The Effect of Increased Top Brine Temperature on the Performance and Design of OT-MSF Using a Case Study

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Abstract

A mathematical model of a Once-Through Multi-Stage-Flash (OT-MSF) desalination system is developed. This study shows the impact of top brine temperature (TBT) of up to 160°C on both the design and performance characteristics of MSF systems. Such a high TBT can be achieved by nanofiltration pretreatment to remove scale-forming compounds. System performance is evaluated by the thermal performance ratio (PR) and the required specific area (sA). For a fixed brine reject temperature (T_{end}) and inter-stage temperature drop (ΔT), adding stages results in the TBT increasing by ΔT for each stage added and the PR increases monotonically with the TBT. On the other hand, the required sA decreases and then increases again beyond a certain TBT. The Sirte desalination plant in Libya is taken as a case study. It is found that by increasing the TBT to 161°C from a typical value of 118°C keeping T_{end} and ΔT fixed; the PR can be increased by 41.5%, reaching a value of 14.6 while the required sA increases by 0.9%. Although there is a penalty in terms of the increased number of stages required to achieve this arrangement, there is a clear advantage in terms of PR, with a relatively small compromise in sA.

Keywords: Once-through Multi-stage-flash, Top brine temperature, Nanofiltration, Sirte

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Nomenclature

A	area	m^2
C_p	heat capacity at constant pressure	kJ kg^{-1} K^{-1}
d	diameter of pipe carrying seawater through feed-heaters	m
f	flash flow rate	kg s^{-1}
h	enthalpy	kJ kg^{-1}
$h^{\bullet}$	convective heat transfer coefficient	W m^{-2} K^{-1}
L	latent heat	kJ kg^{-1}
$LMTD$	Logarithmic Mean Temperature Difference	$^{\circ}$C
m	mass flow rate	kg s^{-1}
N	number of stages in MSF	
P	pressure	bar
PR	performance ratio	
sA	specific area requirement	m^2 s kg^{-1}
T	temperature	$^{\circ}$C
TBT	top brine temperature	$^{\circ}$C
ΔT	inter-stage temperature drop	$^{\circ}$C
u	flow velocity in feed heater pipes	m s^{-1}
U	overall convective heat transfer coefficient	W m^{-2} K^{-1}
x	quality factor	
y	salinity	mg kg^{-1}

Greek Symbols

δ	boiling point elevation	$^{\circ}$C

Subscripts

b	brine
bh	brine heater
d	distillate

end	brine exiting MSF
feed	feed
i	stage number in MSF
in	inside of pipe carrying seawater in feed heater
out	outside of pipe carrying seawater in feed heater
s	steam
sat	corresponding to saturation state
v	vapor
water – side	water side (inside) of pipe carrying the incoming seawater through feed heater

1. Introduction

Multi-Stage-Flash (MSF) desalination was the dominant method of large-scale desalination at the advent of desalination technology in the 1960s [1], [2]. Since that time, it has given way to reverse osmosis (RO) and Multi-Effect-Distillation (MED), which emerged as the two other major large-scale desalination technologies. However, MSF has retained an important status especially in the Middle East and North Africa (MENA), where it occupies 86.7% of the desalination capacity as of 2005 [2]. There are clear reasons for it to remain in this position: MSF plants are integrated with power plants to produce both water and electricity; plant operation is unaffected by high feed temperature, salinity, and turbidity and requires minimal manual intervention; and they have long life-times up to 30 years [1]. Optimization of MSF performance and identification of design and operational strategies to reduce capital and operational costs thus remain quite important.

Although Brine-Recirculation MSF (BR-MSF) plants are the state of the art MSF technology, Once-Through MSF (OT-MSF) systems serve as a good starting point for analysis of the effect of top brine temperature (TBT) on MSF performance due to their relative simplicity. Furthermore, although OT-MSF plants have been studied widely [3][4][5][6], the effect of increased TBT on required specific heat transfer area (sA) has not been investigated in detail. Although authors have studied the effect of TBT on OT-MSF performance ratio (PR) and sA, they have not considered important aspects that are covered in the current work. For example, in the work by El-Dessouky and Ettouney [6], the authors investigate the effect of TBT on performance ratio (PR) up to 110°C. The main development of the current work over that of El-Dessouky and Ettouney is in the significantly increased range of TBT studied which is important, given that NF and other pretreatment for MSF have shown potential to increase TBT

up to 160°C [7]or even 175°C [8]. Studies as recent as 2016 have also discussed design and performance of OT-MSF, indicating the ongoing interest in this field. For example, the work of Hanshik et al. [9] looks into the effect of higher TBT on other aspects of MSF design such as distillate production rate, cooling seawater outlet temperature, electrical power needed for pumps and heating energy required in the brine heater. They do not, however, look into the specific area requirements. Furthermore, they consider a fixed number of stages, and hence higher TBT is attained by changing ΔT at a fixed number of stages. As shown later in the current work, the effect of changing ΔT for a fixed number of stages on PR is much smaller than keeping a fixed ΔT and varying the number of stages. The work of Bandi et al. [10] is a complex cost optimization study on three configurations of MSF, including OT-MSF however it does not look explicitly at the effect of TBT on sA.

The TBT in an MSF plant is restricted by scale formation in the brine heater, especially since scalants such as calcium-sulfate ($CaSO_4$) and calcium-carbonate ($CaCO_3$) exhibit reduced solubility with increase in temperature[11]. MSF plants in the Kingdom of Saudi Arabia typically have TBT between 90°C and 115°C and performance ratio (PR) between 6.5 and 9.5 [12], [13]. The reduction of scaling ions would allow a higher TBT and hence an increase of the flashing range and PR in MSF.

Researchers have identified TBT as one of the most dominant parameters determining the performance of MSF [4][14]. Fiorini and Sciubba [14] noticed from a thermo-economic analysis of an MSF plant that the TBT is the most important parameter governing the plant operation, since it affects both plant performance and cost of steam. They recommended operation at the highest possible TBT. In the work of Tanvir and Mujtaba [15] the authors assume a fixed TBT of 90°C and observe that since seawater temperature inevitably increases during the summer, the

temperature driving force and recovery ratio of MSF unavoidably declines in this season. If the plant is instead operated at higher TBT in all seasons, the fluctuation of plant-performance with temperature can be mitigated.

Pretreatment of the incoming feed seawater by nanofiltration (NF) is a well-established means to attain high TBT in MSF. A series of studies performed by the SWCC (Saline Water Conversion Corporation) [13][7][16][17][18][19][20][21] since the late 1990s describe the two hybrid NF-MSF schemes: one where NF product is the MSF feed, and one where the MSF feed is SWRO (seawater reverse osmosis) reject, which in turn was pretreated with NF. In pilots of both configurations, the MSF TBT reached 130°C, the system design limit, without scale formation in the brine heater; theoretical studies show the potential for a TBT up to 160°C. Al-Rawajfeh [8] theoretically investigated pretreatment with NF, and estimated that a TBT up to 175°C could be reached with a TDS reduction of 37-38%. Mabrouk [22] piloted a CSP (Concentrated Solar Power)-powered NF-MSF system with a TBT of 100°C, reaching a GOR of 15. This work on NF-MSF also showed that the reduction in MSF energy consumption at higher TBT (130°C) outweighs the additional capital cost of the NF pretreatment.

To date, the literature has focused on the hybridization of NF with BR-MSF [7][16], which dominates installed capacity. The primary advantage of BR-MSF over OT-MSF is its lower consumption of chemical additives to prevent scaling per unit distillate, while its primary setback is the large specific pumping power required to recirculate the brine. If NF can truly replace chemical pretreatment, the advantages of the OT variant – its lower specific pumping power requirements in particular – become more attractive. This is supported by the study by Tusel et al. [23] on an OT-MSF plant in Sirte, in which the authors mention that although OT-MSF plants were almost entirely switched to BR-MSF plants by the 1970s, the reasons for the switch were

reversed by the 1990s due to the emergence of reasonably priced corrosion-resistant materials and cost-effective antiscalants that can withstand high temperature. Thus the costs relating to additional parts such as major pumps and valves in BR-MSF currently outweigh its advantages, especially in the Arabian peninsula where the high salinity of incoming seawater leads to a small difference in recovery ratio between the two configurations and thus the lower specific-pumping power of the OT-MSF arrangement is reason to prefer this system.

Several researchers are studying novel nanofiltration membranes, such as the composite nanofiltration membrane with a chemically crosslinked rGO laminate film acting as an ion-selective barrier created by Zhang et al. [24] and the low pressure nanofiltration membranes created by researchers in Singapore [25]. The work by Roy et al. [26] introduced comprehensive modeling of large-scale NF modules and included an analysis of flat-sheet and spiral-wound modules. Their model allows the user to vary membrane parameters and thus model various kinds of NF membranes under various operating conditions. These developments indicate that as nanofiltration membranes continue to improve, there is impetus for improvement in NF-thermal desalination hybrids.

In this work, the effect of increasing the TBT of once-through MSF on performance ratio (PR) and required specific area (sA) is investigated. The study first considers the effect of increasing the TBT for a plant with a fixed brine exit temperature (T_{end}) and inter-stage temperature (ΔT) drop by successively adding more stages. Subsequently, the effect of varying the brine exit temperature for a fixed TBT and inter-stage temperature drop is considered, thereby capturing the effect of seasonal and diurnal variations in incoming feed water temperature at different TBT values. These two modes of analysis are then applied to a case study of the OT-MSF plant in Sirte [23] to investigate the effect of increasing its TBT up to 182°C, in order to determine if plant

performance can be improved beyond that of the current operation. To the best of the authors'
knowledge, investigating the effect of increased TBT on the specific surface area requirement
has received little attention for OT-MSF systems.

2. Mathematical Model

Figure 1 shows a schematic diagram of the Once-Through Multi-Stage Flash system (OT-MSF)
investigated. The system contains a brine heater and several stages, each consisting of a feed
heater and flashing chamber. The governing equations for this system are given in this section.
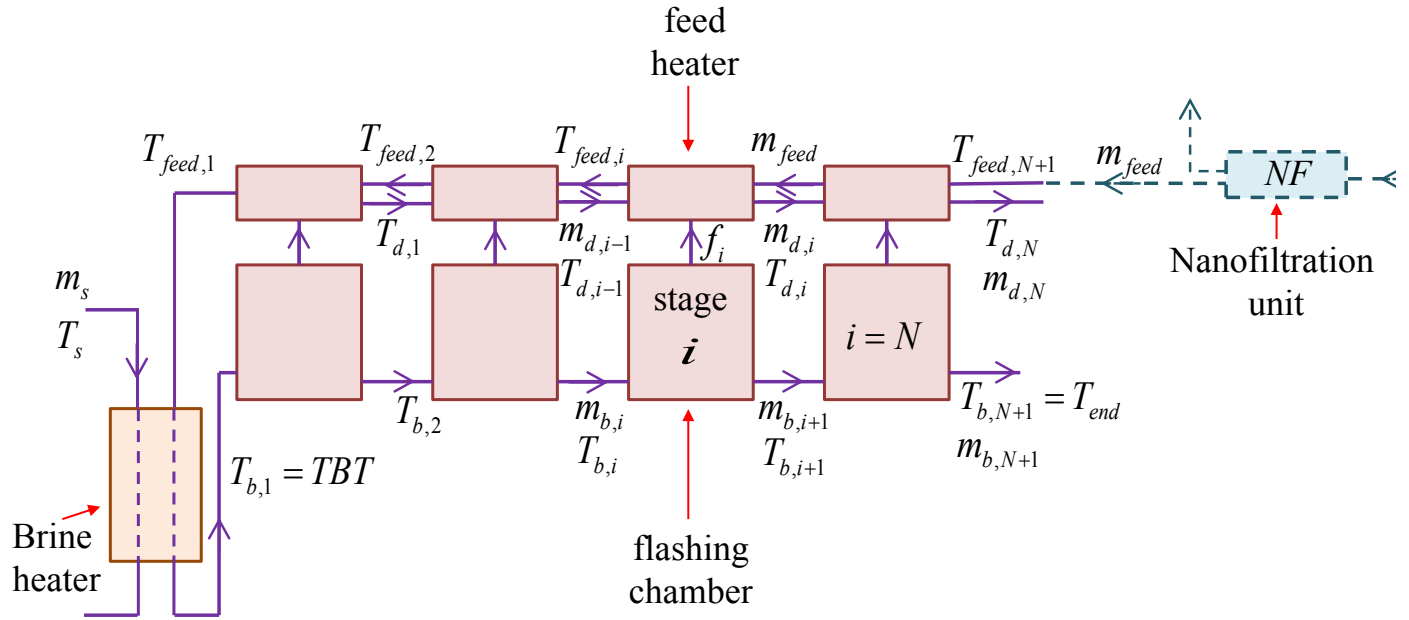

Figure 1: Schematic diagram of OT-MSF system

2.1 Brine heater energy balance:

$$m_{feed}(h_{b,1} - h_{feed,1}) - m_s L_s = 0 \tag{1}$$

where m_{feed} is the feed mass flow rate entering the MSF system (the permeate flow rate exiting from the NF unit), m_s is the mass flow rate of steam, L_s is the latent heat of vaporization of the steam, and $h_{feed,1}$ and $h_{b,1}$ are the enthalpies for saturated liquid corresponding to the temperatures $T_{feed,1}$ and $T_{b,1}$ as shown in Fig. 1. In this work, $h_{feed,i}$ is calculated by $h_{feed,i} = C_p T_{feed,i}$ where C_p is 4.18kJ/kg-K. For calculation of enthalpies, the reference state is taken at $T_{ref} = 273.15K = 0\,^{\circ}C$ so that $h_{ref} = 0$kJ/kg. The variation of C_p with feed temperature is neglected, since going from $25^{\circ}C$ to $160^{\circ}C$, more than $100^{\circ}C$ increase in temperature, the heat capacity of water changes by only 4%. While attaining high top brine temperature (TBT), it is necessary to pressurize the feed to a pressure slightly above the corresponding saturation pressure in order for flashing to occur upon entering the first evaporator. Thus, although the enthalpy of the heated feed exiting the brine heater is $h(T_{b,1}, P = P_{sat} + \Delta P)$, there is negligible difference of this value with $h(T_{b,1}, P = P_{sat})$. In the current model, the enthalpy of the feed exiting the brine heater is considered to be $h(T_{b,1}, x = 0)$.

2.2 Evaporator energy balance:

For stages 1 to N

$$m_{b,i+1}h_{b,i+1,x=0} - m_{b,i}h_{b,i,x=0} + f_i h_{v,i} = 0 \tag{2}$$

where f_i is the mass flow rate of flashed vapor in stage i, $m_{b,i} = m_{feed} - \sum_{j=1}^{i-1} f_j$ is the brine mass flow rate entering stage i, and $h_{v,i}$ is enthalpy of the flashed vapor in stage i ($h_{v,i} = h(T_{b,i+1}, x = 1)$, is the enthalpy at temperature $T_{b,i+1}$, with quality $x=1$).

2.3 Evaporator salt balance:

For stages 1 to N

$$m_{b,i+1} y_{b,i+1} - m_{b,i} y_{b,i} = 0 \tag{3}$$

where $y_{b,i}$ is salinity of brine entering stage i and $m_{b,i} = m_{feed} - \sum_{j=1}^{i-1} f_j$ is the brine mass flow rate

entering stage i.

2.4 Feed heater energy balance:

$$m_{feed}\left(h_{feed,i} - h_{feed,i+1}\right) + m_{d,i} h_{d,i,x=0} - m_{d,i-1} h_{d,i-1,x=0} - f_i h_{v,i} = 0 \tag{4}$$

where $m_{d,i} = \sum_{j=1}^{i} f_j$ is the mass flow rate of distillate exiting stage i and $h_{d,i}$ is the corresponding

distillate enthalpy. The (pure) distillate temperature is given by

$$T_{d,i} = T_{b,i+1} - \delta \tag{5}$$

where δ is the boiling point elevation.

The interstage temperature drop is assumed to be constant and is given by

$$\Delta T = \left(\frac{T_{b,1} - T_{b,N+1}}{N}\right) \tag{6}$$

The surface area required for heat exchange in each feed heater is calculated using an overall heat transfer coefficient obtained by considering the water-side and steam-side heat transfer coefficients in series. The water-side heat transfer coefficient is given by Eqn. 7 [27], while the steam-side heat transfer coefficient is considered to be 7000 W/m^2-K throughout the range of

temperature considered. This is justified by the fact that, as per Fig. 3 in the work by Baig et al. [27], the heat transfer coefficient on the steam-side varies by only ~8% from 100°C to 150°C and can be considered almost constant with increase in temperature:

$$
h_{water-side}^{\bullet} = (0.656u)^{0.8} \left(\frac{d_{in}}{d_{out}}\right) \left(\frac{3293.5 + T_{feed}(84.24 - 0.1714T_{feed}) - y_{feed}(8.471 + 0.1161y_{feed} + 0.2716T_{feed})}{\left(d_{in}\left(\frac{100}{1.7272}\right)\right)^{0.2}}\right) \quad (7)
$$

In Eqn. 7, T_{feed} is the feed temperature in the stage under consideration. Further, d_{in} and d_{out} are the internal and external diameters of the tubes carrying the feed water during preheating and are taken as 16 mm and 16.5 mm respectively [23].

The required heat exchange area of the feed heater in the given stage is now calculated using the LMTD as follows:

$$
A_i = \frac{m_{feed}C_p(T_{feed,i} - T_{feed,i+1})}{U_i LMTD_i} \quad (8)
$$

where

$$
LMTD_i = \frac{(\Delta T_{1,LMTD} - \Delta T_{2,LMTD})}{\ln\left(\frac{\Delta T_{1,LMTD}}{\Delta T_{2,LMTD}}\right)} \quad (9)
$$

and

$$
\Delta T_{1,LMTD} = (T_{d,i} - T_{feed,i+1}) \quad (10a)
$$

$$\Delta T_{2,LMTD} = (T_{d,i-1} - T_{feed,i})$$ (10b)

Using a similar procedure, the heat transfer surface area requirement in the brine heater is given by:

$$A_{bh} = \frac{m_{feed} C_p (T_{b,1} - T_{feed,1})}{U_{bh} LMTD_{bh}}$$ (11)

in which the overall heat transfer coefficient in the brine heater U_{bh} is considered to be constant at 3000 W/m²-K, as per Fig. 4 in the work of Baig et al. [27], where the overall heat transfer coefficient in the brine heater is approximately 3000W/m²-K from 80°C to 140°C (varying by 8.4% over this range of temperature).

Finally, the required specific area (sA) and performance ratio (PR) are given by:

$$sA = \left(\frac{\sum_{i=1}^{N} A_i + A_{bh}}{m_{d,N}} \right)$$ (12)

$$PR = \frac{m_{d,N}}{m_s}$$ (13)

3. Validation

The model is validated against an analytical model by El-Dessouky and Ettouney [6]. For a 24 stage OT-MSF plant with top brine temperature TBT = 106°C, incoming seawater temperature of 25°C, brine reject temperature T_{end} of 40°C, and seawater salinity 42000 mg/kg, El-Dessouky and Ettouney [6] (case study 6.4.3) report a performance ratio (PR) of 3.96 whereas the current

model predicts a PR of 3.97, a deviation of 0.25% from the reference. Figure 2a shows the brine salinity and feed temperature across all the stages in the reference and in the present model. The figure indicates a very good agreement between the current model and the reference with a maximum deviation of 0.49% and 0.39% for the brine salinity and feed temperature, respectively. Validation is also done in reference to Fig. 4a in Baig et al. [4] (cf. Fig. 2b in the current work), observing the effect of inter-stage temperature drop ΔT on the PR for a fixed number of stages (N=24 and N=32). The maximum deviation between the reference and current work was found to be 2.4% and 1.7% for N=24 and N=32, respectively.
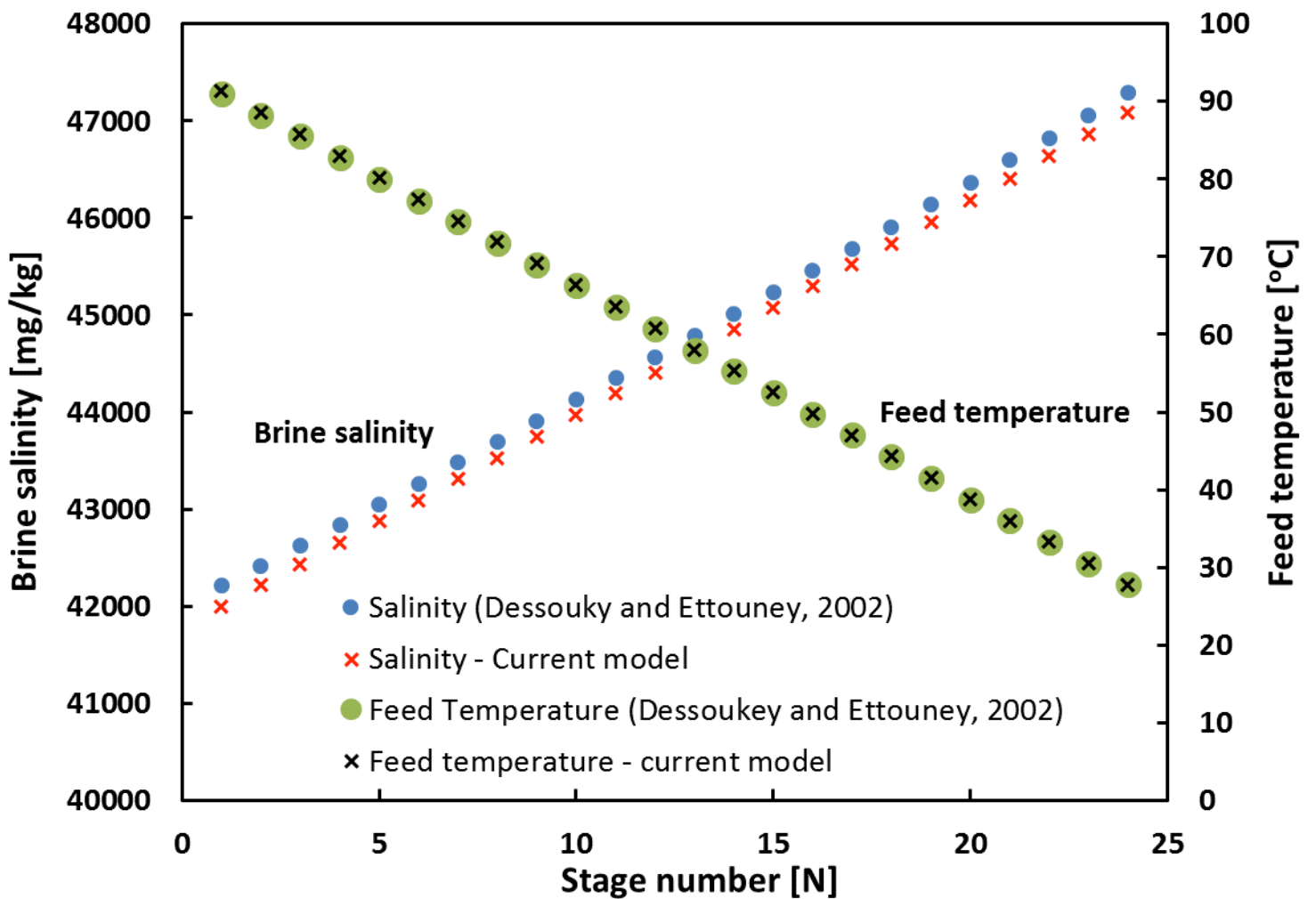
Figure 2a. A stage-wise comparison of brine salinities and feed temperatures between El-Dessouky and Ettouney [6] and the present work shows good agreement, with maximum deviations of 0.49% and 0.39%, respectively.
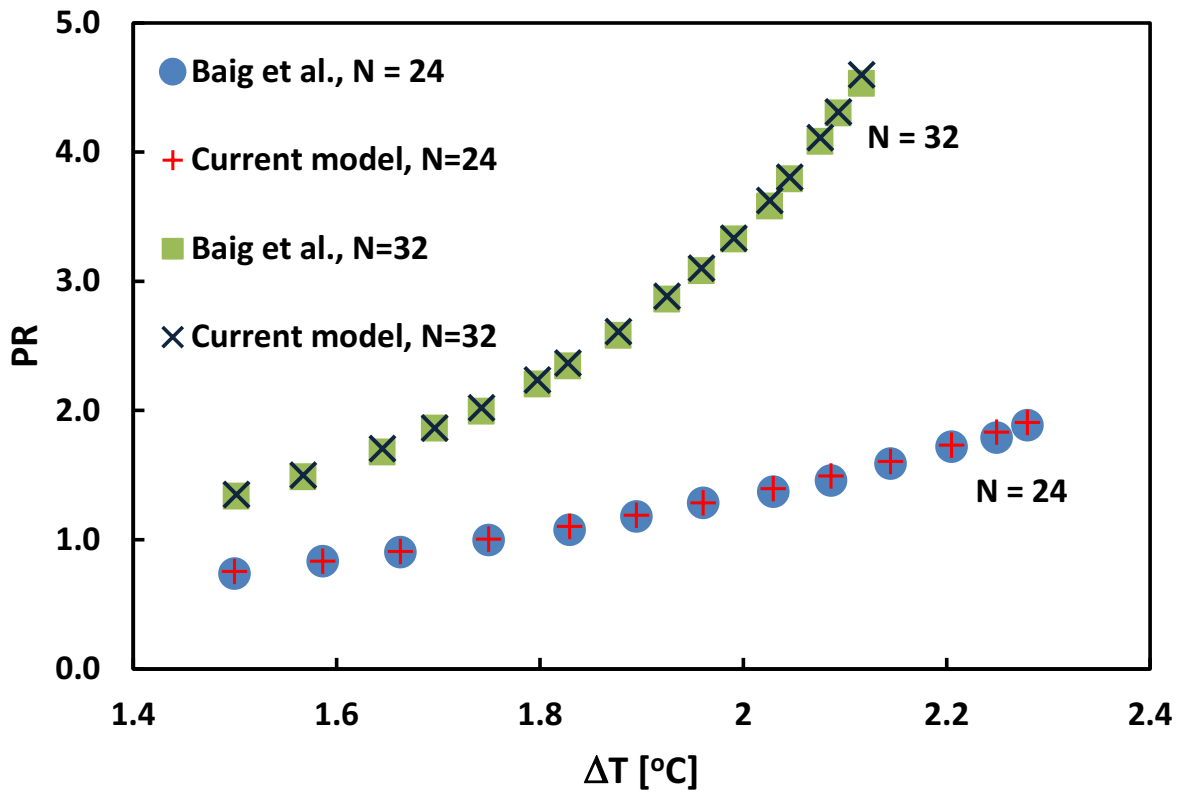
Figure 2b. Validation with Baig et al. [4] for the effect of inter-stage temperature drop ΔT on the PR for a fixed number of stages (N=24 and N=32) shows a maximum deviation between the reference and current work to be 2.4% and 1.7% for N=24 and N=32, respectively.

4. Results and Discussion

4.1 Effect of increased TBT on OT-MSF performance.

Figure 3 shows the variation of the performance ratio (PR) and the specific heat transfer area required (sA) when the TBT is increased by increasing the number of stages and keeping ΔT and T_{end} fixed. Similar to the case study by El-Dessouky and Ettouney[6] considered in the validation section, the brine reject temperature is fixed at 40°C, seawater inlet temperature and mass flow rate are taken as 25°C and 3384 kg/s respectively, the steam temperature is kept 10°C above the TBT and a boiling point elevation of ~1°C is considered in the evaporators. Three values of inter-stage temperature drop 2°C, 2.4^{o}C and 3°C are considered for the parametric study. The figure shows that increasing the TBT has the effect of monotonically increasing the PR for all values of ΔT used, over the given range of TBT considered. The trend of variation of PR with TBT appears linear but is in fact non-linear, which becomes clear especially at temperatures beyond 150°C. Referring to Eqn. 13, the reason is that, although the variation of $m_{d,N}$ with TBT is linear, the variation of m_s is non-linear, such that the slope increases with TBT (concave upward). The reason for such variation of m_s is further explained from Eqn. 1: the term $m_{feed}(h_{b,1} - h_{feed,1})$ is almost constant with increase in TBT while L_s varies non-linearly such that the slope decreases with increasing TBT (concave downward). Thus, since $m_s \propto \dfrac{1}{L_s}$, its variation with TBT is also non-linear, but with slope increasing with TBT (opposite curvature to variation of L_s).
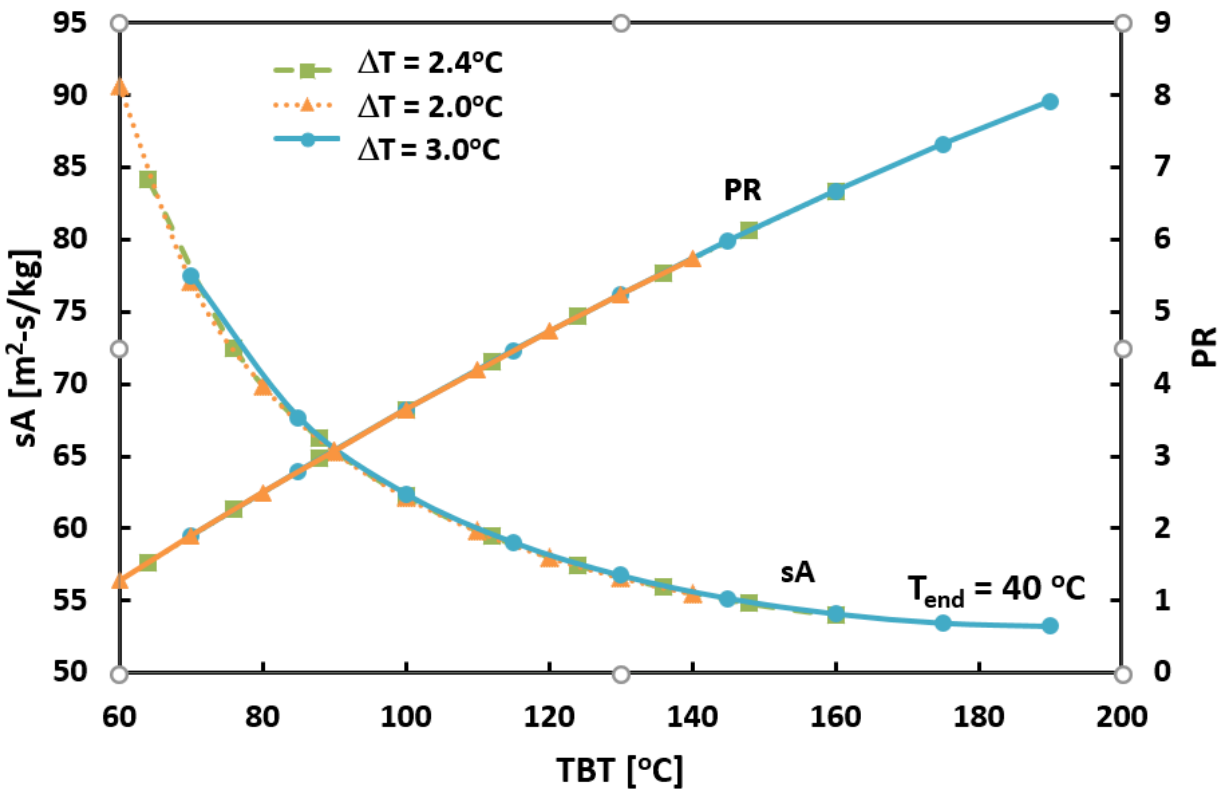
Figure 3: Effect of increasing TBT on the PR and sA by adjusting the number of stages when the brine reject temperature and ΔT are fixed. It is seen that the PR increases almost linearly with increase in TBT while the sA decreases and its rate of decrease becomes smaller with increase in TBT.

On the other hand, the sA monotonically decreases over the given range of TBT, but its rate of decrease is less as a higher TBT is approached. This trend in the sA is explained by the nature of variation of total area with increase in TBT. Although the distillate production increases linearly with TBT, the variation of total area with increase in TBT is not linear and there is a small increase in the slope of increase of the total area with TBT. This feature is attributed to the variation of LMTD with increase in TBT.

At all values of ΔT considered, the PR at a TBT of 160°C is ~6.67 (68% higher than that in the case study by El-Dessouky and Ettouney[6], which considered TBT = 106°C and N = 24) and the number of stages required is 60 and 50 for the lowest and highest ΔT considered. Since a different correlation for heat transfer coefficient (which can be extended to higher TBT) was used for the present work rather than that used in the work of El-Dessouky and Ettouney[6], the value of sA is significantly different from that reported in reference [6]. The correlation used by El-Dessouky and Ettouney gives a value of overall heat transfer coefficient ~2000 W/m^2-K over the range of temperature studied while the current correlations give a value of 3000-4500 W/m^2-K depending on the stage of MSF considered. Furthermore, the upper limit of temperature for the heat transfer coefficient used by El-Dessouky and Ettouney is 110°C as per Appendix C in the reference [6].

From an analysis of PR and sA, the overall recommendation referring to Fig. 3 is to operate the OT-MSF at an intermediate value of TBT so as to maximize PR such that increasing the TBT any further provides diminishing returns. Further, it is recommended to use the lowest value of ΔT that will balance the trade-off between the negative aspects i.e. increased number of stages and lowered PR, with the beneficial aspect of the decreased sA requirement at lower ΔT.

4.2 Effect of reduced brine reject temperature on OT-MSF performance

Figure 4 shows the effect of increasing the number of stages (N) at constant TBT and ΔT on the PR and sA by adjusting the brine reject temperature T_{end}. TBT values of 120°C, 140°C and 160°C are considered and ΔT is fixed at 2°C. At lower values of N the values of T_{end} are higher, which implies that a corresponding amount of thermal energy is rejected to the environment during brine rejection. If the number of stages is increased, this energy could be harnessed to increase

distillate production and the brine would be rejected at a lower temperature. Such an increase in the number of stages provides the advantage of an increased performance ratio but requires increased specific heat transfer area. It is seen from Fig. 4 that at the lowest TBT of 120$^{\text{o}}$C, decreasing the brine reject temperature from 38$^{\text{o}}$C to 30$^{\text{o}}$C increases the PR by almost threefold from 5.57 to 15.9, the penalty being that the sA increases almost three times from 65.21 m^2-s/kg to 181.17 m^2-s/kg. The corresponding increase in number of stages is from 41 to 45. At the highest TBT of 160$^{\text{o}}$C, the same drop in brine reject temperature causes, again, a threefold increase in PR from 7.8 to 21.8 while the sA increases by a factor of three, from 61.66 m^2-s/kg to 191.09 m^2-s/kg. The number of stages increases from 61 to 65. As seen from Fig. 4, at a higher TBT, for a given value of T_{end}, PR is higher. Furthermore, while at lower T_{end}, sA is highest for the highest TBT, the trend is inverted for higher T_{end} values.
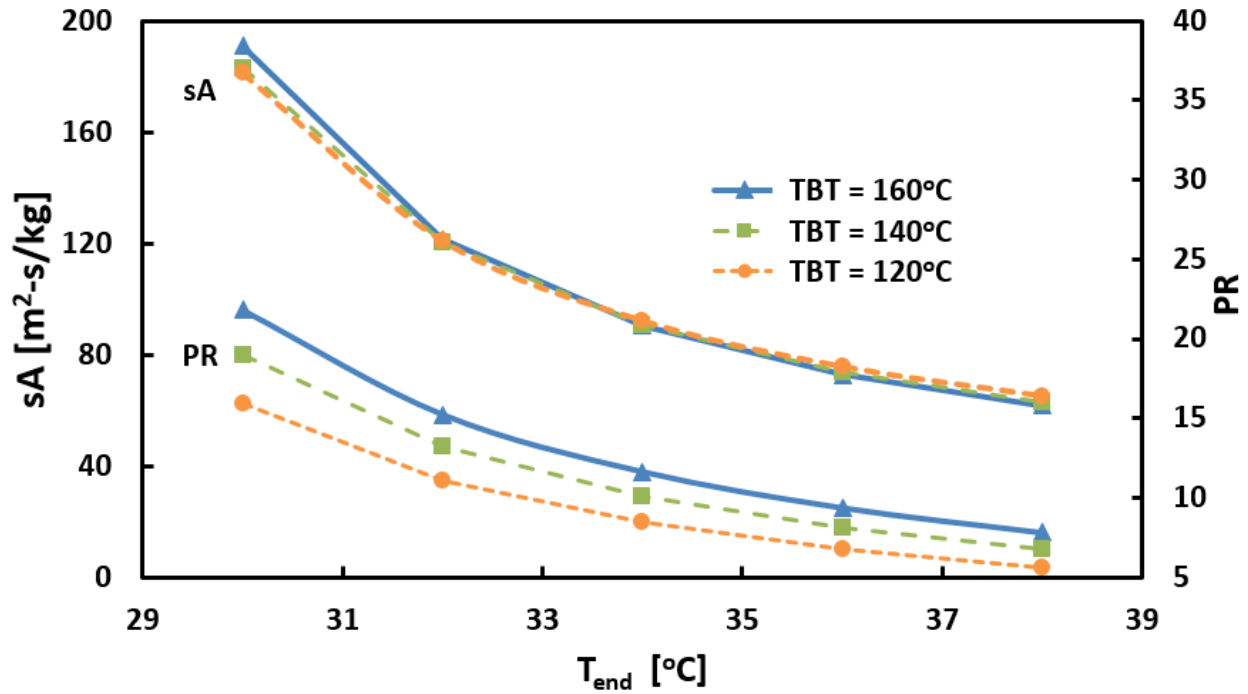
Figure 4: Variation of PR when brine reject temperature T_{end} is varied by adjusting the number of stages, keeping TBT and ΔT fixed. It is seen that at a higher TBT, for a given value of T_{end}, PR is higher. While at lower T_{end}, sA is highest for the highest TBT, the trend is inverted for higher T_{end} values.

Practically, T_{end} varies when seawater inlet temperature varies due to factors such as weather change. In areas of cooler weather, it would be beneficial to operate a larger number of stages and select an optimal value of TBT such that the sA requirement and increase in PR are balanced. A larger number of stages for a given TBT will also allow the brine reject temperature to be as close to the environmental temperature as possible, while keeping ΔT small. As mentioned in case 4.1, the ΔT should be kept at an optimal value so that it is not too large to cause larger sA requirement but also large enough to not require too large a number of stages. In all cases, however, a significant improvement in PR is observed with increasing TBT while

incurring a relatively small penalty in sA. This suggests that operation at higher TBT irrespective of environmental temperature is energetically favorable.

4.3 Case Study: Effect of increased TBT on Sirte OT-MSF plant.

In light of the preceding discussions, the effect of increased TBT by adding stages is studied on an existing OT-MSF plant operating in Sirte. The OT-MSF system described by Tusel et al. [23], 1994 has a TBT of 118°C with 39 stages, $\Delta T = 2.07^o$C and operates at a PR of 10. As a starting point, the current operating condition of the Sirte plant is used to validate our model. Figure 5 shows the anticipated change in its PR and required sA if the TBT is increased by increasing the number of stages, keeping the ΔT and brine reject temperature fixed at the original values. As mentioned in section 4.1, although the PR increases monotonically with number of stages and hence TBT, the sA poses a restriction by showing a minimum at an intermediate value of TBT. The cause for this trend in the sA can be described similarly to that described in section 4.1 and is due to the non-linear variation of total area with TBT such that its slope increases with increase in TBT, hence forming an arc. Thus, the sA, defined as the ratio between total area and distillate production (which varies linearly with TBT) is non-linear and shows a minimum with TBT. As shown in Fig. 5, the red dotted line shows the current performance of the Sirte plant whereas the blue dotted line shows the predicted performance at a TBT of 161.6^{o}C, when 60 stages are employed. At this TBT, the sA curve begins to rise and hence is a good choice of the optimal operating point. Compared to the original operating conditions, the PR increased by 41.5% to 14.64, while the sA requirement and steam mass flow rate increased by 0.9% and ~5% respectively. These numbers indicate that the penalties of the increased TBT are relatively low and if the shift in the steam extraction point in the power plant is not problematic, operation at elevated TBT is shown to be advantageous. At 70 stages, where a TBT of 182.3^{o}C is attained,

although the PR has further increased to 16.52, the sA has increased by 5.7% compared to the current operating conditions. It is, however, worth keeping in mind that the heat exchanger tubes contribute to about 18% of plant capital cost [1], which would help in estimating the additional cost associated with increased number of stages.
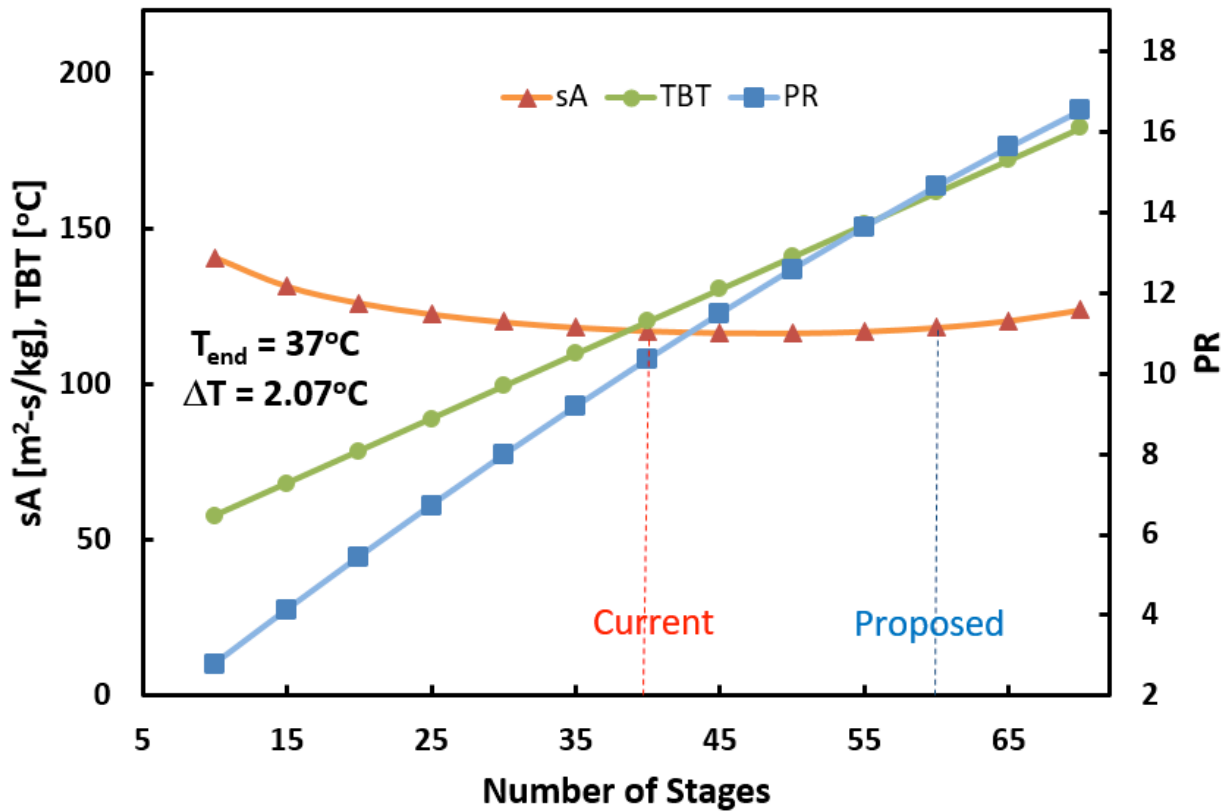

Figure 5. Variation of PR and required sA if the TBT of the Sirte plant is increased by increasing the number of stages, keeping the ΔT and brine reject temperature fixed. The red dotted line represents the current performance of the plant, with a TBT of 118°C and 39 stages. The blue dotted line shows the predicted performance at a TBT of 161.6°C and 60 stages, at which point the PR is increased by 41.5% compared to the current operation while the sA requirement increased by 0.9%, thereby showing that there is a possibility of increasing plant PR with a relatively small compromise in sA requirement.

Figure 6 shows the effect of varying the brine reject temperature T_{end} on PR at fixed TBT and ΔT, by adjusting the number of stages. At TBT=118°C i.e. the usual operating temperature of Sirte, decreasing T_{end} from 40°C to 32°C increased the PR almost 6 times while the required number of stages increased from 39 to 43. At a TBT of 160°C the increase in PR due to the same change in T_{end} was similar as that seen for TBT=118°C and the required number of stages increased from 60 to 64. As mentioned previously, T_{end} is a function of inlet feed temperature, which depends on environmental temperature. Thus the study of the variation in T_{end} reflects the plant performance in different seasons or over the span of a day. The relatively small change in the required number of stages with change in T_{end} indicates that the number of operational effects does not need to be changed with seasonal or diurnal temperature variation for optimal plant performance at a given TBT. However, at par with the discussion in section 4.2, it is also seen that when T_{end} is lower, the sA is higher and increases rapidly with decreasing T_{end}, thereby indicating that at cooler weather conditions, the plant may not be able to operate optimally due to the increased heat exchange area requirement.
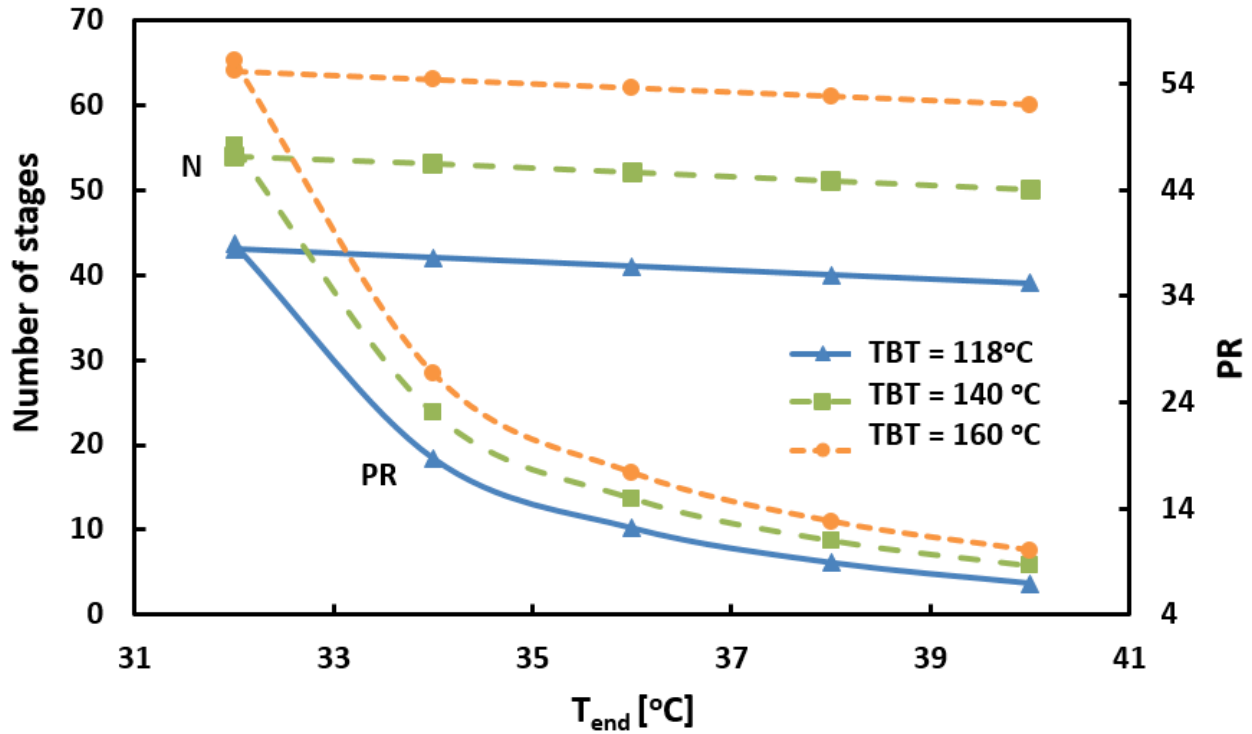
Figure 6: The effect of varying the brine reject temperature T_{end} on PR at fixed TBT and ΔT, by adjusting the number of stages.

Conclusions

The effect of increasing the top brine temperature (TBT) on the performance and design characteristics of an OT-MSF plant has been investigated by observing the performance ratio (PR) and the specific area requirement (sA) at higher TBT and also how these values change due to seasonal variation. The end goal is to determine whether an existing OT-MSF plant would perform better at higher TBT and to suggest changes in its design and operation by suggesting an optimal value of TBT and ΔT within the constraints of environmental conditions.

The conclusions of the study are as follows:

1. For a fixed inter-stage temperature drop ΔT and brine reject temperature T_{end}, if number of stages N is increased, thereby increasing TBT, the performance ratio PR increases monotonically with N (and hence TBT) whereas sA decreases such that beyond a certain value of TBT, the change in sA with TBT is negligibly small. As seen in Fig. 5, if the TBT is allowed to increase even further, the sA will begin to increase again. Thus, an OT-MSF plant should be operated at the optimal TBT where PR is high and sA is minimum. The inter-stage temperature drop must also be kept at an intermediate value, since at higher ΔT, there is the penalty of higher sA, although it should not be too small in order to avoid a large number of stages required to attain the required TBT.

2. When the TBT and ΔT are fixed and the number of stages is increased to reduce T_{end}, the PR and sA are both found to increase sharply. It is seen that at a higher TBT, for a given value of T_{end}, N and PR are each higher. While at lower T_{end}, sA is highest for the highest TBT, the trend is inverted for higher T_{end} values. Thus, for practical purposes, an intermediate value of TBT should be chosen so that the maximum advantage of increased PR can be taken without suffering a high penalty of increased specific area. Furthermore, for cooler regions, an OT-MSF plant should be designed consisting of a larger number of stages than usually used in hotter regions so that the ΔT can be minimized and the brine reject temperature can be kept as close to the environmental temperature as possible.

3. There is potential to improve the PR of the existing Sirte plant in Libya by increasing the TBT to 160°C, keeping all other operational conditions unchanged. At this TBT, PR is expected to increase by 41.5% from the existing value to 14.64, while the sA requirement increases by 0.9%, which is a relatively small penalty.

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