



Design of a Multi Stage Flashing (MSF) Desalination Plant in Surman – Libya

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تصميم محطة تحلية بالوميض متعدد المراحل في مدينة صرمان - ليبيا

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Abstract

Thermal water desalination is one of the most important techniques to solve the water scarcity problem in many regions of the world. Out of around 7.8 billion people in the world, only about 6 billion of them have access to clean water: Notably, climate change plays a major role in accelerating the evaporation rate of water from water bodies, which in turn increases the scarcity. Multi-stage flash, recognized to have a high rate of water production in comparison with other available technologies, accounts for 35% of water desalination facilities worldwide.

In this work, three designs with different number of Stages 22, 26, 29 respectively are presented for the one-off type and another three more with recirculating brine are presented as well. The temperature drop of the brine stream was 2.72 °C/stage, 2.31 °C/stage, 2.07 °C/stage in for three designs respectively. The top brine temperature was 100°C. The results show that 59.5 kg/s for the three designs of the type one time, of superheated steam is required to desalinate 162 kg/s of 1587 kg/s, influent mass flow of brine.

In the three designs with recirculating brine the results show that 24.35 kg/sec, 20.62 kg/sec, and 18.47 kg/sec respectively of superheated steam it is required to desalinate 162 kg/s of 354.375 kg/s of the seawater flowing and 1586 of the flow of recycle brine. The PR ratios were as follows 2.72 for the first three designs and 6.65, 7.85, 8.77 respectively to the recycled brine designs, PR was achieved using the third design, which features a 29-stage brine recycling configuration.

Keywords: Desalination, MSF, Desalination Plant Design, PR ratio, Libya

المخلص

تُعد تقنية التحلية الحرارية للمياه واحدة من أهم الوسائل لحل مشكلة شح المياه في العديد من مناطق العالم؛ فمن بين سكان العالم البالغ عددهم حوالي 7.8 مليار نسمة، يحصل نحو 6 مليارات فقط على مياه نظيفة. والجدير بالذكر أن التغير المناخي يلعب دوراً رئيسياً في تسريع معدل تبخر المياه من المسطحات المائية، مما يؤدي بدوره إلى تفاقم مشكلة الندرة. وتستحوذ تقنية "الوميض متعدد المراحل - (Multi-stage flash)" المعروفة بمعدلات إنتاج المياه العالية مقارنة بالتقنيات الأخرى المتاحة - على 35% من مرافق تحلية المياه حول العالم.

يستعرض هذا العمل ثلاثة تصاميم تختلف في عدد المراحل (22 و 26 و 29 مرحلة على التوالي) لنظام التمريرة الواحدة (one-off type)، بالإضافة إلى ثلاثة تصاميم أخرى تعتمد نظام إعادة تدوير المحلول الملحي (recirculating brine) وقد بلغ انخفاض درجة حرارة تيار المحلول الملحي 2.72 و 2.31 و 2.07 درجة مئوية لكل مرحلة في التصاميم الثلاثة على التوالي، مع تثبيت درجة الحرارة القصوى للمحلول الملحي عند 100 درجة مئوية. وأظهرت النتائج أن التصاميم الثلاثة من نوع "التمريرة الواحدة" تتطلب 59.5 كجم/ثانية من البخار المحمص (superheated steam) لتحلية 162 كجم/ثانية من إجمالي تدفق كتلة المحلول الملحي الداخل البالغ 1587 كجم/ثانية.

بالنسبة للتصاميم الثلاثة التي تعتمد إعادة تدوير المحلول الملحي، فقد أظهرت النتائج الحاجة إلى 24.35 و 20.62 و 18.47 كجم/ثانية من البخار المحمص (على التوالي) لتحلية 162 كجم/ثانية من تدفق مياه البحر البالغ 354.375 كجم/ثانية، مع تدفق إعادة تدوير للمحلول الملحي يبلغ 1586 كجم/ثانية. وقد بلغت نسب الأداء (PR) 2.72 للتصاميم الثلاثة الأولى، و 6.65 و 7.85 و 8.77 للتصاميم التي تعتمد إعادة التدوير على التوالي؛ حيث تم تحقيق أفضل نسبة أداء (PR) باستخدام التصميم الثالث الذي يتميز بتكوين إعادة تدوير المحلول الملحي عبر 29 مرحلة.

الكلمات المفتاحية: تحلية، وميض متعدد المراحل، تصميم محطة تحلية، نسبة الأداء، ليبيا

Introduction

Water is an indispensable compound for human survival and all other biological life forms, despite lacking caloric or organic nutritional value. While global access to potable water has seen progressive expansion over recent decades, approximately 780 million individuals remain deprived of safe drinking water. Furthermore, roughly 36% of the global population—amounting to 2.5 billion people—continues to lack access to improved sanitation facilities. Driven by rapid demographic growth and elevating living standards, analysts project that global water demand will surge to 6,900 billion by 2030, marking a substantial increase from the 4,500 billion required in 2009.

In response to this escalating demand, the desalination sector has experienced substantial expansion. At present, over 16,000 desalination facilities operate globally, yielding an estimated production capacity of 74.8 million cubic meters per day (m^3/day). Notably, the Gulf States account for a significant proportion of this output, generating between 40% and 50% of the world's total desalinated water. Technologically, reverse osmosis (RO) and multi-stage flash (MSF) distillation dominate the industry, collectively constituting more than 86% of the total installed desalination capacity.

Although water blankets 71% of the Earth's surface, the overwhelming majority is entirely unsuitable for human consumption due to high salinity. Specifically, roughly 97% of global water resources are salty or otherwise non-potable. Of the remaining 3% of freshwater, over 2.5% is sequestered in inaccessible frozen states, primarily located within the ice caps of Antarctica, the Arctic, and various glaciers. Consequently, a mere 0.5% of the planet's total water inventory—distributed across freshwater lakes, rivers, and subterranean aquifers—remains readily accessible for human utilization.

Surman, a coastal municipality situated 60 kilometers west of Tripoli in northwestern Libya, serves as a residential hub for an estimated population of 40,000. In recent years, adverse climate change impacts have significantly affected the region, manifesting as prolonged droughts and a marked decline in precipitation. These environmental stressors have severely depleted local groundwater reserves, precipitating a critical shortage of potable water. To mitigate this escalating water security crisis, the primary objective of this study is to design a multi-stage flash (MSF) distillation plant engineered to yield a continuous production capacity of 162 kilograms per second (kg/s) of desalinated water.

Literature reviews

Integrating renewable thermal technologies, such as solar thermal systems and Linear Fresnel Collectors, with desalination processes significantly improves energy efficiency and mitigates environmental impacts [1, 2]. Regardless of the heat source, precise mathematical modeling remains crucial for the simulation, design, and optimization of Multi-Stage Flash (MSF) desalination systems. Over the past decades, steady-state MSF models have been broadly classified into two categories. Simplified models rely on idealized assumptions—including linear temperature profiles and fixed brine properties—enabling preliminary performance estimation with minimal computational effort [3–6]. Conversely, rigorous models provide detailed, stage-by-stage thermodynamic and heat-transfer representations, though they demand substantially greater mathematical complexity [7–12]. Soliman [4] introduced an early simplified section-wise model for rapid evaluation; however, its reliance on constant thermo-physical properties limits accuracy, particularly in high-temperature regions where seawater properties fluctuate. In contrast, Helal et al. [7] developed a rigorous tridiagonal model (TDM) that systematically linearizes complex governing equations. While the TDM approach enhances predictive accuracy, it significantly increases computational load.

Both modeling paradigms remain integral to contemporary MSF analysis. Recent applications include simplified optimizations [13], linearized stage-wise models predicting plant productivity [14, 15], rigorous frameworks implemented in advanced simulation environments like gPROMS [16, 17], and dynamic models derived from Helal's methodology [18]. Despite these continuous advancements, a notable research gap persists: there is a distinct need for computationally efficient models that accurately capture variable thermo-physical properties without necessitating the extreme mathematical complexity of detailed stage-wise formulations. Solar-driven desalination presents a sustainable alternative to conventional fossil-fuel-dependent methods, effectively mitigating both economic and environmental burdens. Among current technologies, Multi-Stage Flash (MSF) distillation is particularly prominent due to its superior efficiency and high production capacities. Operational optimization is critical for maximizing performance; Darwish et al. [19] demonstrated that flashing efficiency significantly improves with higher brine inlet temperatures, broadened flashing ranges, and reduced brine levels and flow rates. Experimental studies further validate the efficacy of solar integration: Farwati [20] reported annual distillate yields of 8.2 m³ and 13.2 m³ using a 1 m² flat plate collector (80 °C) and a concentrated parabolic collector (122 °C), respectively. Additionally, Reddy et al. [21] utilized transient modeling for an evacuated solar MSF system to identify optimal design parameters, predicting daily yields between 13.33 and 28.04 kg/m². Substantial thermodynamic enhancements are also achievable through advanced heat recovery strategies; Al-Weshahi et al. [22] showed that recovering hot distillate in a BC-MSF unit increases exergy efficiency from 5.8% to 14%. Lastly, Liu, Hu et al. [23] designed an innovative, compact solar MSF system capable of producing 1.25 kg/h/m² of freshwater, achieving a total system efficiency approaching 0.9.

Description and classification of MSF plants.

The Multi-Stage Flash (MSF) process advances desalination by inducing bulk liquid vaporization, thereby mitigating the severe surface scaling and operational downtimes characteristic of legacy submerged-tube evaporators. The industry-standard brine recirculation (BR-MSF) configuration optimizes efficiency by integrating heat recovery and rejection sections. External steam elevates brine temperatures, driving successive flashing across multiple chambers. Concurrently, condenser tubes recover the vapor's latent heat to preheat recycled brine, while surplus thermal energy is environmentally dissipated, ensuring sustained thermal efficiency and continuous operation.

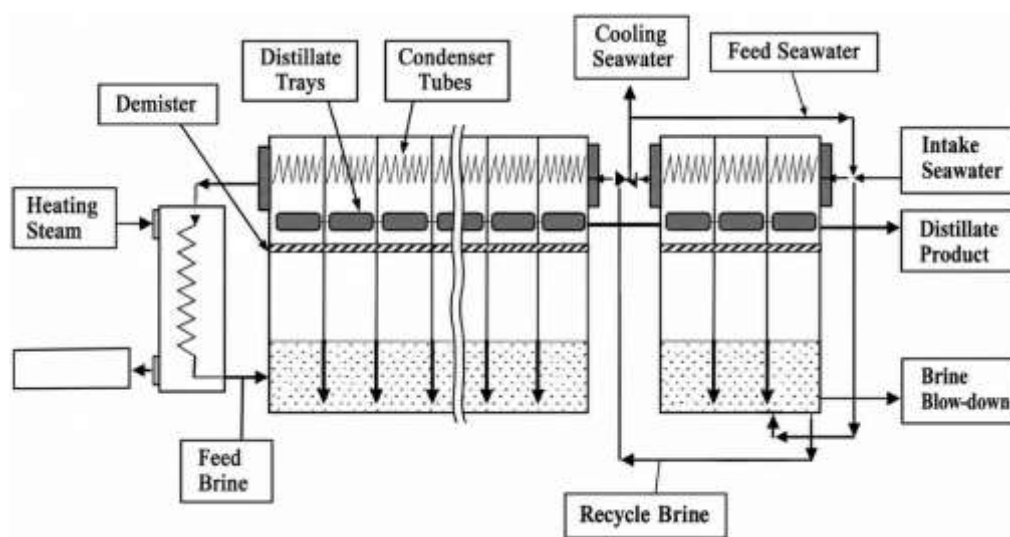


Figure 1. Brine circulation multi Stage flashing process

1. MSF Flashing Stage

As depicted in Figure 2, a conventional Multi-Stage Flash (MSF) stage integrates several critical components. The basal brine pool facilitates flashing, regulated by a submerged orifice that seals vapor spaces and optimizes turbulence.

A wire-mesh demister extracts entrained droplets to mitigate scaling and product contamination. Flashed vapor subsequently condenses on the preheater tube bundle, transferring latent heat to the internal brine stream, while the resulting freshwater cascades via a distillate tray. Concurrently, a venting system extracts non-condensable gases to preserve vacuum integrity and heat transfer efficiency. Finally, the primary brine heater utilizes motive steam to achieve the target Top Brine Temperature (TBT).

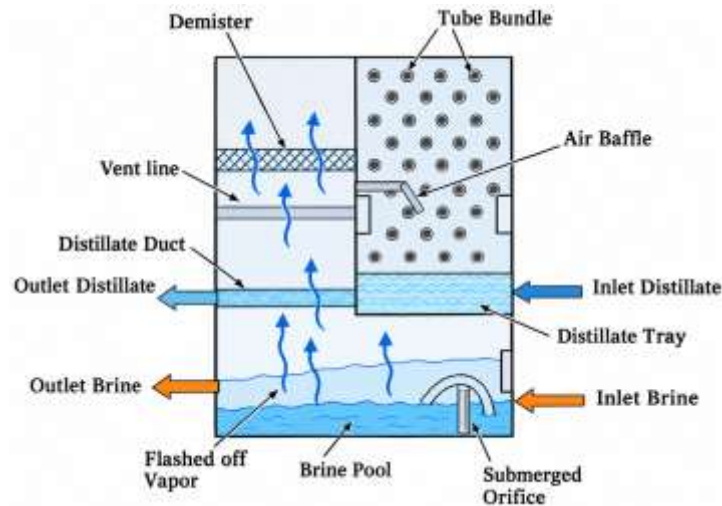


Figure 2: MSF flashing stage

2. Once through Multi Stage Flashing OT-MSF

The Once-Through Multi-Stage Flash (OT-MSF) system optimizes thermal efficiency by partitioning the flashing process across multiple stages, thereby minimizing per-stage temperature gradients. Intake seawater is progressively preheated within condenser tubes before reaching peak temperature in the brine heater. This heated brine sequentially flashes across successive chambers; the condensing vapor yields freshwater distillate while simultaneously preheating the incoming feed. Because all unevaporated brine is directly discharged without recirculation, the blowdown intrinsically dissipates excess thermal energy, eliminating the requirement for an independent cooling stream. Although OT-MSF configurations resolve the limited performance ratio characteristic of single-stage units, they still necessitate excessive seawater intake. This operational constraint is ultimately mitigated by recycling a fraction of the blowdown brine into the intake feedwater.

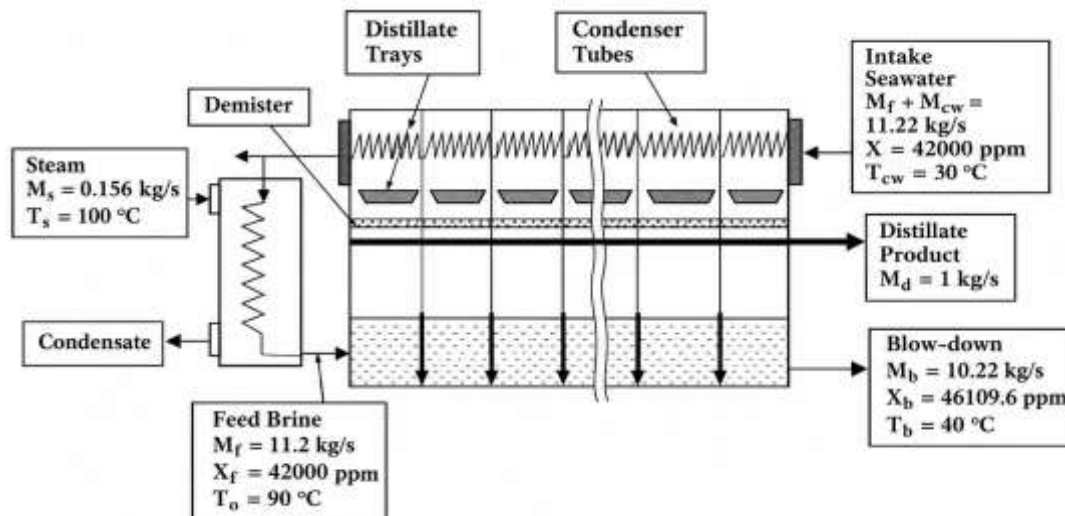


Figure 3: Once through Multi Stage Flashing process

3. Brine Circulation Multi Stage Flashing BR-MSF

Brine recirculation aims to reduce feed seawater flow, thereby minimizing chemical additive consumption and pretreatment infrastructure requirements. Furthermore, blending the higher-energy recycled brine with the intake feed inherently enhances overall thermal efficiency. In the fundamental mixer configuration (Fig. 4), a fraction of the blowdown brine is directly combined with the intake seawater. This yields a feed stream with elevated temperature and salinity before entering a standard once-through MSF setup. Although this simple recirculation

approach improves the thermal performance ratio, it introduces significant operational challenges, specifically necessitating high recirculation rates and exacerbating feed salinity.

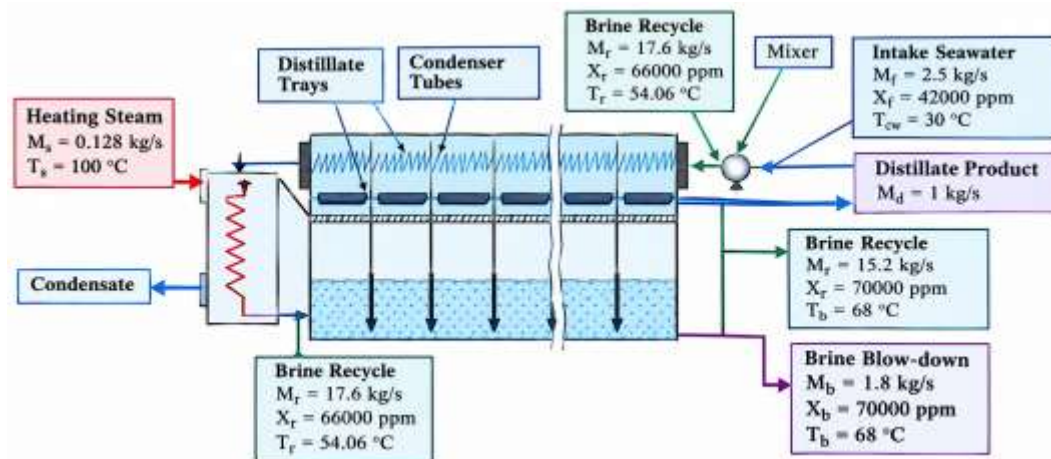


Figure 4: Simple mixer brine recycle MSF desalination process

4. MSF with brine recirculation and a heat rejection section

The heat rejection section in Multi-Stage Flash (MSF) systems regulates recycled brine temperatures by dissipating excess thermal energy. This configuration significantly minimizes pretreatment costs by restricting chemical dosing strictly to the make-up feed rather than the bulk seawater intake. Although theoretically modeled, single-stage heat rejection remains industrially unviable; inherent thermodynamic losses depress condensing vapor temperatures, causing thermal profile intersections that necessitate an infinite heat transfer area. While two-stage configurations demonstrate operational feasibility, minimizing their terminal temperature difference substantially increases the requisite surface area. Consequently, integrating a third heat rejection stage is proposed to mitigate these terminal temperature difference constraints, thereby optimizing system design and reducing the overall heat transfer area requirements.

Methodology and design

1. MSF Desalination Plant Parameters

Multi-stage flash distillation (MSF) system modelling involves a number of operating and design variables that have great influence on the performance of multistage flash MSF desalination plants. An estimation of all these variables requires both analytical solutions and experimental/field analysis. Table 1 shows the technical parameters used in the mathematical model.

2. Assumptions

A simplified model assumptions include the following:

- Constant and equal specific heat for all liquid streams.
- Equal temperature drop per stage for the flashing brine.
- Equal temperature drop per stage for the feed seawater pre-heater (condenser).
- The latent heat of vaporization in each stage is assumed equal to the average value for the process.
- Effects of the boiling point rise and on the stage energy balance are negligible.

Table1. Technical design parameters used in the mathematical model

Parameter	Unit	Symbol	Value	Reference of values
Desalinated water flow rate	kg/s	M_d	162	Assumed
Salt concentration	Ppm	X_i	38,000	Literature
		X_f	38,000	
Brine salt concentration	Ppm	X_b	70,000	Literature
Feed seawater temperature	$^\circ\text{C}$	T_f	20	Calibrated

Steam temperature	°C	T_s	110	Calibrated
Top brine temperature	°C	T_o	100	Calibrated
Brine temperature in the last stage	°C	T_n	40	Calibrated
Intake seawater temperature	°C	T_{cw}	20	Calibrated
Heat capacity of liquid streams	kJ/(kg·°C)	C_p	4.18	Literature
Vapor velocity in the last stage	m/s	V_v	6	Literature
Brine mass flow rate per width	kg/(m·s)	V_b	180	Literature
Weir friction stages	–	C_d	0.5	Literature
Total Number of stages 1	–	n	22	Designed
Total Number of stages 2	–	n	26	Designed
Total Number of stages 3	–	n	29	Designed
Number of heat rejection stages	–	0	0	
		j	3	

Mathematical model

The MSF-OT simplified model is a very useful tool, which can be used to obtain quick design data, evaluate system performance, and develop a good initial guess for more detailed mathematical models.

1. Overall Material and Salt Balance

The overall material boundaries for both systems account for the feed (M_f), the distillate (M_d), and brine blowdown (M_b).

$$\text{Overall mass balance: } M_f = M_d + M_b$$

$$\text{Overall salt balance (assuming salt free distillate): } X_f M_f = X_b M_b$$

2. Stage Material and Salt Balance

The models diverge based on the primary driving flow rate: the feed seawater flow (M_f) for OT, and the recycle brine flow (M_r) for BR.

$$\text{Sensible to latent heat ratio: } y = \frac{C_p \Delta T}{\lambda_{av}}$$

Where average temperature is $T_{av} = \frac{T_o + T_n}{2}$

Flashing vapor formed in stage i (D_i):

$$\text{OT Configuration: } D_i = M_f y (1 - y)^{(i-1)}$$

$$\text{BR Configuration: } D_i = M_r y (1 - y)^{(i-1)}$$

Total distillate flow rate (M_d):

$$\text{OT Configuration: } M_d = M_f (1 - (1 - y)^n)$$

$$\text{BR Configuration: } M_d = M_r (1 - (1 - y)^n)$$

Brine stream flow rate leaving stage i (B_i):

$$\text{OT Configuration: } B_i = M_f - \sum_{k=1}^i D_k$$

$$\text{BR Configuration: } B_i = M_r - \sum_{k=1}^i D_k$$

Salt concentration in the brine stream leaving stage i (X_i):

$$\text{OT Configuration: } X_i = \frac{M_f X_f}{B_i}$$

$$\text{BR Configuration: } X_i = \frac{M_r - \sum_{k=1}^i D_k}{B_i}$$

BR Recycle Salt Balance: The salt concentration in the recycle stream (X_r) is governed by:

$$X_r = \frac{(X_f - X_b)M_f + M_r X_b}{M_r}$$

3. Temperature Profiles

Both systems assume a linear temperature profile for the flashing brine but apply different frameworks for the condensers.

$$\text{Temperature of flashing brine in stage } i: T_i = T_o - i\Delta T$$

$$\text{Where the temperature drop per stage is } \Delta T = \frac{T_o - T_n}{n}$$

Key Configuration Difference:

OT Configuration: The condenser utilizes a single continuous feed seawater stream. The seawater temperature leaving the condenser of stage i is: $t_i = T_f + (n - (i - 1))\Delta t$

$$\text{Where } \Delta t_i = \Delta T_i$$

BR Configuration: The system splits into a heat recovery section ($n - j$ stages) and a heat rejection section (j stages).

$$\text{Condenser temperature in recovery stage } i: T_{ri} = T_n + (n - j)\Delta T - (i - 1)\Delta T$$

$$\text{Condenser temperature in rejection stage } i: T_{ji} = T_{cw} + (n - i + 1)(\Delta T_{ji})$$

$$\text{Where the rejection temperature drop is: } \Delta T_{ji} = \frac{T_n - T_{cw}}{j}$$

4. Heat Transfer Areas

The heat transfer calculations require determining the motive steam flow (M_s) and the respective Logarithmic Mean Temperature Differences (LMTD).

Brine Heater Steam Flow (M_s):

$$\text{OT Configuration: } M_s = \frac{M_f Cp(T_o - t_1)}{\lambda_s}$$

$$\text{BR Configuration: } M_s = \frac{M_r Cp(T_o - T_{f1})}{\lambda_s}$$

$$\text{Brine Heater Area } (A_b): A_b = \frac{M_s \lambda_s}{U_b (LMTD)_b}$$

$$\text{Where: } U_b = 1.7194 + 3.2063 \times 10^{-3} T_s + 1.5971 \times 10^{-5} T_s^2 - 1.9918 \times 10^{-7} T_s^3$$

Key Configuration Difference:

OT Configuration: Assumes equal condenser heat transfer area across all n stages. The total plant heat transfer area (A) is: $A = A_b + nA_c$

$$\text{Where: } A_c = \frac{M_f Cp(t_1 - t_2)}{U_c (LMTD)_c}$$

BR Configuration: Requires separate condenser area calculations for the heat recovery (A_r) and heat rejection (A_j) sections. The total condenser area (A_c) is: $A_c = (n - j)A_r + (j)A_j$

$$\text{Where } A_r = \frac{M_r Cp(T_{r1} - T_{r2})}{U_r (LMTD)_r} \text{ and } A_j = \frac{(M_f + M_r) Cp(T_{sh} - T_{cw})}{U_j (LMTD)_j}$$

5. Stage Dimensions

Both configurations utilize identical mathematical relationships for stage dimensioning, differing only by the controlling mass flow variable (M_f for OT, M_r for BR).

Gate Height for stage i (GH_i):

$$\text{OT Configuration: } GH_i = \frac{M_f - \sum_{j=1}^{i-1} D_j}{C_d W \sqrt{2 \rho_{bi} \Delta P_i}}$$

$$\text{BR Configuration: } GH_i = \frac{M_r - \sum_{j=1}^{i-1} D_j}{C_d W \sqrt{2 \rho_{bi} \Delta P_i}}$$

Stage width (W):

$$\text{OT Configuration: } W = \frac{M_f}{V_b}$$

$$\text{BR Configuration: } W = \frac{M_r}{V_b}$$

Other Shared Dimensions:

$$\text{Brine pool height: } H_i = 0.2 + GH_i$$

$$\text{Length of the last stage: } L = \frac{D_n}{\rho_{vn} V_{vn} W}$$

$$\text{Cross-sectional area: } A_s = LW$$

6. Performance Parameters

Performance metrics evaluate the system's thermal and physical efficiency.

$$\text{Thermal Performance Ratio (PR): } PR = \frac{M_d}{M_s}$$

Specific Heat Transfer Area (sA):

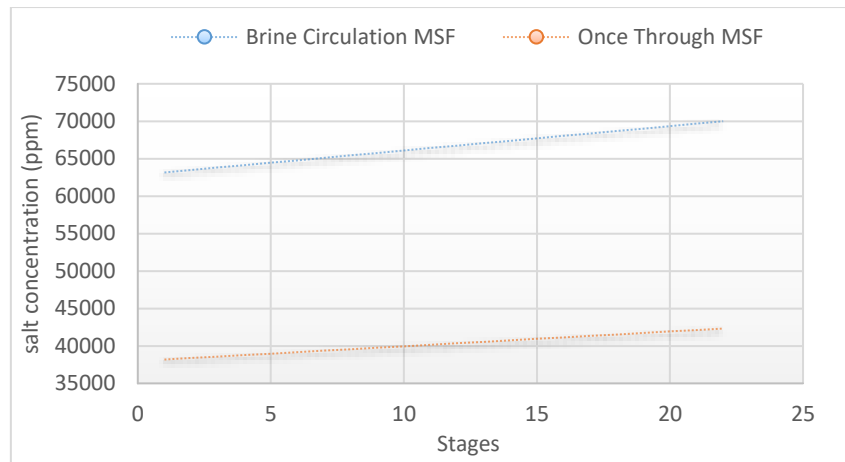
$$\text{OT Configuration: } sA = \frac{A_b + nA_c}{M_d}$$

$$\text{BR Configuration: } A = \frac{A_b + A_c}{M_d}$$

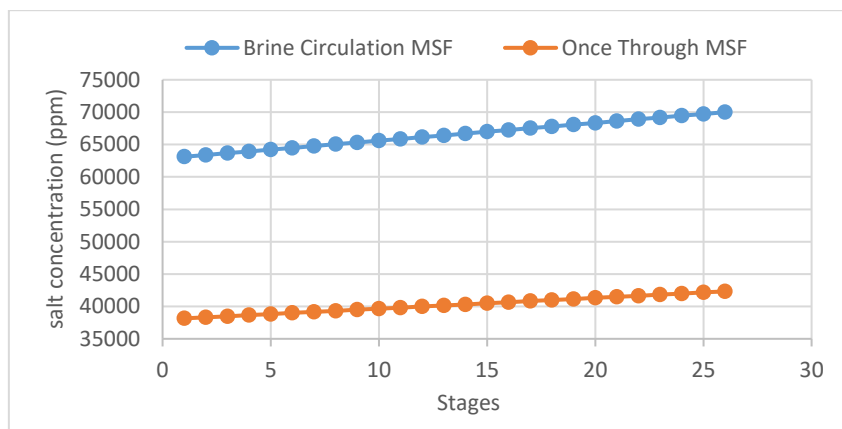
BR Exclusive - Specific Cooling Water Flow Rate (sM_{cw}): The BR configuration requires calculation of cooling water to reject excess heat.

Results and discussion

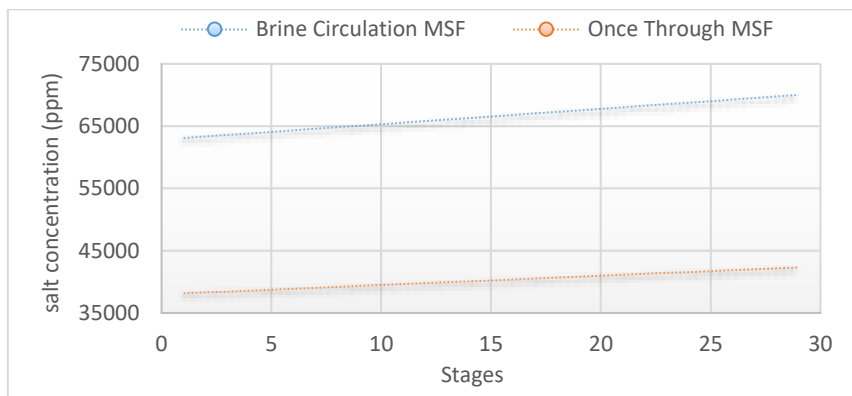
Figure 5 presents the brine concentration profiles across the flashing stages for two MSF desalination models. The curves demonstrate a gradual increase in salinity through successive stages due to continuous evaporation and freshwater extraction. Significantly, the Brine Recirculation (BR-MSF) model yields a much higher brine concentration than the Once-Through (OT-MSF) model. This difference stems from the recirculation process, which mixes concentrated brine with feedwater to optimize thermal recovery and reduce energy demand. Nevertheless, while the BR-MSF system offers high thermal efficiency, the resultant blowdown—characterized by elevated salinity and temperature—presents a major environmental risk, threatening the marine ecosystems surrounding the discharge location.



(a) n = 22



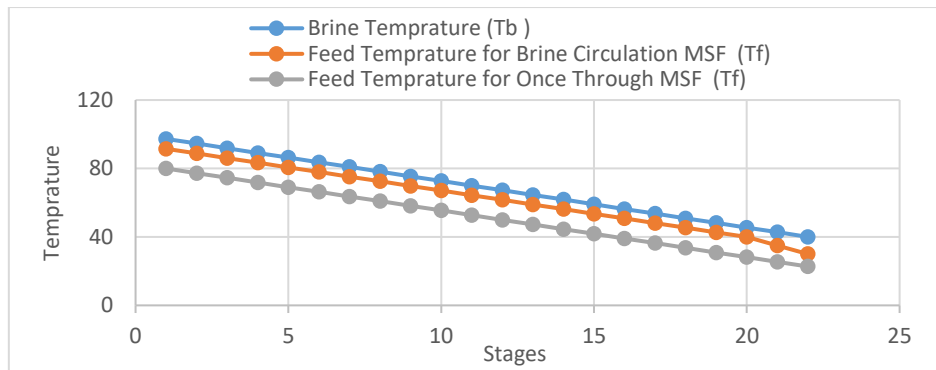
(b) n = 26



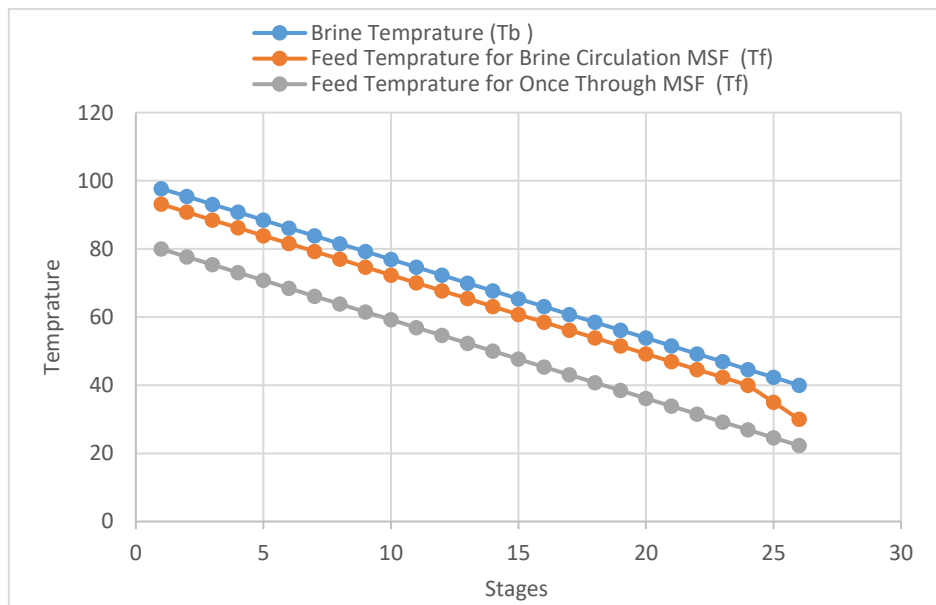
(c) n = 29

Figure 5: Shows the salt concentration for tow MSF Plant model

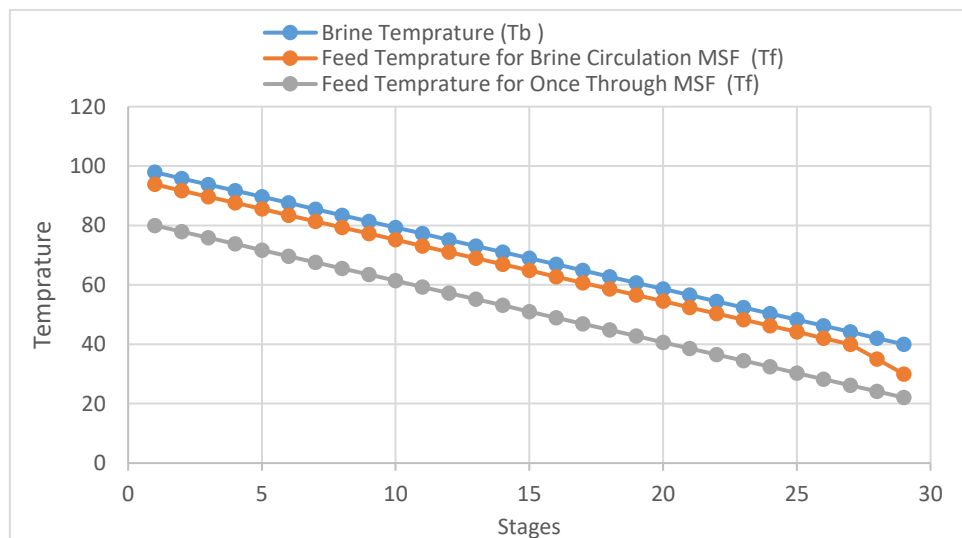
Figure 6 presents the thermal gradients for the brine and feedwater in the MSF plants. Figures 2(a–c) illustrate a gradual decline in brine temperature across the stages due to latent heat loss, inversely accompanied by a rise in feedwater temperature driven by heat absorption during vapor condensation. The feedwater reaches its maximum temperature upon exiting the first stage prior to entering the brine heater. Significantly, the Brine Recirculation (BR-MSF) model demonstrates a higher feedwater temperature gradient than the Once-Through (OT-MSF) model, owing to the high thermal content of the recycled brine. This feedwater preheating narrows the thermal gap in the brine heater, drastically reducing the required heating steam mass flow rate (m_s). As a result, the required heat transfer area for the brine heater decreases, directly elevating the plant's overall thermal efficiency and performance ratio.



(a) $n = 22$



(b) $n = 26$



(c) $n = 29$

Figure 6: Temperature Distributions for tow MSF Plant models.

As illustrated in Figure 7, the total condenser area of the Once-Through (OT-MSF) configuration remains constant regardless of stage count. Lacking a heat rejection section, this open system's performance ratio and logarithmic mean temperature difference (LMTD) are constrained by fixed boundary temperatures. Consequently, additional

stages merely subdivide the thermal span without altering total heat transfer, rendering the required area dependent strictly on production capacity and the macroscopic temperature gradient.

Conversely, the Brine Recirculation (BR-MSF) model necessitates a larger total area that scales proportionally with stage count, driven by the expansion of the heat recovery section. Increasing stages elevates feedwater temperature and reduces LMTD, requiring extended surface area to maximize latent heat recovery. While this effectively minimizes external steam demand in the brine heater and improves overall plant efficiency, this enhanced internal heat recovery concurrently reduces surplus thermal energy, thereby diminishing the requisite heat transfer area within the heat rejection section.

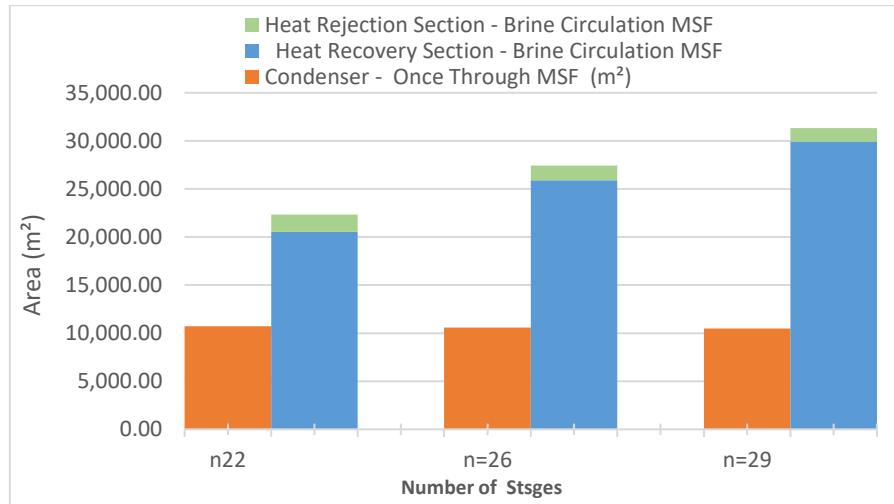


Figure 7: Condenser area for tow MSF Plant models.

Figure 8 further demonstrates that the BR-MSF model necessitates a smaller brine heater area than the OT-MSF configuration. By optimizing latent heat recovery, the BR-MSF system elevates feedwater inlet temperatures, narrowing the thermal gap to the Top Brine Temperature (TBT) and reducing the requisite thermal load. Consequently, increasing stage count continuously decreases the BR-MSF heater area. Conversely, inherent thermodynamic constraints in the OT-MSF model render final feedwater temperatures largely unresponsive to stage additions, thereby maintaining a constant thermal load and brine heater surface area.

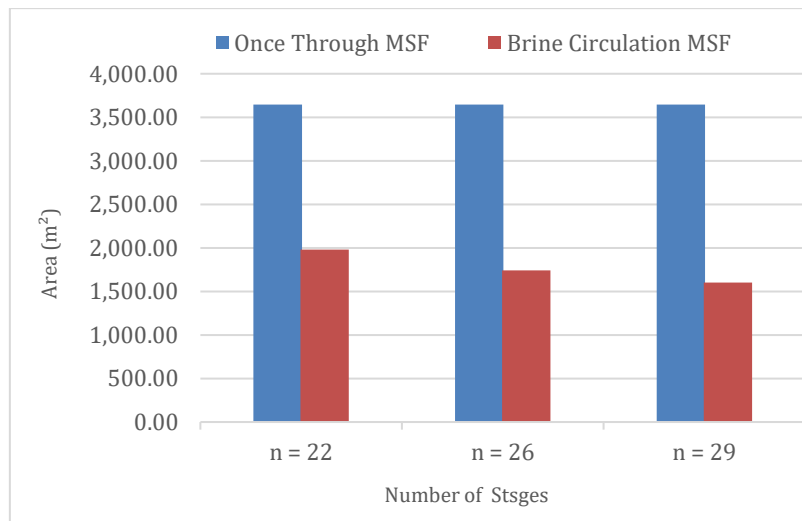


Figure 8: Brine heater area for tow MSF Plant models.

As demonstrated in Figure 9, the BR-MSF configuration achieves a significantly higher Performance Ratio (PR) than the OT-MSF model. By facilitating brine recirculation, the BR-MSF system enhances heat recovery; consequently, increasing the stage count elevates feedwater inlet temperatures, minimizes steam demand, and proportionally increases the PR. Conversely, inherent thermodynamic constraints in the open OT-MSF system render final feedwater temperatures and steam demand largely insensitive to stage additions, resulting in a distinctly static PR.

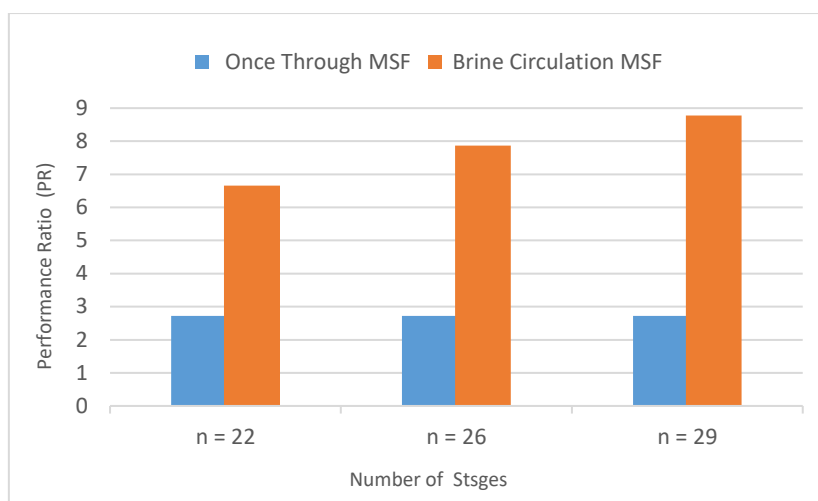


Figure 9: Performance ratio for tow MSF Plant models.

Conclusion

This study presents the stage-by-stage thermodynamic and operational parameters for each evaluated design configuration. The primary data extracted per stage include feed water temperature, brine temperature, water salinity, distillate yield, and the mass flow rate of the rejected brine (blowdown).

The thermal profile of the flashing brine stream exhibits a continuous decline from a Top Brine Temperature (TBT) of 100 °C in the first stage to a final discharge temperature of approximately 40 °C in the last stage. Specifically, the brine temperature exiting the first stage dropped to 97.27 °C, 97.69 °C, and 97.93 °C for the first, second, and third designs, respectively. These values correspond to average stage temperature drops (ΔT_i) of 2.72 °C, 2.31 °C, and 2.07 °C across the three configurations.

Scientifically, this designed temperature drop (ΔT_i) dictates the thermal gradient of the system; it represents both the step-wise cooling of the flashing brine stream and the corresponding step-wise temperature increment of the feed water within the condenser tubes.

Finally, the overall system efficiency was assessed using the Performance Ratio (PR). The standard configurations yielded a PR of 2.72. In contrast, implementing brine recirculation significantly enhanced thermal efficiency, achieving PR values of 6.65, 7.85, and 8.77 for the three respective recirculation designs. The optimal thermodynamic performance (PR = 8.77) was attained in the third design, which utilizes a 29-stage brine recirculation configuration.

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