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Design of a MSF Desalination Plant to be supplied by a New Specific 42 MW Power Plant Located in Iran

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***Abstract*—**Nowadays, desalination of salt water is considered an important industrial process. In many parts of the world, particularly in the gulf countries, the multi-stage flash (MSF) water desalination has an essential contribution in the production of fresh water. In this study, a simple mathematical model is defined to design a MSF desalination system and the feasibility of using the MSF desalination process in proximity of a 42 MW power plant is investigated. This power plant can just provide 10 ton/h superheated steam from low pressure (LP) section of heat recovery steam generator (HRSG) for thermal desalting system. The designed MSF system with gained output ratio (GOR) of 10.3 has 24 flashing stages and can produce 2480 ton/d of fresh water. The expected performance characteristics of the designed MSF desalination plant are determined. In addition, the effect of motive water pressure on the amount of non-condensable gases removed by water jet vacuum pumps is investigated.

***Keywords*—**Design, Dual-purpose power plant, Mathematical model, MSF desalination

I. Introduction

BY increase in population, the demand for potable water has been significantly increased. Thus, using economically admissible methods to produce drinking water is considered as a highly essential issue. In this regard, desalination of salt water has become a necessary industrial activity across the world. Nowadays, most of the Middle East countries use the multi-stage flash (MSF) desalination process to produce drinking water. In Iran which is a dry country, water production is an important challenge, and using MSF desalination method has recently become an important subject of research.

Nowadays, thermal desalination processes are popular techniques for production of drinking water in the Middle East countries. Thermal desalination is based on distillation process through which brackish water or seawater is converted to potable water for use in domestic and industrial activities. Thermal desalination system can be constructed in proximity of a power plant.

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Then, the thermal energy for distillation would be provided by steam coming from turbine or heat recovery steam generator (HRSG) sections of the power plant [1], [2]. Vapor compression (VC), multi-effect distillation (MED) and multi-stage flash distillation (MSF) are some conventional thermal desalination methods which the MSF desalination system is more common than the other systems [3], [4]. 65 percent of the world's desalination plants use MSF desalination technology and more than 80 percent of seawater desalination in Gulf countries is performed by MSF desalination method [5], [6]. Kuwait, Qatar, Oman, United Arab Emirates and Saudi Arabia are the Middle East countries that considerably use MSF desalination [2], [7]-[9].

Some of the southern cities of Iran such as Sirik, Gorzeh and Jask which are located in proximity of Persian Gulf have the potential of using thermal desalting methods like multi-stage flash desalination. Considering the proximity to Persian Gulf and the fact that some new 42 MW power plants are going to be built in these cities, it would be highly valuable to design and construct some thermal desalination plants in this area. The power plants are combined cycle power plants consisting of gas and steam turbines (Fig. 1). As shown in Fig. 1, required steam for desalination plant is prepared from LP section of the HRSG.

The focus of this study is to introduce an efficient MSF desalination plant supplied by a 42 MW power plant that provides just 10 ton/h steam, with respect to the allowable salinity of blowdown (80000 ppm) [7]. Thus, practical correlations are defined to design the MSF desalination system and then operating parameters are determined.

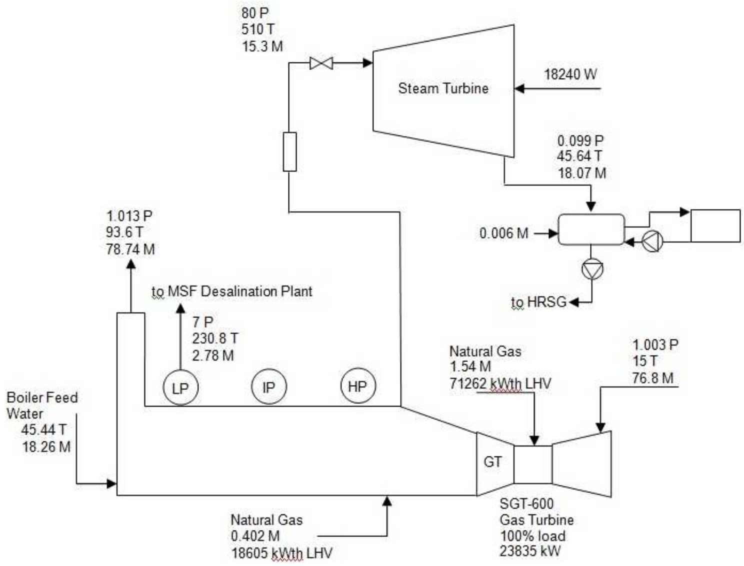

Fig. 1 Schematic diagram of the 42 MW combined cycle power plant. P: bar, T: °C, M: kg/s, LHV: Low Heat Value

II. Material and Methods

A. Process Description

The schematic diagram of the MSF process with brine recirculation is shown in Fig. 2. The process contains 24 flashing stages which have similar layout. Stages 1-21 comprise heat recovery section and stages 22-24 are considered as the heat rejection section. Each stage usually contains brine orifice, condenser/preheater tubes, water boxes, distillate tray, venting line, demister and partition walls [10]. In the brine heater (heat input section), the preheated brine is heated to reach the maximum allowable brine temperature. The brine heater operates as a shell and tube heat exchanger.

Furthermore, a deaerator is connected to stage 24 for preparation of the make-up flow. The flash chamber shell and the brine heater shell are fabricated from stainless steel, while the condenser tubes in the chambers and the tubes of the brine heater are made of Cu-Ni 70-30. As shown in Fig. 2, three water jet vacuum pumps are implemented for producing required vacuum in the stages. The two of them are considered to operate in heat recovery section and the third one operates in heat rejection section and deaerator unit.

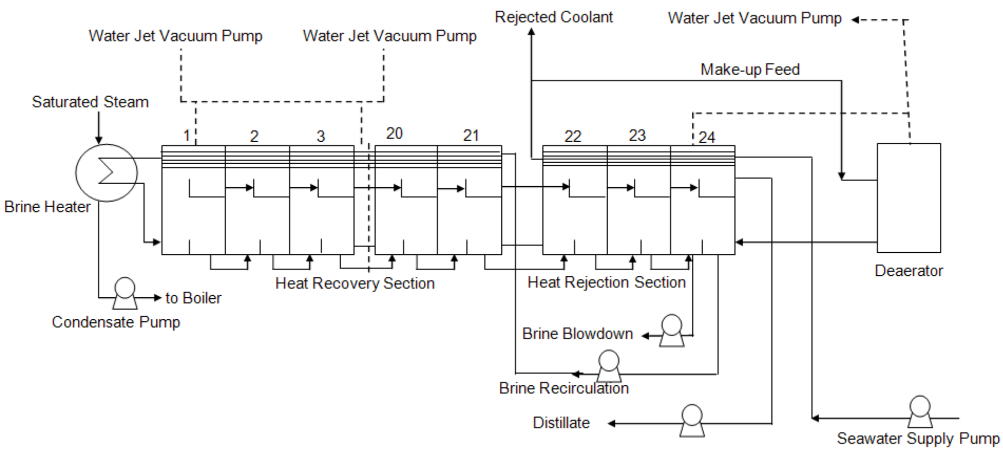

Fig. 2 Schematic diagram of the MSF desalination plant with 24 flashing stages

As mentioned before, the 42 MW power plant prepares 10 ton/h of steam for thermal desalination system. So, 6.5 ton/h of steam is used in the brine heater and the rest is consumed in the deaerator.

B. Design of the system

Usually, the MSF process modeling includes mass and energy balance, heat transfer equations, physical property correlations and the temperature losses due to boiling point variation. The system design methodology is presented at this section.

The seawater temperature, the difference in the temperature of inlet and outlet recycle streams of the condensers and the temperature difference between the inlet and outlet brine streams in flashing chambers are considered to be 26 °C, 2.39 °C and 2.39 °C, respectively. The top brine temperature (TBT) and the blowdown temperature are assumed 94 °C and 34 °C, respectively.

The pressure values inside the vaporization chambers are equal to the saturation vapor pressure.

The specific heat of seawater at constant pressure depends on temperature and water salinity, and is defined as "(1)":

$$C_p = [A + BT + CT^2 + DT^3] \times 10^{-3} \quad (1)$$

where T is temperature (°C) and

$$A = 4206.8 - 6.6197S + 1.2288 \times 10^{-2} S^2 \quad (2)$$

$$B = -1.1262 + 5.4178 \times 10^{-2} S - 2.2719 \times 10^{-4} S^2 \quad (3)$$

$$C = 1.2026 \times 10^{-2} - 5.3566 \times 10^{-4} S + 1.8906 \times 10^{-6} S^2 \quad (4)$$

$$D = 6.87774 \times 10^{-7} + 1.517 \times 10^{-6} S - 4.4268 \times 10^{-9} S^2 \quad (5)$$

where S is water salinity (g/kg).

The amount of vapor ($\dot{m}_s$) produced in each stage depends on the latent heat of evaporation at saturation temperature, recycle flow rate, specific heat of seawater and temperature variation of recycle flow ("(6)").

$$\dot{m}_R C_{pi} \Delta t = \dot{m}_{si} \lambda_{si} \quad (6)$$

where i is the number of stages.

The salinity of brine varies by passing from the first stage to the last one. The amount of increase in brine salinity depends on the brine flow of previous stage and its salinity ("(7)"):

$$S_i = \frac{\dot{m}_{bi-1} S_{i-1}}{\dot{m}_{bi}} \quad (7)$$

The stage width of the MSF system (W) can be determined by "(8)". The brine shell load (SL) is the flashing brine flow rate per unit width of the flash chamber. This design parameter (shell load) affects both of the width of the stage and the non-equilibrium losses in the stage. In this study, it is assumed that the entire produced vapor condenses to water.

$$W = \frac{\dot{m}_R}{SL} \quad (8)$$

$$SL = 457.2 + 53.43D \quad (9)$$

The length of the MSF flashing stage (L) is determined from distilled water (D), steam density (ρ_{steam}), maximum allowable vapor release velocity (V_m) and the stage width (W). The maximum allowable release velocity varies through the first stage to the last one and should not exceed 10 m/s in the last stage of the rejection section [7]. In this study, the maximum release velocities for the first and last stages are considered 1 and 7.7 m/s, respectively. The length of the stage is obtained by the "(10)":

$$L = \frac{D}{\rho_{steam} V_m W} \quad (10)$$

By obtained width and length of the stages, the area of the flash chamber and vapor mass flux can be determined from "(11)" and "(12)":

$$A = W \times L \quad (11)$$

$$\phi_v = \frac{\dot{m}_s}{A} \quad (12)$$

Stage height is the summation of the brine depth, height between brine level and demister, demister height and the height above demister. The brine depth in each flashing chamber is adjusted to seal the orifice. The orifice controls bubble formation and vapor release rate by controlling the brine flow rate. The brine depth is always higher than the gate height (H_G) by about 0.1-0.2 m and should be adjusted below 60 cm. Optimum height between brine surface and demister must be selected to keep the chamber at its minimum height. The demister height (H_d) depends on the steam density and steam mass flux by a correlation as height constant (K_h). The demister height can be obtained by the empirical equation "(15)" [11]. The height above the demister includes the condenser diameter and space between demister and condenser. Condenser diameter depends on the number of tubes fixing on support plates.

$$H_G = \frac{\dot{m}_R}{C_d W} (2\rho \Delta P)^{-0.5} \quad (13)$$

$$H_d = 0.1776 e^{0.0054 K_h} \quad (14)$$

$$K_h = \frac{3.281 \phi_v}{\rho_v \sqrt{\frac{\rho_l}{\rho_v} - 1}} \quad (15)$$

where C_d is the orifice discharge coefficient and can be in the range of 0.4-0.6. In this study, C_d is assumed 0.5. The unit of pressure difference between consecutive stages (ΔP) is pascal.

All the tubes in chamber condensers are made of Cu-Ni 70-30 with inside and outside diameters of 0.0293 and 0.0318 m, respectively. As the condenser section in all chambers operates like a heat exchanger, calculation of total heat transfer coefficient based on outside diameter (U_o) is accomplished by "(16)".

$$\frac{1}{U_o} = \frac{1}{h_i \frac{d_i}{d_o}} + \frac{1}{h_o} + r_t + r_{fi} + r_{fo} \quad (16)$$

$$r_{fo} = \frac{1}{h_o A_o} = \frac{1}{h_o \pi d_o l} \quad (17)$$

$$r_{fi} = \frac{1}{h_i A_i} = \frac{1}{h_i \pi d_i l} \quad (18)$$

$$r_t = \frac{Ln(d_o / d_i)}{2\pi k l} \quad (19)$$

$$h_o = 0.72 g \left[\frac{g \rho_L^2 k_R^3 \overline{L}_v}{N_t \mu_R (T_c - T_{su})} \right]^{0.25} \quad (20)$$

Nusselt number for turbulent stream inside the sleek tubes is defined as "(21)". Using this equation, the heat transfer coefficient inside the tube (h_i) can be determined.

$$Nu_d = \frac{h_i d_i}{k} = 0.023 \mathrm{Re}^{0.8} \mathrm{Pr}^{0.4} \quad (21)$$

The brine heater is a shell and tube heat exchanger which consists of 109 tubes made of Cu-Ni 70-30 with diameter values like condenser tubes. Heat transfer surface area of brine heater is estimated from "(22)".

$$A_h = \frac{\dot{m}_R C_{P,R} (TBT - t_1)}{U_h (LMTD)_h} = N_t \pi d_o l \quad (22)$$

The pressure value inside the brine heater and the vapor saturation temperature are 1.7 bar and 115 $^{\circ}$C, respectively.

$$(LMTD)_h = \frac{t_1 - TBT}{Ln(\frac{T_s - TBT}{T_s - t_1})} \quad (23)$$

The mentioned mathematical models can be used to design a new MSF desalination plant. According to these models, the effect of different operating parameters on performance of the plant can be investigated.

III. Results and Discussion

The performance characteristics of the MSF desalination plant were predicted using the design model mentioned in Material and Methods, and results are demonstrated in this part. To calculate the mathematical equations, the values of some parameters are assumed and given in Table I. Since this study was conducted with the aim of designing a MSF desalination plant appropriate for southern cities of Iran, the salinity of seawater was considered the same as the salinity of Persian Gulf water (43300 ppm).

TABLE I
Assumed Parameters to Design the MSF Desalination Plant

Parameter	Value
Seawater feed temperature, $^{\circ}$C	26.2
Seawater feed concentration, ppm	43300
Top brine temperature, $^{\circ}$C	94
Brine velocity inside the condenser tubes, m/s	2

Table II presents some of the manufacturing characteristics of the designed MSF desalination plant. According to the accomplished calculations, the width of the stages in each section is almost constant while the lengths of the stages are different. Table III gives calculated length value of flashing stages.

TABLE II
Specifications of MSF Desalination Plant

Specification	Heat rejection section	Heat recovery section	Brine heater
Number of stages	3	21	-
Number of tubes	1500	1500	1198
Tube length, m	1.4	1.2	4
Tube outside diameter, m	0.0318	0.0318	0.0318
Tube inside diameter, m	0.0293	0.0293	0.0293
Stage width, m	1	1	-

TABLE III
The Length of the Stages

Stage number	Stage length, m
1	3.07
2	2.58
3	2.29
4	2.11
5	1.99
6	1.92
7	1.88
8	1.86
9	1.86
10	1.88
11	1.92
12	1.97
13	2.04
14	2.11
15	2.21
16	2.32
17	2.45
18	2.61
19	2.78
20	2.97
21	3.19
22	3.42
23	3.72
24	4.07

As mentioned before, total height of each chamber is divided into four segments. The results of calculated gate height, brine depth and demister height are presented in Table IV. The distance between brine level and demister and the space height above the demister are assumed to be 1.6 and 2 m, respectively. Thus, stage height for heat recovery section and heat rejection section is considered 3.9 and 4 m, respectively.

TABLE IV
THE VALUES OF GATE HEIGHT, BRINE DEPTH AND DEMISTER HEIGHT

Stage number	Gate height, m	Brine depth, m	Demister height, m
1	0.083	0.233	0.0086
2	0.086	0.236	0.0113
3	0.090	0.240	0.0145
4	0.093	0.243	0.0179
5	0.097	0.247	0.0217
6	0.101	0.251	0.0257
7	0.106	0.256	0.0296
8	0.110	0.260	0.0335
9	0.115	0.265	0.0371
10	0.120	0.270	0.0403
11	0.125	0.275	0.0430
12	0.131	0.281	0.0451
13	0.137	0.287	0.0465
14	0.144	0.294	0.0473
15	0.151	0.301	0.0474
16	0.158	0.308	0.0470
17	0.167	0.317	0.0457
18	0.175	0.325	0.0444
19	0.184	0.334	0.0425
20	0.194	0.344	0.0404
21	0.205	0.355	0.0385
22	0.216	0.366	0.0357
23	0.229	0.379	0.0322
24	0.085	0.235	0.0018

Temperature values for all the streams inside the vaporization chambers are given in Table V. As indicated, temperature variation for all streams between two consecutive stages is assumed to be 2.39 °C.

TABLE V
TEMPERATURE VALUES (°C) FOR THE DIFFERENT STREAMS WITHIN THE CHAMBERS

Stage number	Temperature of intake recycle brine	Temperature of effluent recycle brine	Temperature of intake brine	Temperature of effluent brine
1	81.2	86	94	89
2	78.81	83.61	91.61	86.61
3	76.42	81.22	89.22	84.22
4	74.03	78.83	86.83	81.83
5	71.64	76.44	84.44	79.44
6	69.25	74.05	82.05	77.05
7	66.86	71.66	79.66	74.66
8	64.47	69.27	77.27	72.27
9	62.08	66.88	74.88	69.88
10	59.69	64.49	72.49	67.49
11	57.3	62.1	70.1	65.1
12	54.91	59.71	67.71	62.71
13	52.52	57.32	65.32	60.32
14	50.13	54.93	62.93	57.93
15	47.74	52.54	60.54	55.54
16	45.35	50.15	58.15	53.15
17	42.96	47.76	55.76	50.76
18	40.57	45.37	53.37	48.37
19	38.18	42.98	50.98	45.98
20	35.79	40.59	48.59	43.59
21	33.4	38.2	46.2	41.2
22	31.01	35.81	43.81	38.81
23	28.62	33.42	41.42	36.42
24	26.23	31.03	39.03	34.03

The design pressure of the shell as a function of saturation temperature is processed and maintained by the vacuum system along the stages. Table VI shows the pressure variations inside the stages. The first and the last stages have maximum and minimum shell pressures with the values of about 0.665 and 0.052 bar abs., respectively. Table VI shows the predicted value of brine salinity in each stage, and indicates that the maximum brine salinity is obtained in the last stage (80836.2 ppm).

TABLE VI
CALCULATED PRESSURE AND BRINE SALINITY FOR ALL FLASHING STAGES

Stage number	Pressure, bar	Brine salinity, ppm
1	0.665	49427.26
2	0.607	49860.64
3	0.552	50300.37
4	0.502	50746.52
5	0.456	51199.31
6	0.413	51658.85
7	0.374	52125.30
8	0.338	52598.95
9	0.305	53079.80
10	0.275	53568.04
11	0.247	54064.01
12	0.222	54567.96
13	0.199	55079.64
14	0.178	55599.40
15	0.159	56127.54
16	0.142	56664.43
17	0.126	57210.39
18	0.112	57765.72
19	0.099	58330.45
20	0.088	58904.67
21	0.077	59488.75
22	0.068	60082.95
23	0.060	60687.39
24	0.052	80836.17

Other calculated parameters of the MSF desalination plant like different stream flow rates are illustrated in Table VII. As shown, total distillate capacity of the MSF system is 2480 ton/d. In addition, calculated heat transfer area for the three sections of the MSF plant shows that the brine heater section has higher heat transfer area compared to the other two sections. Also, the heat transfer area of heat rejection section is higher than the heat recovery section.

TABLE VII
THE VALUES OF SOME OF THE CALCULATED PERFORMANCE PARAMETERS

parameter	value
Distillate capacity, ton/d	2480
GOR	10.3
Intake seawater flow rate, ton/h	410.8
Blowdown flow rate, ton/h	414.3
Recycle brine flow rate, ton/h	513.5
Make-up flow rate, ton/h	155.7
Rejected coolant flow rate, ton/h	70.8
Distillate flow rate, ton/h	103.3
Steam flow rate to brine heater, ton/h	6.5
Steam temperature to brine heater, °C	120
Steam flow rate to deaerator, ton/h	3.5
Steam temperature to deaerator, °C	230.8
Blowdown concentration, ppm	80836.2
Heat transfer area for heat rejection section, m^2	209.7
Heat transfer area for heat recovery section, m^2	179.7
Heat transfer area for brine heater, m^2	478.5

Pursuant to the exhibited mathematical model, thermo-physical properties of each stage were calculated and the results are presented in Table VIII. By increasing in number of stages, the temperature decreased and the brine salinity increased. These variations lead to partial decrease of specific heat capacity. On the other hand, the latent heat of vaporization gradually rises by increasing the number of stages.

TABLE VIII
THERMO-PHYSICAL CHARACTERISTICS OF THE MSF DESALINATION PLANT

Stage number	Specific heat capacity, kJ/kg.°C	Latent heat of vaporization water, kJ/kg
1	3.966	2287.44
2	3.964	2292.92
3	3.962	2299.26
4	3.961	2305.18
5	3.959	2311.49
6	3.958	2317.38
7	3.956	2323.59
8	3.955	2329.71
9	3.954	2335.29
10	3.952	2341.69
11	3.951	2347.93
12	3.950	2353.5
13	3.949	2358.75
14	3.947	2365.99
15	3.946	2372.56
16	3.945	2378.54
17	3.944	2383.96
18	3.943	2388.79
19	3.941	2393.43
20	3.940	2398.93
21	3.939	2405.05
22	3.938	2410.59
23	3.936	2416.17
24	3.935	2422.26

The obtained values of thermal resistance of the tube material, thermal resistance of the scale on the inside and outside of the tubes and the heat transfer coefficients are presented in Table IX. The calculated overall heat transfer coefficient based on the outside surface area for all flashing stages is also shown in Table IX. Passing the stages consecutively leads to decrease in the value of overall heat transfer coefficient due to increase in the concentration of non-condensable gases.

TABLE IX
CALCULATED HEAT TRANSFER COEFFICIENTS AND THERMAL RESISTANCES

Stage number	h_i	h_o	$r_{fi}\times10^{-5}$	$r_{fo}\times10^{-5}$	$r_t\times10^{-6}$	U_o
1	10279	7479	1.0545	1.3352	4.4833	3736
2	10157	7417	1.0672	1.3466	4.4833	3699
3	10039	7359	1.0797	1.3570	4.4833	3665
4	9916	7296	1.0931	1.3689	4.4833	3628
5	9789	7229	1.1073	1.3815	4.4833	3589
6	9657	7160	1.1223	1.3948	4.4833	3550
7	9523	7089	1.1382	1.4088	4.4833	3509
8	9317	6981	1.1634	1.4307	4.4833	3446
9	9255	6941	1.1711	1.4387	4.4833	3426
10	9115	6867	1.1891	1.4543	4.4833	3383
11	8973	6787	1.2079	1.4716	4.4833	3338
12	8839	6713	1.2262	1.4876	4.4833	3296
13	8699	6633	1.2460	1.5055	4.4833	3252
14	8559	6561	1.2663	1.5220	4.4833	3209
15	8413	6478	1.2883	1.5416	4.4833	3163
16	8263	6392	1.3117	1.5623	4.4833	3115
17	8111	6304	1.3363	1.5840	4.4833	3067
18	7958	6415	1.3621	1.5566	4.4833	3068
19	7807	6126	1.3882	1.6302	4.4833	2968
20	7653	6040	1.4162	1.6534	4.4833	2919
21	7500	5956	1.4451	1.6767	4.4833	2871
22	7359	5886	1.4728	1.6966	4.4833	2829
23	7201	5786	1.5052	1.7260	4.4833	2775
24	7046	5749	1.5384	1.7369	4.4833	2738

Average value of overall heat transfer coefficients in heat rejection section, heat recovery section and brine heater is about 2960.5, 3102.4 and 3658.7 W/m^2 °C, respectively.

Relative suction flows of water jet vacuum pumps for different motive water pressures (4, 5 and 6 bar) are shown in Table X. By increase in the motive water pressure, the ratio of exhausted non-condensable gases to inlet motive water increases because high velocities of flow in the mixing zone of the jet pumps provides ideal condition for heat and mass transfer. Furthermore, the amount of removed non-condensable gases decreases when the stage number increases.

TABLE X
EFFECT OF MOTIVE WATER PRESSURE ON THE VALUE OF PUMPING NONCONDENSABLE GASES

Motive water pressure (bar)	4	5	6
Stage number	kg/h of pumped gas per m^3/h of motive water		
1	1.45	1.54	1.62
2	1.2	1.4	1.5
3	1.1	1.25	1.38
4	1	1.12	1.2
5	0.9	1.05	1.09
6	0.8	0.94	1
7	0.75	0.85	0.9
8	0.65	0.74	0.8
9	0.6	0.66	0.75
10	0.55	0.6	0.67
11	0.5	0.54	0.6
12	0.43	0.5	0.55
13	0.39	0.44	0.5
14	0.35	0.39	0.45
15	0.31	0.35	0.4
16	0.28	0.32	0.36
17	0.25	0.29	0.34
18	0.23	0.25	0.3
19	0.2	0.24	0.28
20	0.16	0.19	0.23
21	0.14	0.16	0.18
22	0.1	0.12	0.16
23	0.08	0.1	0.12
24	0.05	0.08	0.1

IV. CONCLUSION

A MSF desalination system is designed to be supplied by a 42 MW power plant providing only 10 ton/h steam. 65% of the total steam prepared by LP section of HRSG in the 42 MW power plant is considered to be consumed in the MSF desalination plant. The designed MSF desalination system has 24 flashing chambers with the same width (1 m) and produces 2480 ton/d potable water (1056 ton/d can be used as drinking water). Height values of heat recovery section and heat rejection section are estimated to be 3.9 and 4 m, respectively. By operating this desalination system, the value of seawater salinity rises from 43300 ppm to the maximum allowable value of about 80000 ppm.

Nomenclature

A	Stage area, m^2
A_i	Heat transfer area based on inner tube diameter, m^2
A_o	Heat transfer area based on outer tube diameter, m^2
A_h	Heat transfer area of brine heater, m^2
C_p	Specific heat at constant pressure, kJ/kg °C
C_d	Orifice discharge coefficient
D	Distillate, MIGD
d_i	Tube inside diameter, m
d_o	Tube outside diameter, m
g	Gravitational acceleration, m/s^2
H_d	Height of the demister, m

H_G	Height of the gate in the flashing chamber, m
h_i	Heat transfer coefficient based on inner tube diameter, W/m^2 $^\circ$C
h_o	Heat transfer coefficient based on outer tube diameter, W/m^2 $^\circ$C
k	Thermal conductivity, kW/m $^\circ$C
K_h	Height constant of demister
L	Length of stage, m
$(LMTD)_h$	Logarithmic mean temperature difference, $^\circ$C
l	Length of tube, m
$\dot{m}$	Flow rate, kg/s
N_t	Total number of tubes
Nu_d	Nusselt number for stream inside tubes
P	Pressure, bar
Pr	Prandtle number
Re	Reynolds number
r_{fi}	Thermal resistance of the scale on the inside of the tubes, m^2 K/W
r_{fo}	Thermal resistance of the scale on the outside of the tubes, m^2 K/W
r_t	Thermal resistance of the tube material, m^2 K/W
S	Salinity, ppm
SL	Shell load, ton/m h
T	Temperature, $^\circ$C
TBT	Top brine temperature, $^\circ$C
T_c	Condensation temperature, $^\circ$C
T_{su}	Surface temperature, $^\circ$C
t	Temperature of recycle flow inside the condenser tubes, $^\circ$C
U_o	Overall heat transfer coefficient, W/m^2 $^\circ$C
U_h	Overall heat transfer coefficient at brine heater, W/m^2 $^\circ$C
V_m	Maximum allowable vapor release velocity, m/s
W	Width of stage, m
ρ	Density, kg/m^3
μ	Viscosity
λ	Latent heat of evaporation, kJ/kg
ϕ	Vapor mass flux, kg/h m^2

Subscripts

b	Brine
i	Stage number
L	Liquid
R	Recycle
S	Steam
v	Vapor

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