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PERFORMANCE EVALUATION OF A MSF DESALINATION PLANT IN QATAR

M.R.S. Okelah* and I.A. Tag**
*Ajman University, United Arab Emirates.
**Professor, Mechanical Engineering Department, University of Qatar, Doha.

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ABSTRACT

In this paper, an assessment of the performance of one of the multistage flash (MSF) desalination units operating in conjunction with the gas-turbine cogeneration power plant in Qatar is carried out under different operating conditions. Drop in performance represented by the decrease in the gained output ratio and the increase in energy input per unit distillate as a function of time is evaluated.

An empirical correlation for the unit output is presented taking into account the effect of thermal losses as related to stages average temperature in addition to the direct effects of both the recirculated flow rate and flash range.

INTRODUCTION

The need for desalination arises in areas where resources of fresh water are missing as is the case in the Arabian Peninsula, where the water consumption per capita can reach as high as 750 litres per day (1). Water of salinity exceeding the limit of 500 ppm is considered unsuitable for human consumption. In the Arabian Peninsula, the continuous increase in population, standard of living, mining, industrialization and initiation of new towns create more needs for fresh water. Desalination became the main source of water for countries like Saudi Arabia, Kuwait and Qatar. A desalination system is then used to produce fresh water of specified properties out of saline water which has salt concentration in the range of 42,000 - 56,000 ppm for Arabian Gulf and 41,000 - 43,000 ppm for Red Sea.

A brief description of Ras Abu-Fontas Power and Water Station, producing 80% of potable water in Qatar, utilizing MSF desalination system is presented in this paper. Details of the desalination plant including: plant outline, main components, process description, design parameters and control strategies are also presented.

RAS ABU-FONTAS POWER AND WATER STATION

Ras Abu-Fontas Power and Water Station is one of the world's largest gas turbine and desalination plants. Completed in 1984, it is considered the primary source of electrical power and potable water in Qatar. It is situated on the Gulf coast approximatey eight kilometers south of the capital Doha. The station which was started in 1972, was develoed for the Ministry of Electricity and Water of Qatar (2). Two final configuration comprises 12 gas turbine generator units and two black start gas turbines with total ISO rating of 965 MW. Each turbine is coupled to a waste heat boiler, feeding multi-stage flash desalination unit connected for either range or unit operation. Under normal operating conditions, peak water production is 216,000 cubic meter per day, can be boosted to 270,000 m^3/day by the use of chemical additives to allow higher operating temperatures.

The twelve large gas turbine-generators are housed longitudinally one after the other in a turbine building of 722 meter in length. Along the front of the building, on the eastern side are the air intake structures, the waste heat boilers with the by-pass stacks and the desalination plants. Local control stations, the electric switchgear and the transformers are arranged in the western side. Among the twelve gas turbine-generator units, six are manufactured by Kraftwerk Union AG (KWU), and are of the V. 93 type. The other six units are manufactured by Mitsubishi Heavy Industries Ltd. (MHI), and are of the MW 701 G type. They all operate in base-load mode, with filtered air intakes. The first two KWU gas turbines, supplied for the initial installation, generate at turbine inlet temperatures of approximately 820°C at base load and at approximately 850°C at peak load. These values were increased to approximately 850°C and 870°C for the four KWU gas turbines installed in the second extension of the plant.

The basic components of the station are:

- 6 units of Mitsubishi (M.H.I) Gas turbines, each 56 MW.
- 6 units of Kraftwerk Union (K.W.U.) Gas turbines, each 44 MW.
- 2 Units of (FIAT) Gas turbine, each 15 MW.
- 12 units of Waste Heat Boilers, each producing 160 tons of steam per hour.
- 10 units of Auxiliary Boilers, each producing 80 tons of steam per hour.
- 12 units of Distillers, each producing 5 million gallons of distilled water per day (3).

Figure 1 shows a layout of a complete unit of the plant for producing both electricity and potable water. It indicates also how the basic components of the unit are connected.

DESCRIPTION OF THE DESALINATION UNIT

The plant consists of the following major sections:

1. Distiller:

The distiller shown schematically in Fig. 2 is designed to produce 18,000 m^3/day of distilled water with a top brine temperature of 91°C or 22,500 m^3/day with a top brine temperature of 112°C (4).

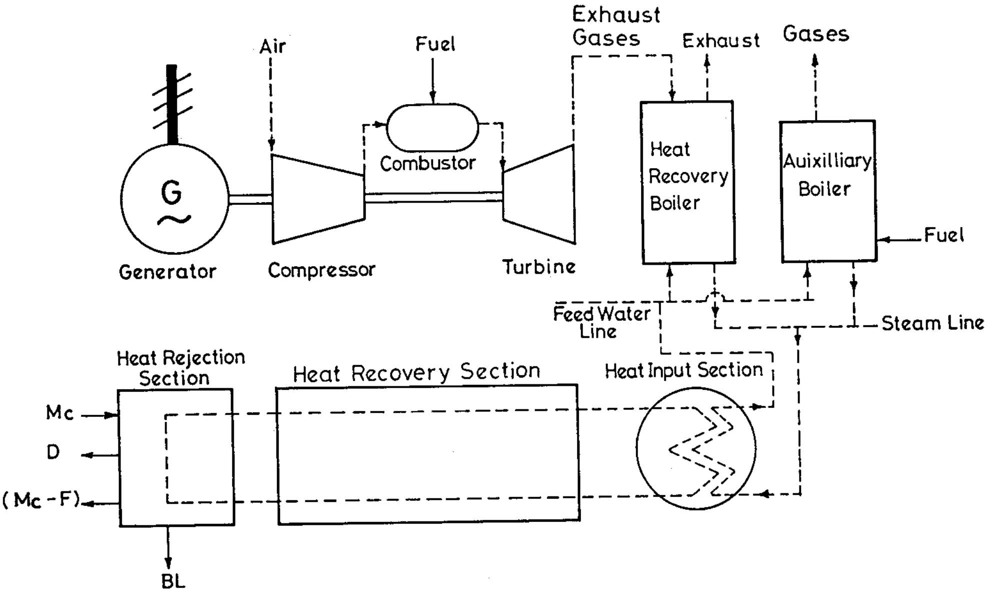

Fig. 1: Layout of a Typical Unit Producing Electricity and Water.

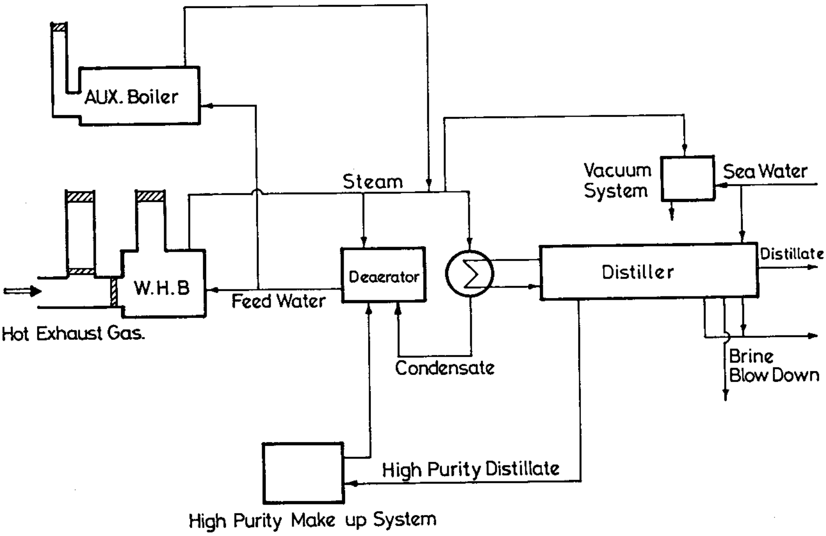

Fig. 2: Conceptual Flow Diagram of an MSF Desalination Unit.

The distiller comprises the following principal sections:

(i) Heat input section:

It consists of the brine heater, where thermal energy is supplied.

(ii) Heat recovery section:

Where heat of condensation is transferred to the brine, and thus pre-heats the recirculated brine in stages 1 through 14.

(iii) Heat rejection section:

Where heat of condensation is partly transferred to the make-up stream and mostly to sea water cooling stream, stages 15 and 16.

Design parameters of distillers:

Two operating conditions are considered: one with a top brine temperature of 91°C when polyphosphate type-chemicals are used for scale inhibition and the other with a top brine temperature of 112°C when Belgard-EV is used for scale inhibition.

The following are the design parameters for the two operating conditions considered:

— Anti-scale inhibitor	Polyphosphate	Belgard-EV
— Top brine temperature, °C	91	112
— Distillate output, m^3/day	18,000	22,500
— Distillate conductivity (max) μS/m at 25°C	5,500	5,500
— High purity distillate normal output, m^3/day	160	160
— High purity distillate max. output, m^3/day	1,600	1,600
— High purity distillate conductivity (max.) μS/m at 25°C	220	220
— Total sea water for all purpose, t/h at 38°C	9,199	9,159
— High pressure steam consumption kg/h at 15 bar	2,805	2,805
— Low pressure steam consumption, t/h at saturated conditions	113	127
— gained output ratio	6.3	7.1

Each distillation unit has two operating modes: mode 1, 85%-100% of 18,000 m^3/day at a top brine temperature of 91°C and mode 2, 70%-100% of 22,500 m^3/day at a top brine temperature of 112°C.

2. Waste Heat Boiler:

The hot exhaust gases from the power generation gas turbine section is normally used in the waste heat boiler section as a heat source to generate the steam required for the distillers. Two operating conditions are considered: the unfired condition and the fired one. Under normal operating conditions, 160 t/h dry saturated steam is supplied at 15 bars, while the feed water temperature is maintained at 140°C.

3. Auxilliary Boiler:

The conditions of steam produced by the auxilliary boilers are identical to those produced by the waste heat boilers. However, the steam capacity is limited to 80 t/h when supplied with feed water at 140°C. The auxilliary boiler efficiency ranges from 85% to 86%.

4. Deaerators:

The deaerator is used to remove the dissolved oxygen from the boiler feed water and to warm this feed water up to a temperature of 150°C to avoid corrosion on internal tube surfaces. The dearator can handle up to a maximum of 160 t/h of condensate at a working pressure of about 2.5 bar gauge. The maximum deaerator working pressure is 3.5 bar gauge. The deaerator steam consumption normally ranges from 5 to 12 t/h.

Major Controls of Desalination Unit:

(i)Maximum brine temperature/steam flow:

The brine temperature at the brine heater outlet is one of the most important elements to control. When brine top temperature exceeds 91°C - in the case of polyphosphate dosing - scale forming will be promoted. If the temperature exceeds 121°C for all cases, hard scales are formed on the heat transfer surfaces and plant efficiency drops. Desuperheating of steam is required before entering the brine heater to avoid scaling problem due to high brine temperature levels.

(ii) Brine flow rate:

The recycled brine flow rate is automatically controlled to maintain brine velocity in the tubes within the prescribed range. The flow control valve is installed between the brine recirculation pump outlet and stage 14. This control valve plays an important role in destroying excess kinetic energy of the brine.

(iii) Feed flow/brine concentration:

The concentration of the recirculation brine is maintained within a prescribed range by constantly discharging a certain portion of the concentrated brine out of the system. This discharge is achieved by the brine blow-down pump. The discharged amount of brine is then automatically replaced by the chemically treated sea water feed. Once excessive brine concentration has occurred, boiling temperature within the distiller will be raised and scaling problem will also be introduced, both of which cause plant deficiency. For this reason, brine concentration control is also one of the most important elements of control.

(iv) Sea water inlet/outlet temperature controls:

In winter, sea water inlet temperature drops to approximately 18°C and the required cooling sea water quantity through the heat rejection section is reduced. Further reduction in cooling sea water flow rate is caused by part-load operation. As a result, tube velocity through the heat rejection section decreases and scale formation on the heat transfer surfaces is promoted. The low sea water inlet temperature introduces higher vacuum in the last stage, causing an increase in vapour velocity through demisters and resulting in higher contamination of distillate.

To avoid these undesired operating conditions, sea water recycle pump is provided to raise the inlet sea water temperature through mixing with the warmed-up cooling water.

(v) Distillate output controls:

The distillate output is controlled by altering the brine recirculated flow rate or by adjusting the temperature across the brine heater (flash range).

ANALYSIS OF THE RECIRCULATION MULTI STAGE FLASH (MSF) SYSTEM

This section presents the results of thermal analysis as derived in References (5) and (6) subject to the following simplifying assumptions:

(a) The distillate product leaving any stage is assumed salt free; this assumption is justified since the salt concentration in the final product usually varies between 5 and 50 ppm.

(b) No mist entrainment by the flashing vapor. This is in agreement with the above mentioned values for salt concentration in the final product.

(c) The heat of mixing of brine solutions is negligible, i.e. adiabatic mixing.

(d) No heat losses are accounted for.

(e) No subcooling of condensate takes place at the brine heater.

The incoming sea water, at flow rate M_c and temperature t_c, Fig. 3, is pumped into the condenser tubes of the last heat rejection stage and preheated successively

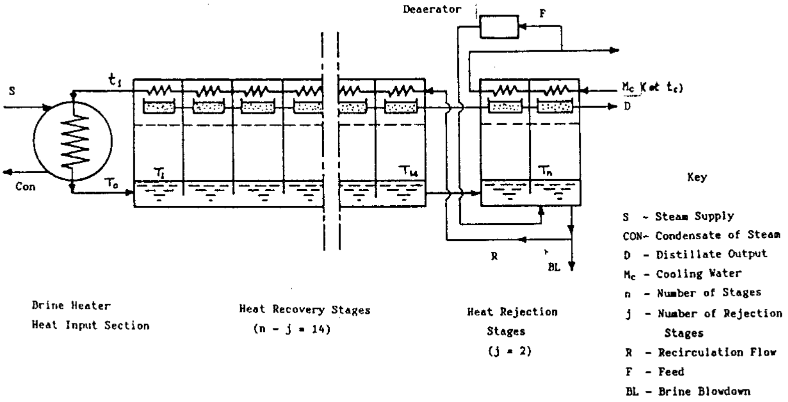

Fig. 3: Recirculation Multi-Stage-Flash, MSF Desalination System.

in heat rejection stages. The cooling water stream leaving the rejection section is divided into two streams: the first (M_c-F), is rejected back to the sea, and the second, the feed F, is chemically treated before joining part of the flashing brine leaving the last stage to form recirculation stream. The recirculation stream, R, is pumped to the last recovery state (n-j) condenser tubes and successively heated by passing through the recovery stage heaters (i.e. condensers) and leaves the first stage at temperature t_1. The recirculation flow, then enters the heat input section, HIS, where it is heated to the top brine temperature, T_0 by condensing the steam supply to the HIS as the main thermal energy input. The temperature increase of the recirculation flow in the brine heater ($T_0 - t_1$) is called the terminal temperature difference. Mass and energy balances yield the following equations:

(a) Feed to distillate ratio F/D

$$F/D = \frac{R/D - 1}{(1 - x_f/x_b)\,R/D - 1} \qquad \text{.........} \quad (1)$$

Where x_f and x_b are salt concentration of the feed and the maximum brine concentration respectively.

(b) Recirculation to distillate ratio R/D

$$R/D = \frac{1}{2} + \frac{L}{C\,(T_o - T_n)} \qquad \text{.........} \quad (2)$$

where L and C are the average values of latent heat of steam and specific heat of brine respectively.

(c) Performance parameters

i. thermal energy input per unit distillate output:

$$E_t = Q/D = \frac{RC\,(T_0 - t_1)/\eta_s}{D} \quad \ldots\ldots\ldots \quad (3)$$

where the energy input is estimated based on heat gained by brine, and η_s is the brine heater efficiency.
or:

$$E = \frac{S\,.\,L_s}{D} \quad \ldots\ldots\ldots \quad (4)$$

where the energy input is estimated based on heat released by steam, which is not as sensitive to temperature measurements as in the case of E_t.

ii. gained output ratio; distillate output per kg of steam consumption (GOR),

$$GOR = D/S = \frac{D}{Q/L_s} = \frac{DL_s}{RC\,(T_o - t_1)/\eta_s} \quad \ldots\ldots\ldots \quad (5)$$

where L_s is latent heat of HIS steam.

iii. performance ratio, (PR) defined by:

$$PR = \frac{D}{Q/2330} = \frac{2330\,D}{RC\,(T_o - t_1)/\eta_s} \quad \ldots\ldots\ldots \quad (6)$$

where 2330 is the average latent heat in the distillation process in kJ/kg.

iv. available energy consumption per unit distillate (Ea) given by:

$$Ea = \frac{Q\,(1 - T_o/T_a) + W}{D} \quad \ldots\ldots\ldots \quad (7)$$

where T_a and W are the ambient temperature and input mechanical work respectively.

RESULTS AND DISCUSSION

In this section the basic performance parameters of one of the desalination units (unit No. 6) at Ras Abu-Fontas Power and Water Station are estimated based on field data and then compared with the analytical predictions.

Among the sixty three variables which comprise the log sheet of the desalination plant, only 18 variables are identified as critical ones which are relevant to the calculations of performance parameters. Table 1 shows a sample of the recorded values taken on-site at Ras Abu-Fontas Power and Water Station on April 28, 1987 for a maximum top brine temperature of 112°C. Table 2 presents selected results of calculations carried out for different top brine temperatures and for different sea water temperatures. Table 3 gives a comparison betweeen the calculated parameters based on field data and the corresponding analytical predictions, based on theoretical formulea of References (5) and (6).

Table 1

Critical Parameters Collected on Field at T_0 = 112°C.

Measured Quantity		Time		
		8.00 am	10.00 am	12.00 noon
Flow Rate m^3/h				
1 Condensate	S	140	142	145
2 Distillate	D	910	910	910
3 High purity Distillate	HP	0	0	0
4 Blow down	BL	1670	1620	1630
5 Make up "Feed"	F	2750	2750	2750
6 Recycled brine (Recirculate)	R	10250	10200	10200
7 Sea water	M_c	8300	7600	7600
Temperature °C				
8 HIS brine inlet	t_1	102	102.5	102.5
9 HIS brine outlet	t_0	112	112	112
10 Condensate	T_s	114	113.5	113
11 Make up "Feed"	T_F	49	49	49
12 Sea water	t_c	35	35	35.5
13 Distillate	T_{vn}	44	45	44
14 Blow down	T_n	46	46.5	46.5
15 High purity	T_{HP}	86	85	85
16 Stage 1 vapor temperature	T_{v1}	103	103	102
17 Stage 14 vapor temperature	T_{v14}	56	55	55
18 HRS brine inlet temperature	t_{14}	46	46	46

Table 2
Selected Results of Performance Parameters

Symbol	Parameter	Value		
t_c	Sea water temp. °C	21.2	34	36
T_0	Top brine temp. °C	91	106	112
Q_1	Heat loss MW	20.05	7.07	21.4
η_m	Average efficiency	0.96	0.97	0.99
E_t	Thermal energy ratio	378.1	339.7	380.4
GOR	Gained output ratio	6.0	7.57	6.57
PR	Performance ratio	6.16	6.86	6.12
E_a	Available energy ratio	86.0	75.7	86.17

Table 3
Analytical predictions vs. Experimental Results

Quantity	Analytical	Experimental	% Error
Fixed parameters			
Distillate "D" m^3/h	910	910	
Sea water/recycle = M_c/R	0.8	0.8	
Condensate temp. °C	114	114	
Sea water temp. °C	35	35	
Top brine temp. °C	112	112	
Calculated and measured:			
HIS brine temp. t_1 °C	103.05	102	−0.98
Blow down temp. T_n °C	45.12	46	1.91
Sea water M_c m^3/h	6867.3	8300	7.26
Recycle brine R m^3/h	8584.1	10250	16.25
R/D	9.433	11.263	16.25
Gained output ratio D/S	8.39	6.50	−29
Performance ratio PR	7.02	5.70	−23.15

Effect of sea water temperature on the performance parameters namely: the gained output ratio, GOR and the energy input per kg distillate, E is presented in Fig. 4 for fixed values of top brine temperature (T_0 = 112.1°C) and flash range ($\triangle T_f$ = 65.8°C). As shown, GOR and E experience insignificant variation with t_c. This is attributed to the control of the cooling water temperature.

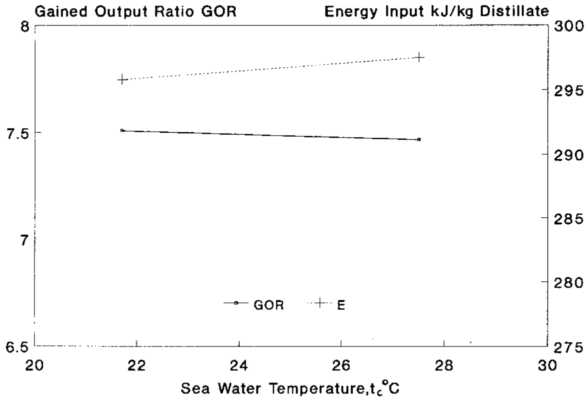

Fig 4: Effect of Sea Water Temperature on Performance Parameters (Fixed T_O & ΔT_f).

Fig. 5 shows the drop in the performance of the desalination unit versus time for the same operating conditions. Two operating periods are selected; one-week and six-week periods. When operating at $T_0 = 112.1°C$, $\Delta T_f = 65.7°C$, and $t_c = 18.5°C$, GOR dropped from 7.264 to 7.239 and E increased from 305.8 to 306.9 kJ/kg over the first period.

For the six-week period, GOR dropped from 7.311 to 7.175 and E increased from 304.1 to 309.6 kJ/kg when operating at $T_0 = 112.1°C$, $\Delta T_f = 66°C$ and $t_0 = 19°C$.

The drop in performance as calculated from the above figures show a nearly equal rates, as shown clearly in Fig. 5. The data presented, are thought to be helpful in assesing the long-term performance of the unit.

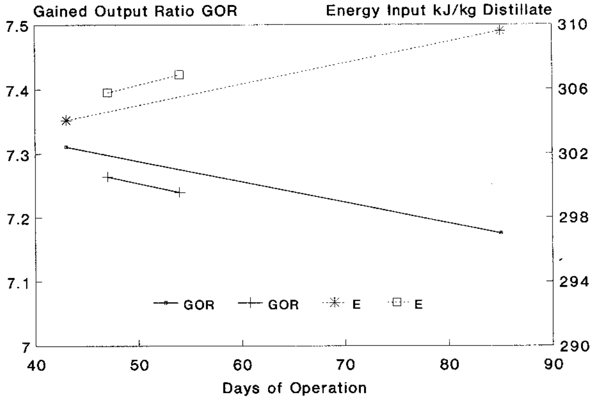

Fig 5: Effect of Operation Periods on Performance Parameters (Fixed T_O, ΔT_f & t_c).

Output of the Desalination Unit:

The amount of distillate, D is considered to be the most important parameter as it represents the productivity of the desalination unit. It is imperative to identify the factors which have direct effect on D. Theoretical analysis presented by equation (2) shows that D is a function of both the recirculate flow rate, R and the flash range ΔT_f.

Equation (2) is rewritten as $D_1 = R\left(\frac{2\,\Delta T_f}{\Delta T_f + 2\,L/C}\right)$, where the subsript of D refers to the theoretical expression. Several researchers have proposed empirical models to correlate the output, D with both R and ΔT_f. A model proposed by a researcher at the desalination plant expressing the distillate, D as a function of R and T_f takes the form: $D_2 = [1\text{-}\exp(-0.0017 \times \Delta T_f)]$. D_1 and D_2 are plotted in Fig. 6 for selected values of the recirculation rate and flash range. It is clearly shown that both D_1 and D_2 increase with T_f and increase linearly with R. Measured values of distillate flow rate D_m, are compared with the corresponding values D_1 and D_2 in Fig. 7. As anticipated, D_1, overestimates the output D_m. The figures also show that D_2 values are always higher than D_m. The numerical values of D_1, D_2 and D_m are given in Table 4 for different values of top brine temperature, T_0. As shown in the table, as the top brine temperature increases, the deviation between the measured output D_m and both D_1 and D_2 increases. This deviation suggests the inclusion of T_0 as a controlling parameter in determining the output D even though ΔT_f remains unchanged.

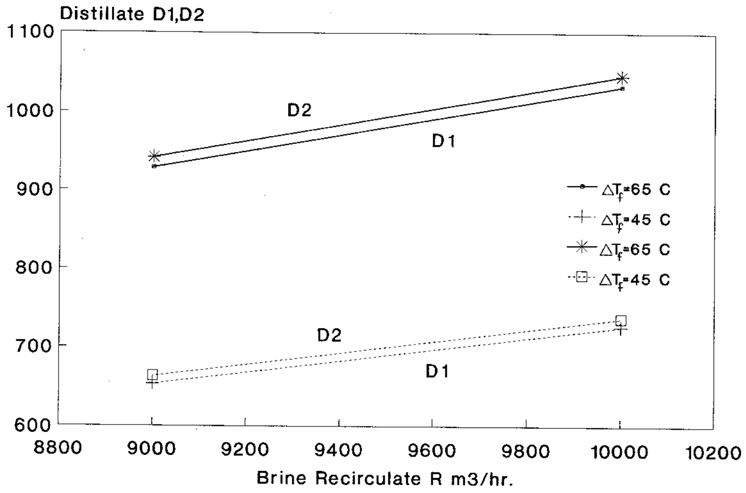

Fig. 6: Distillate vs. Recirculate and Flash Range.

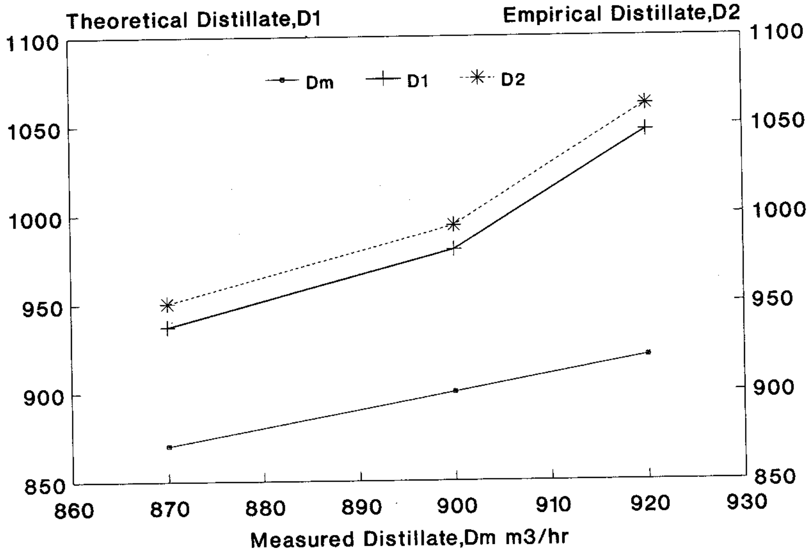

Fig. 7: Theoretical & Empirical vs. Measured Distillate.

Table 4

Comparison between Measured output, D_m and both D_1 and D_2

T_0	ΔT_f	R	D_m	D_1	D_2	D_1/D_m	D_2/D_m
91°C	45.6	9900	720	753.3	724.7	1.0065	1.0213
106°C	62	9500	870	937.2	950.3	1.0770	1.0923
112°C	66	10000	920	1046.7	1061.4	1.1377	1.1537

In this study, a refined model for the output including the effect of top brine temperature is proposed. The influence of this temperature, T_0 is reflected by the average stage temperature expressed as $T_{av} = (T_0 + T_n)/2$. The increase in T_{av} implies increase in thermal losses with the subsequent drop in output for the same energy input and under same operating conditions. This explains the discrepancy between the theoretical and measured outputs with T_0.

Our proposed correlation takes the form:

$$D^* = R\,[1 - \exp(-0.0017\ \Delta T_f)]/f$$

where

$$f = T_{av} \; / \; (T_{av}) \text{ ref.} = \frac{T_0 + T_n}{91 + T_n}$$

The 91 in the denominator is the minimum operating top brine temperature where the deviation between D_2 and D_m is minimum (approximately 2%).

Fig. 8 summarizes the results obtained using the three different models along with the measured output values. The ordinate of the figure reflects the ratio of the outputs D_1/D_m, D_2/D_m, and D^*/D_m while the abscissa gives the top brine temperature, T_0. The close agreement between D^* and D_m is clearly demonstrated in the figure with a maximum error of no more than 2%.

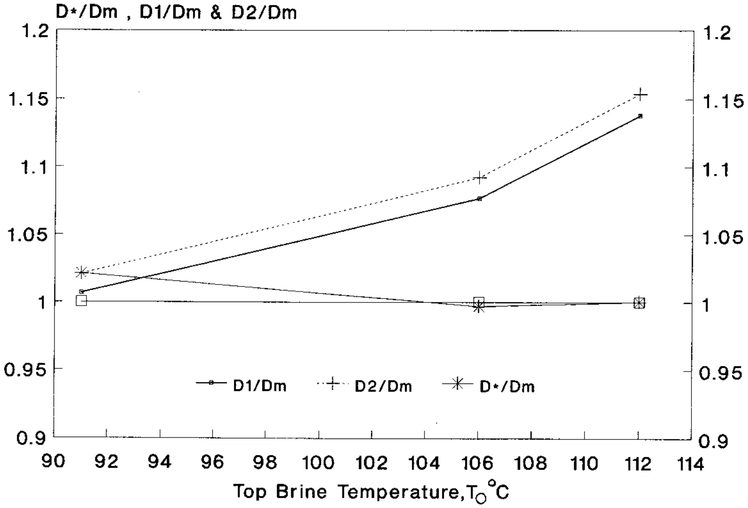

Fig. 8: Theoretical & Empirical Distillate vs. Measured at Different Top Brine Temp.

CONCLUSION

A comprehensive study was carried out on one of the desalination units at the main power and water station in the State of Qatar in order to assess its performance under different operating conditions.

The drop in performance is found to be uniform with the time and can be used to assess long-term performance and overhauling schedules.

The study revealed the importance of including the effect of top brine temperature, in addition to both the flash range and the recirculate flow rate in estimating the output of the unit.

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