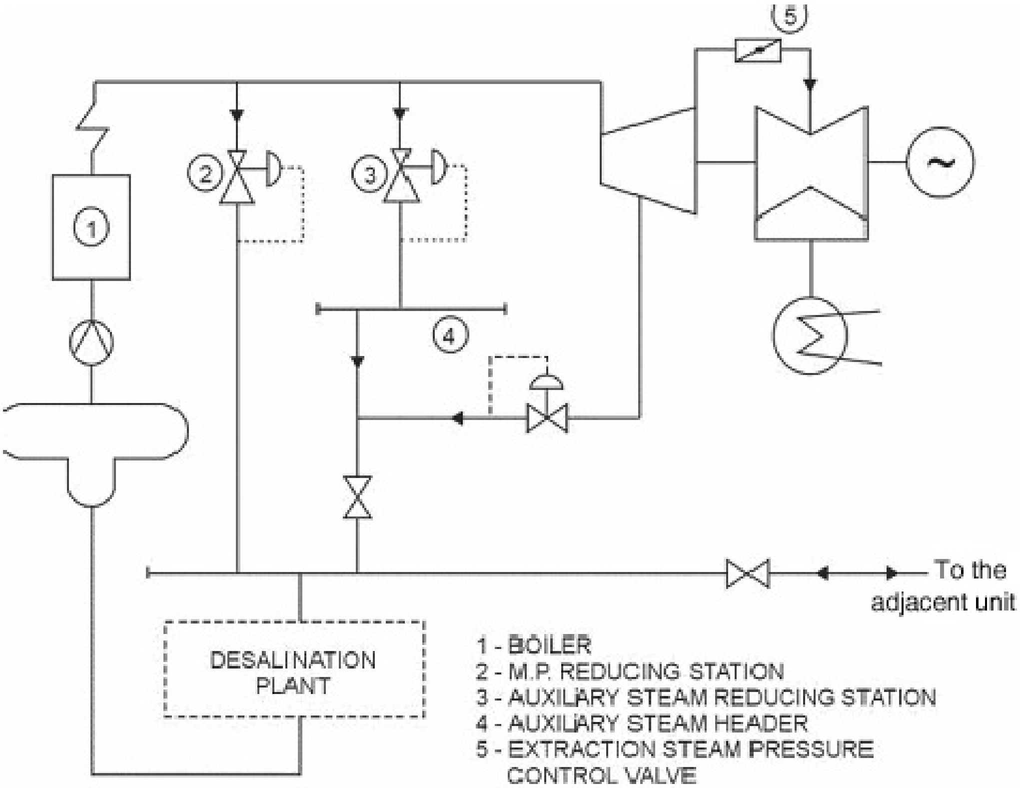


Fig. 6. Arrangement of HP/LP and HP/IP steam reducing stations in the CPDP [5].

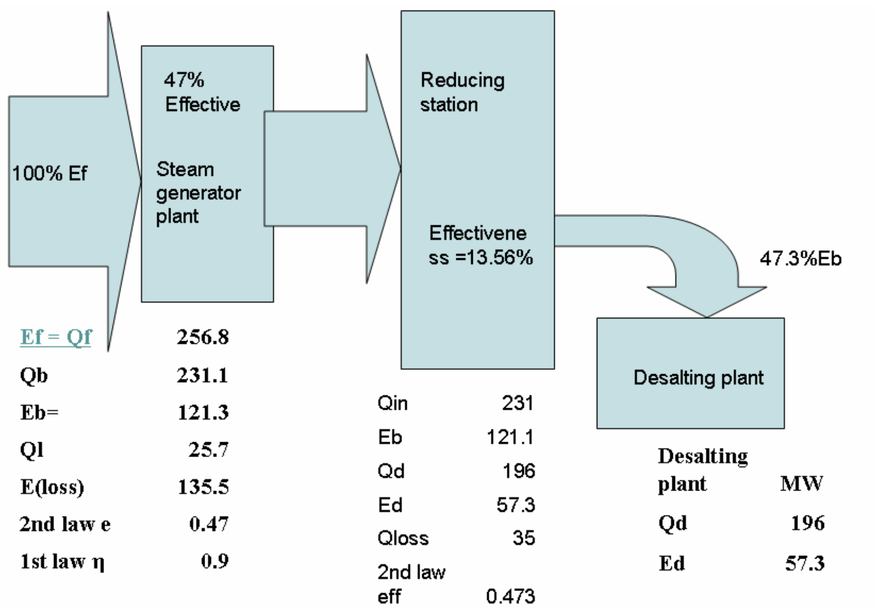


Fig. 7. Exergy distribution in the Azzour plant in case 3a.

supplied from boiler was used to produce about 14% of desalted water in Doha East plant in Kuwait [1].

In case 3b of single purpose desalting plants like Al Shuwaikh, the steam generated by the boiler would be at less pressure and lower temperature than the case of reference plant, and the specific fuel energy is expected to be slightly less. The practice is to use boiler generating saturated steam at 20 bar of maximum efficiency 90% maximum efficiency. Then Q_f = 196/0.9 = 217.78 MW, or 287.42 MJ/m^3. By adding 40 MJ/m^3 for pumping, the total fuel energy/m^3 = 327.42 MJ/m^3 at fuel cost of 327.42/5700) 75 = \$4.31/m^3.

It can be noticed here that the second law efficiency of the boiler is really low. The boiler output is saturated steam of 20 bar, h_s = 2799.5 kJ/kg, s = 6.3409 kJ/kgK, and the return condensate is at 110°C temperature, 461.14 kJ/kg enthalpy, and 1.4185 kJ/kgK entropy. So, the steam flow rate is 196,000/(2799.5−461.1) = 83.82 kg/s, and the exergy across the boiler is 83.82 [(2799.5−461.1)−300(6.3409−1.4185)]/1000 = 72.2 MW and its second law efficiency is 72.2/217.78 = 0.33, and the output steam is then throttled to maximum saturation temperature of 120°C with more exergy loss.

In 2003 Al Shuwaikh plants produced 2806 MIGD = 12.756 million m^3 of desalted water, and consumed 4117.7 million MJ without considering pumping energy of around 40 MJ/m^3 or 362.8 MJ/m^3. This means that the cost of fuel is increased by 362.8/322.8 12.4% when the fuel for pumping energy exported from other stations included. This gives the fuel cost per m^3 distillate equal to \$4.77.

2.4. Case 4: Seawater reverse osmosis SWRO desalting system

The SWRO desalting energy is supplied with typical electric power of 5 kWh/m^3 when brine energy recovery turbine is used. The SWRO plant is not combined with a power plant and does not affect its operation except as a load. In cases 1 and 2, when the power plant has efficiency η_w = 0.388, the fuel energy cost/kWh was found equal to \$0.122/kWh. So, the fuel energy per m^3 desalted water using SWRO is \$0.61/m^3. When a gas/steam turbine combined cycle of efficiency η_w = 0.54 is used, the cost per kWh is 0.0877, and the fuel energy cost per m^3 distillate is \$0.438 (see Table 8).

Table 8
Specific consumed fuel energy, specific work (or equivalent work) in and fuel energy cost per m^3 of desalted water for the cases considered

	Process	Q_{fd}/D MJ/m^3	W_d/D kWh/m^3	Fuel cost, \$/m^3	Comments
Case 1	MSF with turbine extracted steam	209.9	22.37	2.762	Present practice
Case2	MEB with turbine extracted steam	115.5	15.34	1.4675	suggested
Case 3a	MSF with SG steam, Azzour plant	379	40.84[a]	4.99	Partly happened
Case 3b	MSF with SG steam, Shuwaikh	327.4	35.287[a]	4.31	Present practice
Case 4	SWRO using ref. plant power	46.4	5	0.61	Future
	SWRO using gas/steam CC power plant	33.33	5	0.438	Future
Case 5	MVC using gas/steam CC power plant				

[a] W_d/D obtained here by multiplying (Q_{fd}/D) $(\eta_w = 0.388)/3.6$.

3. Analysis

The exergy analysis of the present CPDP at different loads shown in Table 3 [3] gives realistic performance ratings of the plants, which are different from those obtained by the first law analysis. Some comments are in order here.

The main exergy loss occurred in the steam generator, where about of 53% of the fuel exergy is destructed by both combustion and heat transfer processes almost for all loads considered (see Table 3). The limitation of the maximum steam temperature used in power plant is the main contributor to theses losses.

The plant fuel energy consumed to produce 300, 225, 150, and 80 MW power, besides Q_d = 196 MW heat to the desalting units are: 899.22, 700.7, 531.4, 390.32 MW, respectively. When no heat is supplied to the desalting units, the fuel energy for the same power outputs of 300, 225, 150, and 80 MW are: 797.58, 603.06, 414.4, and 252.85 MW, respectively. So, the extra fuel energy added to the steam generator in order for the plant to produce the 196 MW heat required for the desalination units is: 101.64, 97.64, 117, 137.47 MW, respectively, for 100%, 75%, 50%, and 27% of load, respectively. This is the main advantage of using of using CPDP, that less than 60% of Q_d is added to the boiler to produce Q_d at the desalting units.

The plant can work as a single purpose power plant where no heat is extracted to the desalting unit, and the power output produced by the LP turbine is 125.39 out of the 300 MW full power output. The plant can work as a back-pressure turbine power plant when 196 MW heat is extracted to the desalting unit, while the power output produced by the LP turbine is 2.24 MW only out of the 80 MW plant power output. In fact, the steam flow to the LP turbine is for cooling purposes and not for power production.

Although the specific heat to the desalting system is the same, 258 MJ/m^3, and almost the same gain ratio for cases 1 (MSF with steam extracted from the turbine), 2 (MEB with steam extracted from turbine), 3a (MSF with steam direct from CPDP steam generator), and 3b (MSF with steam direct from ordinary boiler for the desalter), the fuel energy charged to these cases 209.9, 115.5, 379, 327.4 MJ/m^3, and fuel cost/m^3 distillate \$2.762, \$1.4675, \$4.99, and \$4.31, respectively. This shows that the terms used to rate these desalting units do not give a realistic evaluation of fuel cost.

The use of more exergy efficient MEB (compared to MSF) system saves more than 40% of the fuel cost due its supply with low temperature steam (compared to MSF). The fuel energy charged for SWRO is significantly less than the MSF and MEB in all cases, especially when the high efficient gas/steam combined cycle is used for power production.

To complete the picture, when compared with mechanical vapor compression MVC system, large MVC units consume typical 10 kWh/m^3 for the compressor and 2 kWh/m^3 for pumping. This brings the specific consumed fuel energy to 80 kJ/kg (80 MJ/m^3) when operated from the efficient gas/steam turbine CC power plant or 111.34 when operated with power of the typical reference steam power plant. When a highly efficient MEB system of PR is in the range 12–16, the specific fuel energy can be decreased to a level less than was reported in case 2, as shown in [6].

4. Conclusion

The rise of fuel energy calls for the use of more energy efficient desalting systems. The exergy analysis provides a rational method of evaluating the fuel energy charged to produce desalted water and electric power in CPDP. According to this exergy analysis, supplying steam directly from steam generator (or boiler) should be avoided as it raises the cost of fuel to at least 8 times and 10 times the case of SWRO supplied with power from steam power plant and gas/steam combined cycle power plant, respectively.

5. Symbols

a	— Specific exergy kJ/kg
BH	— Brine heaters of the MSF units
CPDP	— Cogeneration power desalting plant
D	— Desalted water, kg/s
E	— Extensive exergy, KW or MW
ε	— Effectiveness or second law of efficiency
GR	— Gain ratio, D/S_d
h	— Enthalpy kJ/kg
HHV	— Fuel high heating value, kJ/kg
HPT	— High pressure turbine
IPT	— Intermediate pressure turbine
LPT	— Low pressure turbine
M	— Mass flow rate kg/s
MEB	— Multi effect boiling
MSF	— Multi stage flash desalting units
Q_d	— Heat added to the BH of the MSF units or MEB first effect
Q_f	— Fuel energy added to CPDP
Q_{fw}	— Fuel energy added to produce work *W*
Q_{fd}	— Fuel energy added to produce distillate *D*
s	— Specific entropy, kJ/(kg.K)
S_d	— Steam supplied to the BH of MSF units or first effect of MEB units
T	— Temperature
UF	— Utilization factor $(W + Q_d)/Q_f$

Subscripts

numbers	For state points shown in Fig. 1
b	— Boiler
f	— Fuel
fw	— Fuel for work
fd	— Fuel for desalting
r	— Reheated steam
s	— Steam
w	— Work
o	— Surrounding temperature

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