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Environmental impact of seawater desalination plants: case study in Algeria

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Abstract: This paper focuses on Environmental impacts associated with concentrated brine rejection in the Mediterranean arising from seawater desalination plants in Algeria. We present a case study on the environmental impacts of Cape Djinet Power/MSF seawater desalination plant. These impacts are mainly due to brine discharge but also to a lesser degree the chemicals used in the cleaning of various modules, thermal pollution, etc.. We performed the measurement of four parameters (temperature, pH, salinity and conductivity), exergy analysis and numerical simulation to visualize the effects of rejection. Measurements of temperature and pH are compliant Algerian liquid discharges indicated in the legislative knowing that there are no limits imposed on the conductivity and salinity. Global results show no effect while there is a local impact due to the relatively small size of the resort of Cape Djinet (4x500 m^3/day). CFD simulation was used to visualize the effect of brine discharge in the sea.

Keywords: Seawater, Desalination, MSF, CFD, Performances, Exergy Analysis

1. Introduction

Algeria experienced during the nineties a severe drought with a critical shortage of drinking water threatening even the industrial and irrigation activities [N. Boutarfa2004, A. Sadi2004]. Water shortages, whether cyclical or structural, are a fact known to worsen in the future, while nearly one billion people still lack access to safe drinking water and demand on resources exceeds the renewable supply. In the EUMENA, irregular and declining rainfall situation combined to the rapidly increasing water demand for irrigation, industry and the population incompressible needs is of great concern to policy makers constrained to mobilize more groundwater and surface resources and use intensive water desalination. Desalination is nevertheless a high energy consumption process contributing to GHGs emissions and a potential threat to the environment by inducing damage to the marine environment. The research devoted to the assessment of impacts of desalination on the marine ecosystems are so far limited [S. Latteman2003,2010 , Y. Tamim2005, C. Santana2005]. More than 15,000 desalination plants around the world lead to a substantial production of brine from brackish and seawater desalination, while a half of intake massflowrateis rejected. The discarded brine has an impact on marine environment as its concentration is about twice the intake seawater and include Pre- and post-treatment chemicals. While energy recovery through pressure exchangers or Pelton turbines is widely used, production of salt and additional water from the rejected brine is a part of the solution but is economically not often feasible. In this last case, renewable energy can be used for brine evaporation in order to lower the costs in the context of rapidly growing demand for high purity vacuum salt. For thermal processes, mainly multistage flash (MSF), reducing thermal pollution is a big issue while seawater temperature, salinity, water currents and turbidity increase [I.S. Al-Mutaz, 2012].

Algeria experience in desalination started during the sixties with the building of multi-stage flash distillation (MSF) and mechanical vapor compression (MVC) plants in order to supply with water the growing oil and steel industries [G. Bravo2004]. Forty four (44) MSF seawater desalination plants totalizing a capacity of 111.000 m^3/day are supplying the petrochemical process industry and power generation plants (e.g. most of the Algerian steam power plants are fed with distillate water from small scale

MSF desalination plants). The high purity of the distillate obtained from MSF has imposed this reliable and safe process compared to RO which is mainly used in Algeria for fresh water production. While in Gulf Cooperation Council (GCC) area, MSF is the main water desalination process for either drinking and industrial purposes applications. Most of the thermal desalination capacities installed in the world during the last decade are mainly concentrated in this area where energy is, for instance, affordable at a very low cost. In desalination processes, the levelised water cost (LWC) is mainly dependant on the energy cost. During the last decade distillation processes energy consumption have been lowered and many investigations based on exergy analysis [HouShaobo 2008, A.S. Nafey2006, A.A. Mabrouk2007, N. Scenna2008, A. Sung Joon2008, G. Cali2008, Y. Cerci2003, N. Kahraman2005] and systems analysis environments [M.S. Tanvir2008, A.S. Nafey2006, A.A. Mabrouk2007, J. Rheinländer2003, E. Perz2006, K.Mohammedi2010, D.Boudieb 2012] were conducted for performances and diagnosis improvement. A new design for an MSF–MVC desalination process was investigated by A.A. Mabrouk and al. [A.A. Mabrouk2007] under different operating conditions using a developed Design and Simulation software. A thermo- economic analysis based on energy/exergy balances was performed. The effect of the number of stages in the heat recovery section was studied. The results show that the low unit product cost was obtained at 20 stages. The performance ratio of the proposed MSF–MVC system was 2.4 times the performance ratio of the conventional MSF process. The heat transfer area of the MSF–MVC system was 57% higher than that of MSF while the exergy efficiency of the MSF–MVC system was 67% higher. The thermo-economic analysis results show that the unit product cost of MSF–MVC, under the specified conditions, was calculated by 2.0 $\$/m^3$; this value is 25% less than that of the conventional MSF process.

2. MSF Desalination Plant Case Study (Cape Djinet, Algeria)

The Cape Djinet MSF desalination plant is located 70 km west of Algiers (Algeria), on the Mediterranean coast. The nominal distilled water production is 500 m^3/day from four small scale MSF desalination plants to supply a 700 MW steam power cycle with distilled water. A simplified flow diagram of the analysed MSF plant is shown in Figure 1. The plant consists of three subsystems: The MSF plant with 15+3 flashing stages, the power generation section and the pre/post treatment sections.

Seawater enters the plant at (1) at a rate of 66.38 kg/s. It serves as a coolant in the later flashing stages (seawater temperature rises from 308 to 316.3 K), and is discharged back to the sea (16), while 14.44 kg/s is supplied into the flashing chamber after it is treated with chemicals. The mixture in the flashing unit at 316.3 K with a salinity of 64.828 g/l is pumped back into a cooling line through the flashing chamber, and its temperature rises to 358 K as it cools and condenses the water steam in the flashing stages. The saline water is vaporized in a heat exchanger. The steam is condensed and the distillate water is collected at an incoming massflowrate of 5.78 kg/s while waste brine is partially rejected at a rate of 8.61 kg/s and a salinity of 70.093 g/l. The brine is flashed to lower pressures in the successive stages.

Main parameters and thermodynamic properties at each point of the process cycle are summarized in Table 1 and Table 2.

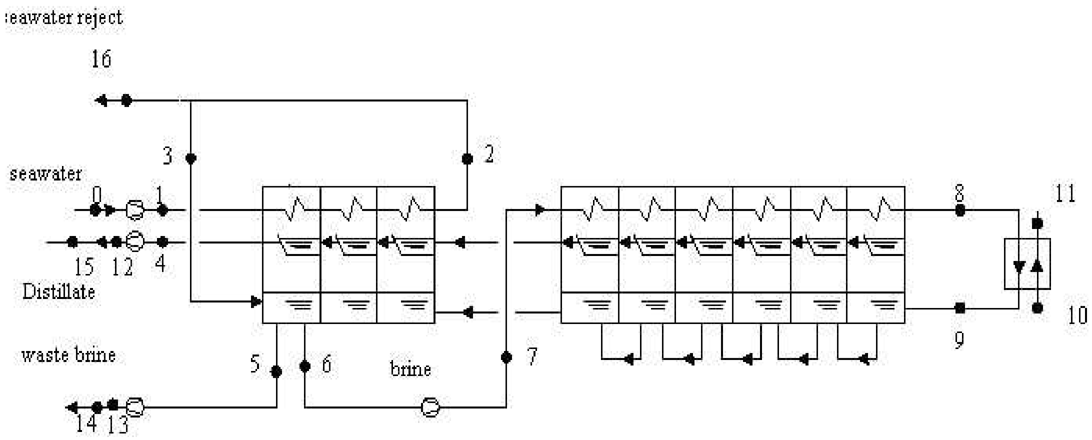

Fig.1: *Cape-Djinet MSF plant simplified flowsheet process*

3. Energy and Exergy Analyses

From the energy balance and after computing the enthalpy and entropy flowrates values of each component [K. Mohammedi, 2008], we can estimate the exergy for salt/water mixture for any state of the process cycle using the following relation:

$$Ex_i = H - H_0 - T_0(S - S_0) \quad (1)$$

The exergy balance is given by the following relation:

$$\sum(1-T_a/Tj).\ Q_j - \sum W_i + \sum m_{in}.(h_{in}-T_a s_{in}) - \sum m_{out}(h_{out} - T_a.s_{out}) - T_a S_{crea} = 0 \quad (2)$$

Salinity of seawater is 39.4g /l, corresponding to salt and water mass fractions $m\ f_s$=0.0394 and $m\ f_w$=0.9606 respectively. The mass fractions of salt and water are obtained from the following relations:

$$M\ f_s = m^s / m_m \text{ and } m\ f_w = m^w / m_m \quad (3)$$

As we have $m_m = m_w + m_s$ then,

$$m\ f_w + m\ f_s = 1 \quad (4)$$

Finally, we obtain the following results for the salt and water mass fractions: $m\ f_s$= 0.0394andmf_w= 0.9606 .

Assuming an ideal solution for the seawater, the specific enthalpy and entropy of the water/salt mixture are calculated using the following relations:

$$h = m\ f_s .h_s + m\ f_w .\ h_w \quad (5)$$

$$s = m\ f_s .\ s_s + m\ f_w .\ s_w \quad (6)$$

The ambient conditions at intake point are: T_0 = 288 K, P_0 = 1.013 bars, Sal_0 = 39.4 g/l. The specific heat of salt is Cp_s= 0.8368k J/kg. The enthalpy and entropy values at temperature T_0 are h_{s0} = 16.736kJ/kg and s_{s0} = 0.05913kJ/kg respectively while for a temperature T the relations (7) and (8) are used:

$$h_s = h_{s0} + Cp_s .\ (T-T_0) \quad (7)$$

and

$$s_s = s_{s0} + Cp_s .\ \ln\ (T/T_0) \quad (8)$$

The thermodynamic properties for different states throughout the unit are summarized in Tables 1 and 2 for the energy and exergy analyses.

Table 1. *Specific enthalpy and entropy of salt and water*

states	T(K)	P(bar)	h_s(kJ/kg)	s_s (kJ/kg K)	h_w(kJ/kg)	s_w (kJ/kg.K)
0	293.15	1.013	16.736	0.05913	83.99	0.296
1	293.15	3.9	16.736	0.05913	84.26	0.296
2	300.66	3.19	23.020	0.08030	115.58	0.402
3	300.66	3.19	23.020	0.08030	115.58	0.402
4	299.25	1.047	21.840	0.07637	109.49	0.382
5	300.45	1.047	22.844	0.07972	114.51	0.399
6	300.45	1.047	22.844	0.07972	114.51	0.399
7	300.45	6.1	22.844	0.07972	114.97	0.399
8	348.55	2.83	63.095	0.20404	315.83	1.020
9	356.15	2.61	69.454	0.22210	347.7	1.11
10	368.15	4	79.496	0.24984	398.33	1.249
11	361.15	4	73.638	0.23377	368.89	1.169
12	299.25	3.3	21.840	0.07637	109.7	0.382
13	300.45	1.8	22.844	0.07972	114.57	0.399
14	293.15	1.013	16.736	0.05913	83.99	0.296
15	293.15	1.013	16.736	0.05913	83.99	0.296
16	293.15	1.013	16.736	0.05913	83.99	0.296

The minimum work input required for partial separation, at the same temperature, of 66.38 kg/s of seawater into 5.78 kg/s of distillate and 8.61 kg/s of outgoing brine, is given by the difference of the minimum separation works/power of exiting and incoming streams, i.e.:

$$W_{\min} = Ex_{\min} = Ex(out) - Ex(in) \quad (9)$$

One can note the exergyflowrates negative values of 5,6,7,13 and 14 states. Kahraman and al. [N. Kahraman and al.2005] give a comprehensive explanation of these singular values by the fact that the exergy due to concentration is different from zero at the dead state temperature and pressure.

Table 3 summarizes the exergy creation and destruction in the main components as well as the minimum work. The exergy efficiency is then computed from the ratio of the minimum work:

$$\eta_{ex} = Ex_{\min} / Ex_{tot} \quad (10)$$

Table 2. *Enthalpy, entropy and exergyflowrates of salt and water mixture*

States	P(bar)	T(K)	Sal g/l	*m*(kg/s)	*h*(kW)	*s*(kW/K)	*Ex* (kW)
0	1.000	293.0	39.4	66.38	5399.36	21.44	0.00
1	3.900	293.0	39.4	66.38	5416.57	21.44	16.59
2	3.190	300.5	39.4	66.38	7430.58	28.41	25.17
3	3.190	300.5	39.4	14.44	1617.28	6.18	5.47
4	1.034	299.1	00.0	5.78	632.85	2.2	62.73
5	1.034	300.3	65.3	8.61	934.31	3.76	-53.8
6	1.034	300.3	65.3	66.38	7203.19	29.00	-414.81
7	6.100	300.3	60.0	66.38	7232.36	29.00	-385.60
8	2.830	348.4	60.0	66.38	19886.01	69.49	397.57
9	2.610	356.0	60.0	66.38	21890.52	75.4	670.37
10	4.000	368.0	00.0	75.00	29868.75	93.67	3408.98
11	4.000	361.0	00.0	75.00	27660.75	87.67	2959.88
12	3.300	299.1	00.0	5.78	634.06	2.2	63.95
13	1.800	300.3	65.3	8.61	934.87	3.76	-53.20
14	1.013	293.0	65.3	8.61	685.34	2.81	-47.87
15	1.013	293.0	00.0	5.78	493.02	1.71	67.17
16	1.013	293.0	39.4	51.94	4224.80	16.77	0.00

Table 3. *Exergy creation and destruction in the main components*

	Component	Equation	*Ex* (kW)
Creation	Seawater intake pump	$Ex_p = Ex_1 - Ex_0$	16.59
	Recirculation pump	$Ex_p = Ex_7 - Ex_6$	29.21
	Brine pump	$Ex_p = Ex_{13} - Ex_5$	0.6
	Distillate pump	$Ex_p = Ex_{12} - Ex_4$	1.22
	Reheater	$Ex_r = Ex_9 - Ex_8$	272.8
	totalexergy creation		566.65
Destruction	Seawater intake pump	$Ex_{d,p} = Ex_{ele} - Ex_p$	28.21
	Recirculation pump	$Ex_{d,p} = Ex_{ele} - Ex_p$	36.59
	Brine pump	$Ex_{d,p} = Ex_{ele} - Ex_p$	2.15
	Distillate pump	$Ex_{d,p} = Ex_{ele} - Ex_p$	2.98
	Reheater	$Ex_{d,r} = (Ex_8 + Ex_{10}) - (Ex_9 + Ex_{11})$	176.3
	Waste seawater	$Ex_{d,charge} = Ex_2 - (Ex_3 + Ex_{16})$	19.7
	Distillat	$Ex_{distillat} = Ex_{12} - Ex_{15}$	3.22
	Waste brine	$Ex_{d,Brine} = Ex_{13} - Ex_{14}$	5.33
	Flashing stages		289.97
	Total exergy destruction		564.45
Minimum work		$W_{min} = Ex_{14} + Ex_{15} - Ex_0$	19.3

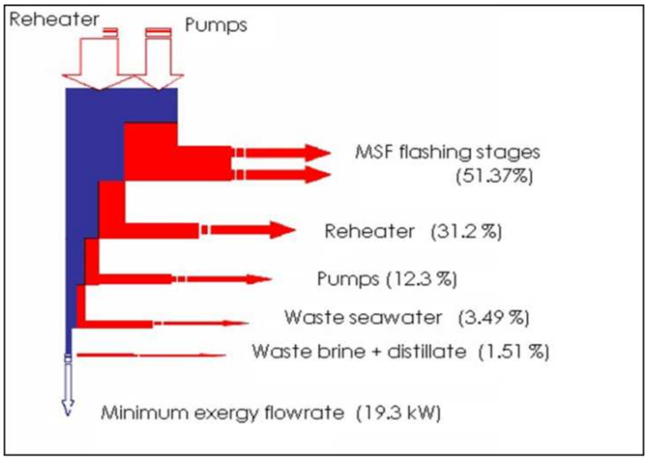

Fig. 2: *The MSF plant exergy destruction fractions and exergy flow diagram*

The exergy efficiency of the MSF plant is around 3.4% computed from (10) while the exergy destruction fractions values are summarized in Fig. 4. Performances improvement could be obtained by increasing flashing stages and/or integration of the MSF process to the power plant by suppressing the combustor and feeding the MSF process directly from the power plant high pressure turbine. We should complete the thermodynamic investigation with the life cycle analysis in order to optimize the plant and also foresee a competitive integration to a steam cycle conventional power plant.

4. Measurement of Seawater Temperature, pH, Salinity, Conductivity vs. Time

Samples were collected from three sites: brine discharge point, the reject channel and the seawater intake of Cap Djinet power/MSF desalination plant.

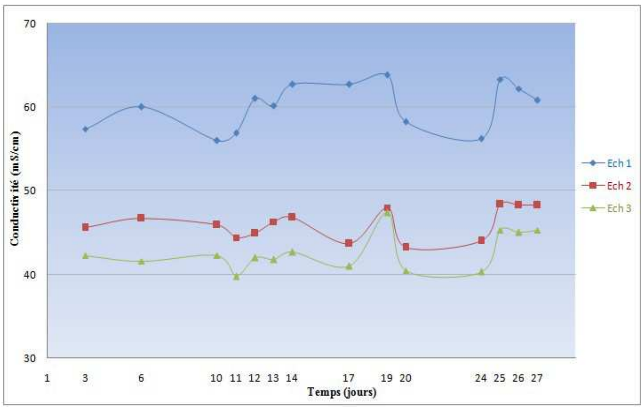

Fig.3: *Seawater Conductivity*

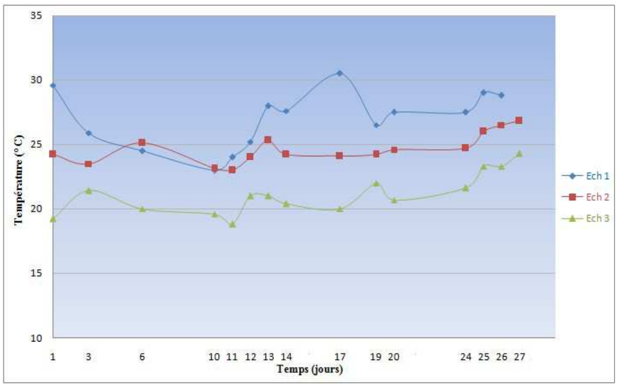

Fig.4: *Seawater Temperature*

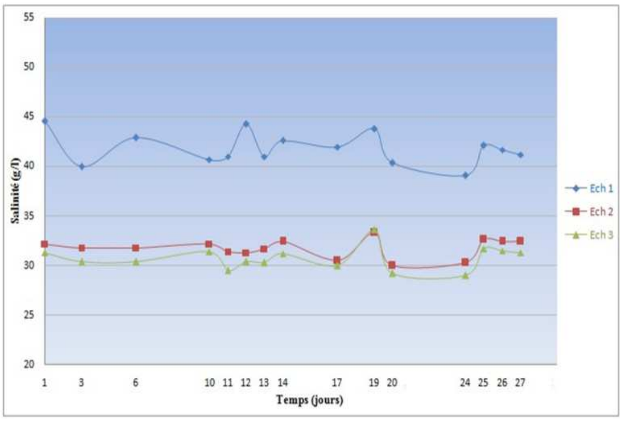

Fig. 5: *seawater salinity distribution*

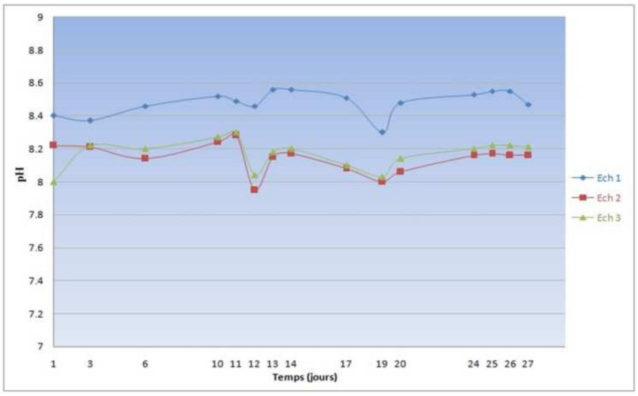

Fig. 6: *Seawater pH distribution*

5. Numerical Simulation of the Thermal Plume

The numerical simulation of Cape-Djinet plant brine reject flow has been done for winter and summer weather conditions. The results show that the thermal plume of the brine reject diffusion process is concerning 500 m^2 area with a 3 to 5°C temperature variation.

Fig. 7: *Cape Djinet brine reject channel (Google earth)*

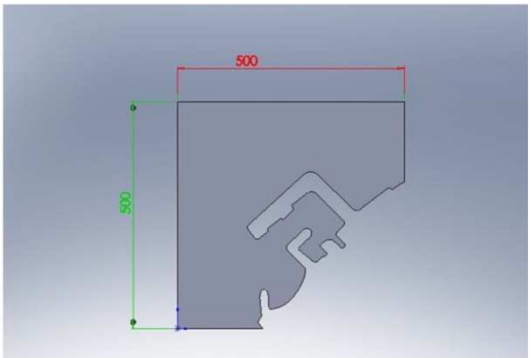

Fig. 8: *Cape Djinet rejection domain*

Fig. 9: *Cape Djinet rejection Domain meshing*

We performed simulations at 500s, 720s and 1200s

6. Summer Case Results

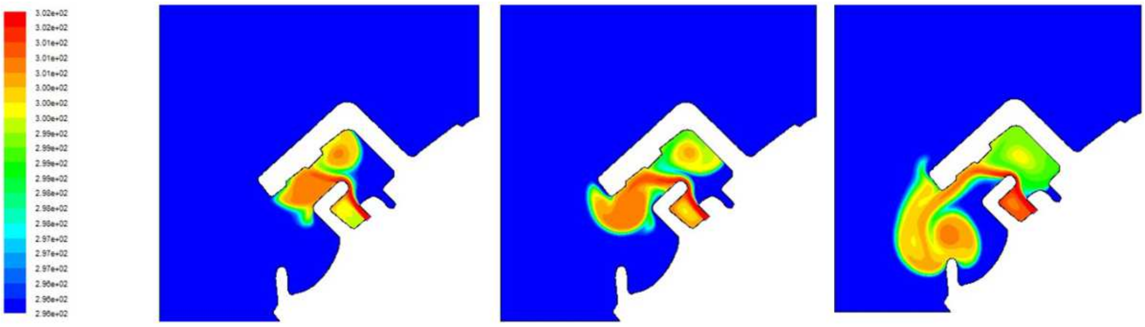

Fig. 10: *Temperature distribution evolution at t=500 s, t=720 s, t=1200 s*

From the numerical simulation results, we can observe that the flow does not reach the stationary regime. The temperature values are higher in the reject pool with a value of ΔTmax = 5 ° C, While the thermal spot runs away from the shore with a distance more than 500m but with a temperature less than ΔTmax T = 3 ° C.

7. Winter Case Results

For this second case, the initial temperature of the whole domain is 15°C, while the inlet conditions are such that velocity is 1.8 m/s for a temperature of 23 °C.

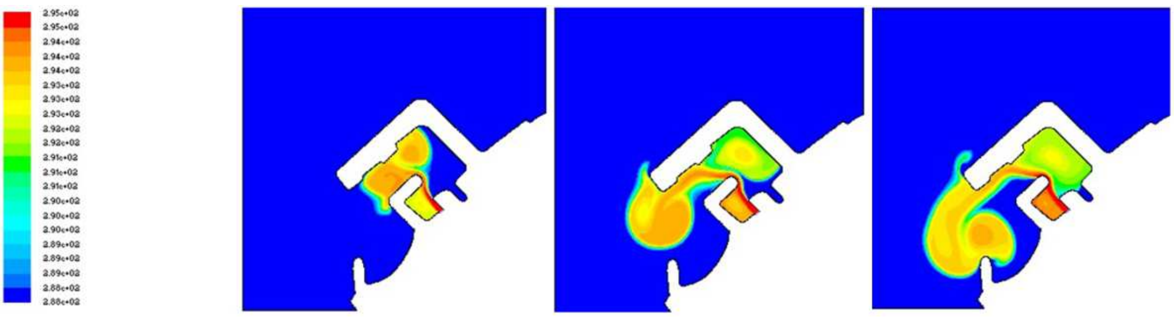

Fig. 11: *Temperature distribution evolution at t=442 s, t=925 s, t=1259 s*

The numerical simulation results show again that we do not reach the stationnary regime with a temperature difference of ΔT_{max}=7°C in the rejecting basin. The evolution of the flow shows the same observations we already reported in the winter case.

8. Conclusion

This paper focused on the marine environmental impacts in the Mediterranean arising from seawater desalination plants in Algeria. We presented a case study on brine rejection of Cape Djinet/MSF (Algeria) seawater desalination/power plant including exergy performances computation. The environmental impacts are mainly due to brine discharge but also to a lesser degree to the chemicals used in the cleaning of various modules, thermal pollution, etc.. We performed the measurement of four parameters (temperature, pH, salinity and conductivity) and a numerical simulation to visualize the effects of rejection. Measurements of temperature and pH are compliant Algerian liquid discharges indicated in the legislative knowing that there are no limits imposed on the conductivity and salinity [JO RADP 2006]. Global results show no impact while there is a local impact due to the relatively small size of the Cap Djinet desalination plant (4x500 m^3/day). The exergy analysis results showed that the MSF desalination unit is the key component where most irreversibilities and available energy destruction are occurring (CO_2 emissions too).

We propose to extend this study to the Hama desalination reverse osmosis 200,000 m^3/day plant (Algiers), then to all Algerian coast desalination plants (1600 km) and initiate an environmental impact assessment initiative across the western Mediterranean basin.

Notations

Cp:	specific heat	(kJ/ kg K)
Ex:	exergy	(kJ)
Ex	rate of exergy flow	(kW)
H:	enthalpy	(kJ)
h:	specific enthalpy	(kJ/kg)
m:	mass flowrate	(kg/s)
m*f*:	mass fraction	-
p:	pressure	(bars)
Q:	heat	(kJ)
S:	entropy	(kJ/K)
Sal:	salinity	(g/l)
T:	temperature	(K)
W:	power	(kW)

Acronyms

MSF:	Multi-Stage Flash
RO:	Reverse Osmosis
MVC:	Mecha.VaporCompress.

Subscripts

crea:	Creation
d:	destruction
ele:	electric motor
w:	water
ex:	exergy
i:	state
in:	incoming
j:	heat source
m**:**	brine
min:	minimum
out:	exiting
p:	pump
r:	reheater
s:	salt
tot:	total
00:00	ambient conditions

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