

ASSESSMENT OF THE MAJOR DESIGN FEATURES OF SWCC MSF DESALINATION PLANTS¹

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ABSTRACT

The design features of SWCC MSF plants are quite unique. The number of stages varies from as low as 16 up to 34 stages; distiller capacity from 2.5 to 10 MIGD and performance ratio are in the range of 2.39 to 4.57 Kg /1000 kJ. Top brine temperature varies from 90 to 115°C ; brine recycles rate from 946 to 1882 ton/h ; stage width from 10.2 to 19.4 m and stage length from 2.28 to 4.7 m. Such diverse and accumulated design features provided a great opportunity to serve a twofold purpose. Firstly, to carry out a comprehensive thermodynamic diagnosis that identifies the design constraints and irreversibilities inherited in the design of the different MSF plants and can be subsequently used as a guide to identify the features of an improved design. Secondly, extensive available design information that can be effectively used to identify and to establish design equations for future design use.

A comprehensive second law analysis was carried out using the second law of thermodynamic to assess the thermodynamic constraints inherited in the design of eleven MSF distillers representing SWCC major MSF plants situated in the Red Sea and Gulf coasts of Saudi Arabia. It was found that the total available energy losses of the examined distillers ranged between 16.7 to 23.6 kWh/m³. This amounted to about ten folds of that of an ideal reversible separation process and to about four folds of that of a SWRO membrane process.

A detailed parametric analysis was also carried out to simulate the interrelationship between the different design and operating parameters of the MSF distiller and presented in the form of grid networks. The comprehensive simulation study shall be

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effectively used as a guide to improve the irreversibility associated with and consequently lead to the reduction of the high energy requirements of the MSF distiller.

Different geometric dimensions of the MSF distiller are normally selected by different manufacturers and are based on simulation studies and field tests as well as rules of thumb. Available design information of SWCC plants are effectively used to establish empirical equations to predict important design parameters such as shell load, stage width, flash chamber area and stage length.

1. INTRODUCTION

A wide range of design features characterize SWCC MSF desalination plants. Summary of the salient design features of SWCC MSF distillers were previously reported [1]. Extensive available design information of SWCC MSF plants provides a great opportunity for critical analyses of the performance of different distillers. Thermodynamic analyses of the design of MSF distillers will enable pinpointing thermodynamic constraints that are inherited in each design and give relevant guidance for process improvement.

Although coupling of MSF process with power generation systems has greatly contributed to reducing energy requirement by about 50% or more compared to single purpose desalination plants using the same kind of fuel [2], it is still considered as an energy intensive process in comparison with other desalination processes. The need for detailed thermodynamic analysis is thus evident in order to get a detailed understanding of the process and search for optimal process irreversibility. A commercial computer program was acquired by the SWCC Research and Development Center and was used for the simulation of the MSF process. The algorithm and overall logic of the program were first studied and modified to suit SWCC MSF distillers [3&4]. The program has the capability to predict the physical and the thermodynamic properties of all liquid and vapor streams involved in the process and to simulate the MSF process under various conditions using the concepts of the first and the second law of thermodynamics .

The objective of this paper is three-fold. Firstly, to carry out a detailed parametric study to simulate the interrelationships between the different design and operating parameters

of the standard MSF distiller. The parametric study will determine the impact of the variation of the different design and operating parameters on thermal performance and irreversibility of the MSF distiller. Secondly, it is intended to carry out a thermodynamic analysis to determine the irreversibilities, which are associated with the design of eleven MSF distillers representing SWCC major MSF plants. Finally, a simulation study shall be performed to predict the geometric dimensions of the flash chambers of SWCC major cross flow MSF desalination plants.

2. PARAMATERIC ANALYSIS

A comprehensive parametric analysis was carried out to examine the interrelationships between the top brine temperature, number of stages, performance ratio, exergy losses and the terminal temperature approach of a standard MSF distiller. The terminal temperature approach is the difference in temperature between the condensing vapor and the recirculating brine stream leaving the condenser. This is an important design parameter that is dependent on the heat transfer area and overall heat transfer coefficient. The interrelationships between the different parameters are presented in the form of grid network, as shown in Figures 1 and 2 for terminal temperature difference (TTD) of 2 and 4°C, respectively. The top brine temperature (TBT) was varied between 90°C (the lowest TBT for additive scale operation) and 120°C (the highest TBT for acid operation plants). The number of stages were varied between 16 and 40. The maximum number of stages is limited by the pressure drop required to move the flashing brine from one stage to another, especially at the cold end. In addition, for flashing to occur the minimum inter-stage temperature drop must be greater than the boiling point elevation. Figures 1 and 2 show that for the same number of stages and same top brine temperature, increase of TTD from 2 to 4°C results in the reduction of the heat transfer area and this is due to the large driving force for heat transfer. Both figures reveal that increasing the number of stages while keeping top brine temperature constant such as lines AC & BD in figures 1 & 2, results in an increase of both performance ratio and specific condensing area and a decrease of exergy losses. Increase of number of stages decreases temperature drop per stage, which will reduce the irreversibility of the system due to the reduction in condenser and flash exergy losses and results in an improved thermal performance. Increase of performance ratio will reduce steam consumption and consequently minimize

operating cost while increase in surface area results in an increase of capital expenditure. Therefore, optimum performance ratio (i.e. that of lowest production cost of water, which is site specific) has to be determined by making cost tradeoffs between the cost of process energy and capital cost of the process. Conversely, increasing TBT while keeping number of stages constant (lines such as AB and CD) in figures 1 and 2 will increase the performance ratio and decrease the specific condensing area but its net effect on exergy destruction is not significant. Within the selected range of number of stages and top brine temperatures, the simulation analysis revealed that the dependence of exergy losses on the number of stages is more appreciable than that due to variation of TBT.

The conditions that represent an improve MSF distiller with the least amount of energy consumption, are presented by point D in Figures 1 and 2. In both cases, the maximum achievable performance ratio was obtained at the highest TBT of 120°C and the maximum possible number of stages (40 stages). At these conditions, the maximum performances ratios obtained were 13 kg/2326 kJ and 9.8 kg/2326kJ at TTD of 2 and 4°C, respectively. However, the improved energy performance obtained with a TTD of 2°C is at the expense of high requirements of specific condensing area. The specific condensing areas are 330 and 205 m²/(kg/s) for TTD of 2 and 4°C, respectively.

The parametric analysis also demonstrated that the MSF distiller is inheriting certain thermodynamic constraints, which limit the value of maximum achievable PR. In the present analysis, the maximum PR obtained is 13 kg/2326 kJ at TBT of 120 °C and forty stages.

3. THERMODYNAMIC ANALYSIS OF SWCC MSF DISTILLERS

A comprehensive thermodynamic analysis was carried out to assess the irreversibility inherited in the design of eleven MSF distillers representing SWCC major MSF plants situated in the East and West Coast. The plants which were covered in the study included Al-Jubail Phase I & II, Al khobar Phase II & III and Al Khafji from the Gulf coast and Jeddah Phase II,III and IV, Yanbu Phase I, Shoiaba Phase I and Al-Shugaig plants from the Red Sea coast. For each MSF distiller the total exergy losses as well as their breakdown among the major subsystems were determined.

Table 1 shows that there is a wide variation in the magnitude of the average specific exergy losses incurred by the eleven different MSF distillers and it ranged between 15.2 to 23.7 kWh/m³ compared to the expenditure of only 2 kWh/m³ exergy of an ideal reversible process and around 5 kWh/m³ for an RO process. The design and operating parameters, which are mostly responsible for specific exergy losses of an MSF distiller, include the number of stages, TBT and specific condensing area. Increase of number of stages and/or top brine temperature will result in a low temperature drop per stage, which in turn reduce the exergy losses. Increase of specific condensing area also has a positive impact on the reduction of the exergy losses.

The major design and operating features of the eleven selected MSF distillers are super-imposed on the simulated envelopes shown in Figures 1 and 2. Eight of the MSF plants are located on Figure 1 with the TTD of 2 °C. The remaining three MSF plants, which are Al-Khobar Phase-II and III and Jeddah Phase-II, are located in Figure 2 with the TTD of 4 °C. The majority of the plants superimposed on Figure 1 and 2 lied within a narrow shadowed band. The boundaries of this band are:

1. Number of stages = 19 to 24
2. Top brine temperature = 90 to 112 °C
3. Performance ratio = 7.8 to 8.6
4. Specific condensing area = 260 to 300 m³/(kg/s)

The only exception, which is not lying inside the scope of this band, is Yanbu Phase-I plant which was designed to operate on acid treatment with top brine temperature up to 121 °C.

The three plants, which are not lying within the boundaries of Figure 1 and are compatible with the Figure 2, are Al-Khobar Phase-II and III and Jeddah Phase-II. These three plants represent the two extreme boundaries of the design and operating features of SWCC MSF plant. Al-Khobar Phase-II & III plants uniqueness stemmed from the relatively very low number of stages (16 stages) while the Jeddah Phase-II

plant is characterized of very high number of stages (34) and represents the other end of the spectrum.

Selection of the most appropriate design and operating parameters for an improved MSF distiller to minimize the overall cost of water production can only be based on a detailed optimization study. Figure 3 shows the variation of the cost of water production with performance ratio for a 10 MIGD distiller. It also shows the influence of energy cost on water cost. With an oil price of \$24/bbl, the optimum performance ratio corresponding to the minimum water cost is eleven.

For lower fuel costs of \$ 12 and 18 per bbl, the optimum performance ratios are 8 and 9 respectively. Most of SWCC MSF plants are having performance ratios between 7.8 and 8.6 as mentioned above and therefore, based on low fuel cost. Due to effective alkaline scale control and good selection of construction material, MSF distillers can be designed to operate at TBT up to 115°C.

4. DESIGN CORRELATIONS

Design of MSF plants is normally based on empirical equations and/or simulation testing that is carried out by the manufacturer before the design was initiated. The extensive design information available on SWCC MSF desalination plants can be effectively utilized to test the validity of theoretical and empirical design equations, which are normally recommended to predict the main design dimensions of MSF flash chambers. Simulation study was carried out to predict the width ,length and height of the flash chambers of SWCC major cross flow MSF desalination plants.

4.1 Stage Width

The width of MSF flashing stage can be determined from the recycle brine flow M_R (kg/h) and the shell load, SL (kg/hr.m) of the stage. The shell load is the flashing brine flow rate (kg/h) per unit width of the flash chamber and is a design parameter that affects the width of the stage and affects the non-equilibrium losses in the stage. The width of the stage is obtained by the following relationship:

$$\text{Stage Width, (W)} = \frac{\text{Brine Recycle } (M_R)}{\text{Brine Shell Load (SL)}} \quad (1)$$

Both the recycle flow and the shell load are dependent on the rate of distillate production. The brine recycle flow can be determined from the distillate production using the following approximate relationship.

$$\left(\frac{M_R}{M_D}\right)^2 - \left(\frac{L}{C_p \Delta T} * \frac{(PR+1)}{PR} + \frac{1}{2}\right) * \left(\frac{M_R}{M_D}\right) + \frac{L}{2 PR C_p \Delta T} = 0 \quad (2)$$

Where,

M_R = Design Recycle Flow rate, (kg/h)

M_D = Design production rate, (kg/h)

PR = Plant performance rate (Design)

ΔT = Flash Range, °C

C_p = Sp ht. at avg. temp, kJ/kg.°C

L = Latent ht at av. temp, kJ/kg.°C

Based on the selected rate of water production and top brine temperature, the recycle flow can then be estimated using equation 2.

The Shell Load (SL) was determined by a rule of thumb. Having determined the brine recycle flow and shell load, equation (1) is then used to find out the stage width. Table 2 shows a comparison between the actual (design) width of SWCC MSF distiller and those estimated from the derived brine recycle flow and shell load. The actual values of the stage widths are within the range of -19.96 to +16.17 percent of the theoretical values.

4.2 Area of the Flash Chamber

The minimum required area of the flash chamber (A) m² can be determined from the following equation:

$$\text{Area (m}^2\text{)} = \frac{\text{Stage Vapor Flowrate (m}^3\text{/s)}}{\text{Vapor Release Velocity at Brine Surface (m/s)}} \quad (3)$$

The vapor release velocity has a strong influence on the liquid carry over in the flash chamber. The higher the release rate, the higher will be the amount of brine entrainment in the vapor. The vapor release velocity in a distiller varies from stage to stage. It increases from lowest value in the first stage up to the highest value in the last stage due to the high specific volume in the low-pressure stages.

The vapor release velocity can be estimated from Souders-Brown equation:

$$\text{Vapor velocity at flash surface, } v \text{ (m/s)} = K \sqrt{\frac{\rho_l - \rho_v}{\rho_v}} \quad (4)$$

Where, K = Empirical constant dependent upon the decontamination factor

ρ_l = Density of brine(kg/m³)

ρ_v = Density of vapor (kg/m³)

For each plant, a simulation study for the design data as provided by the contractor was carried out to determine vapor volumetric flow rate in the first and last stage of distillers and accordingly the corresponding flash chamber areas were calculated using equations (3) & (4).

A comparison of design and calculated values of the stage area for different SWCC MSF distillers are shown in Table 3. The actual values of the first and last stages areas are in most cases higher than the theoretically estimated values.

Having determined the stage area and width, the stage length is accordingly calculated by using the following equation:

$$\text{Stage Length (m)} = \frac{\text{Stage Area (m}^2\text{)}}{\text{Stage Width (m)}} \quad (5)$$

A comparison of design and calculated values of stage length are shown below in Table 3.

The actual values of the flash chamber lengths are in most cases around 5.0 to 37.7 percent higher than the calculated values.

4.3 Stage Height

Stage height is the summation of three heights: the brine depth, height between brine level and demister top and the height above demister pads. The brine depth should be kept below 60 cm to avoid high non-equilibrium losses. The brine depth is necessary to maintain stages seals and prevent vapor flow through that result in priming and loss of distillate purity. The demister must be placed at a height above the flashing brine that allows the chamber height to be kept to a minimum. The mesh must be placed at a sufficient distance above the jet height to prevent carry over of brine into the distillate tray.

The minimum demister/mesh height will vary from stage to stage for a given vapor rate. A good estimation of demister height above the brine jet level can be obtained from the following empirical equation.

$$\text{Mesh height above jet (cm)} = 0.1776 * e^{0.0054 * K_h} \quad (6)$$

$$\text{Where, Height Constant} = K_h = \frac{3.281 G}{\rho_v \sqrt{\frac{\rho_l}{\rho_v} - 1}} \quad (7)$$

G = Vapor mass rate (release rate) (kg/h m²)

ρ_v = Vapor density (kg/m³): ρ_l = Brine density (kg/m³)

Table 3 shows comparison between the actual stage height between brine level and demister. The values of the actual height are in most cases about three times higher than the theoretically

Direct comparisons between the actual flash chamber width, length and demister height and those predicted from imperial correlations were carried out for each of SWCC major MSF plants. They revealed the followings:

- 1) The actual values of stage widths are within -19.96 to $+16.17$ percent of the theoretical values.
- 2) The actual values of the flash chamber length are in most cases within 5 to 37.7 percent higher than those predicted from the empirical relationships.
- 3) The actual values of the stage height between brine level and demister are in most cases around 55 to 71 % higher than those predicted from the empirical relationship.

5. CONCLUSIONS AND RECOMMENDATIONS

- 1) The parametric analyses indicated that MSF processes could be improved towards high performance ratios by increasing the top brine temperature, number of stages and the specific heat transfer area.
- 2) The standard MSF design configuration is inheriting thermodynamic constraints that limit the maximum achievable performance ratio (PR) to less than 13 kg/2326 kJ.
- 3) Second law simulation studies revealed that there was a wide variation in the magnitude of the average specific exergy losses of the examined MSF distillers and it ranged between 16.7 to 23.6 kWh/m³ compared to the expenditure of only 2 kWh/m³ exergy of an ideal reversible process and around 5 kWh/m³ for an RO process.
- 4) Due to effective alkaline scale control and good selection of material of construction MSF distillers can be designed to operate at TBT up to 115°C and with performance ratio of about 11 kg/2326 kJ.

5. It is recommended to obtain a more detailed and comprehensive design data and establish more relevant correlations. A design capability at SWCC may then be attained for future use.

6. REFERENCES

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Table 1. Total Exergy Losses of SWCC MSF plants

S.N.	Plant	Total Exergy losses (kWh/m ³)
1	Al-Jubail Phase - I	18.3
2	Al-Jubail phase - II	15.8
3	Al-Khafji phase - I	15.2
4	Al-Khobar phase - II	17.8
5	Al-Khobar phase - III	23.7
6	Al-Shoqaq phase -I	16.7
7	Shuaiba phase - I	17.4
8	Jeddah phase - II	15.3
9	Jeddah phase - III	19.7
10	Jeddah phase - IV	21.27
11	Yanbu phase - I	17.6

Table 2. Comparison of Theoretical and Actual (Design) Values of Stage Width and Area of SWCC MSF Plants

SWCC MSF Plants	Stage Width			Stage Area		
	W (Actual), m	W Theoretical), m	% Difference	Area range (Actual), m ²	Area range (Theoretical),m ²	% Difference
Al-Jubail I	14.00	15.76	-12.54	39.2 - 40.60	30.42 - 34.09	22.39 - 16.03
Al-Jubail II	19.40	16.26	16.17	56.26 - 56.26	31.46 - 35.25	44.09 - 37.34
Jeddah III	12.73	11.37	10.67	31.83 - 64.0	33.01 - 46.94	3.71 - 26.65
Khobar II	13.20	15.83	-19.96	39.6 - 48.18	37.82 - 46.78	4.49 - 2.90
Khobar III	15.30	17.63	-15.25	56.61 - 59.67	55.14 - 74.83	2.59 - 25.41
Shoaiba I	14.10	14.35	-1.75	32.15 - 48.65	37.86 - 46.99	17.76 - 3.41
Shoaiba II	16.90	17.61	-4.18	61.02 - 83.52	51.33 - 74.56	15.87 - 10.73
Shugaig I	17.42	15.96	8.39	62.71 - 62.71	35.80 - 43.09	42.91 - 31.30
Yanbu I	10.20	9.21	9.69	23.97 - 40.80	18.53 - 31.65	22.70 - 22.43
Yanbu II	17.76	16.06	9.59	51.50 - 83.47	41.82 - 58.90	18.81 - 29.44

Table 3. Comparison of Theoretical and Actual (Design) Values Range of Stage Length and stage height of SWCC MSF Plants

SWCC MSF Plants	Stage Length			Stage Height between Brine Level & Demister		
	Length range (Actual), m	Length range (Theoretical), m	% Difference	Height (Actual), m	Height (Theoretical), m	% Difference
Al-Jubail I	2.80 - 2.90	1.93 - 2.16	31.04 - 25.39	2.00	0.714	64.30
Al-Jubail II	2.90 - 2.90	1.93 - 2.17	33.30 - 25.25	1.80	0.714	60.33
Jeddah III	2.50 - 5.03	2.90 - 4.13	16.09 - 17.91	1.89	0.607	67.88
Khobar II	3.00 - 3.65	2.39 - 2.95	20.38 - 19.06	1.85	0.714	61.40
Khobar III	3.70 - 3.90	3.13 - 4.24	15.48 - 8.81	2.00	0.607	69.65
Shoaiba I	2.28 - 3.45	2.64 - 3.28	15.74 - 5.06	2.10	0.607	71.09
Shoaiba II	3.39 - 4.64	2.92 - 4.23	13.99 - 8.73	2.00	0.607	69.65
Shugaig I	3.60 - 3.60	2.24 - 2.70	37.68 - 25.01	1.60	0.714	55.37
Yanbu I	2.35 - 4.00	2.01 - 3.44	14.40 - 14.10	2.06	0.607	70.53
Yanbu II	2.90 - 4.70	2.61 - 3.67	10.20 - 21.96	2.11	0.61	71.23

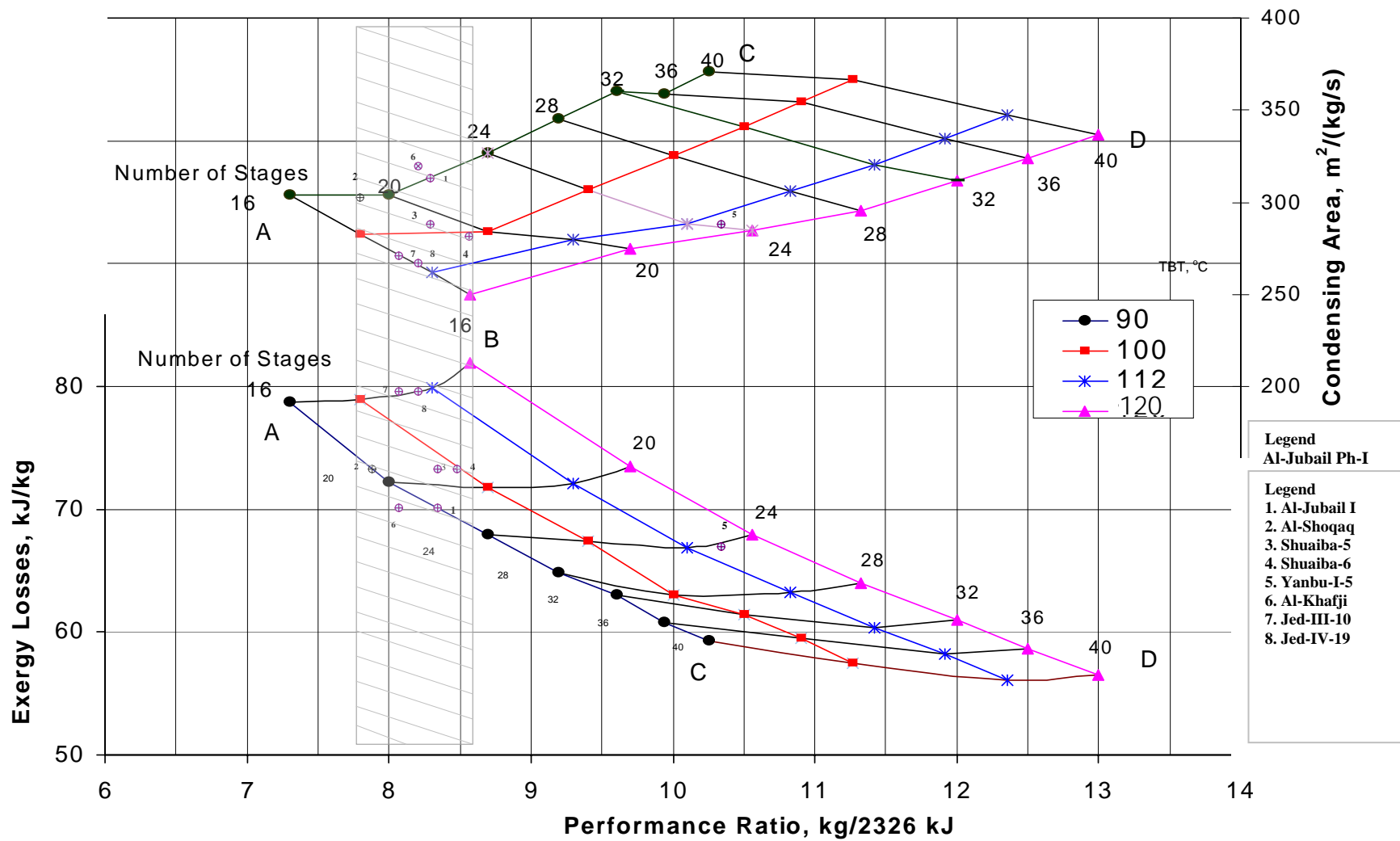


Figure 1: Dependence of Performance Ratio, Exergy Losses and Specific Condensing Area on TBT and Number of Stages (Terminal Temperature Difference TTD = 2°C)

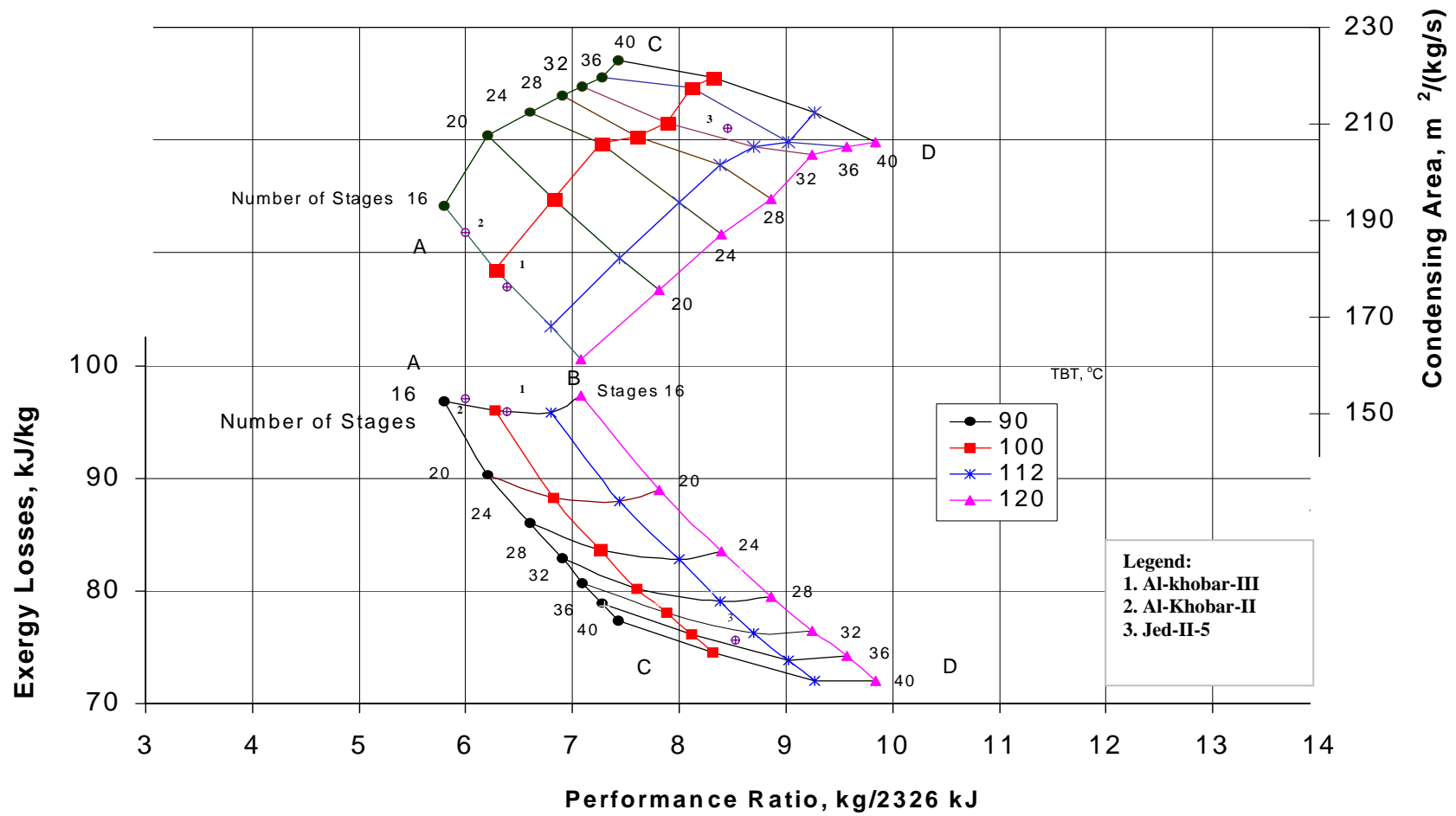


Figure 2: Dependence of Performance Ratio, Energy Losses and Specific Condensing Area on TBT and Number of Stages (Terminal Temperature Difference TTD =4°C)

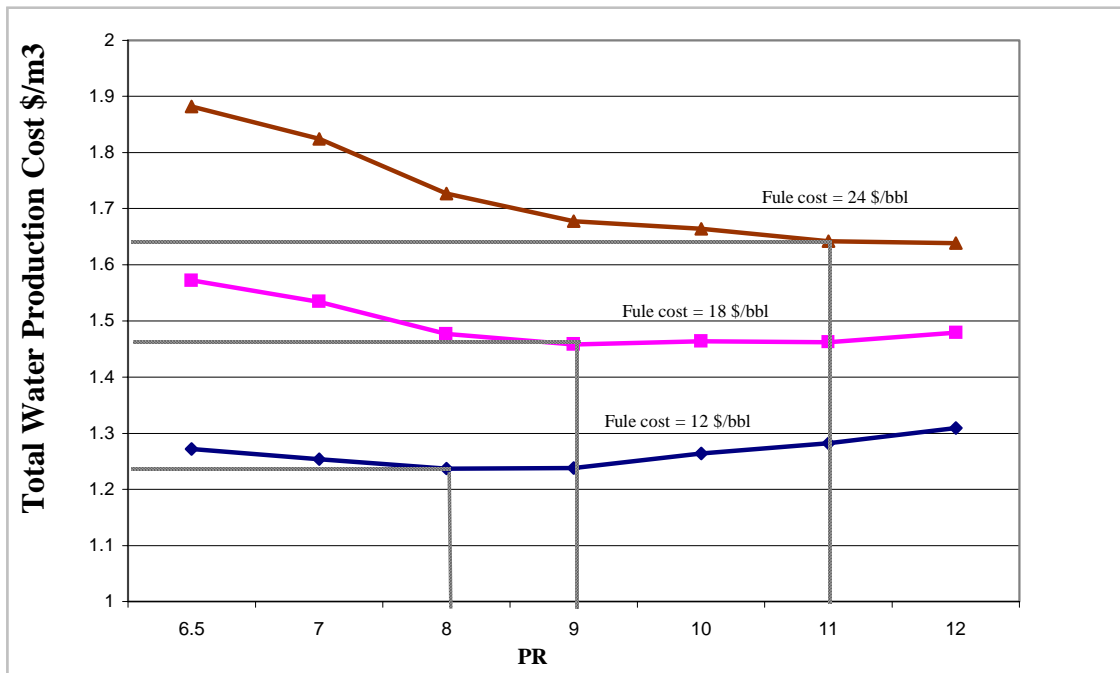


Figure 3. Variation of total water production with performance for 10 MIGD MSF distiller