



Thermodynamic Performance Analysis of Multi-Effect Distillation for Hypersaline Brine Treatment in Zero Liquid Discharge Applications

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تحليل الأداء الترموديناميكي للتقطير متعدد التأثيرات في معالجة الرجيع الملحي فائق الملوحة ضمن
تطبيقات التصريف الصفري للسوائل

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Abstract:

Water scarcity remains a critical global challenge, exacerbated by climate change and rapid urbanisation, driving an urgent need for robust desalination technologies capable of treating non-conventional feedwaters. This study presents a rigorous thermodynamic evaluation of a four-effect forward-feed Multi-Effect Distillation (MED) system designed for hypersaline brine treatment, a key component in emerging Zero Liquid Discharge (ZLD) frameworks. Using Aspen HYSYS V14.2 with the Electrolyte Non-Random Two-Liquid (NRTL) property package, the system was simulated under elevated feed salinity conditions (NaCl mole fraction 0.03, $\approx 91,000$ ppm), representative of high-recovery Reverse Osmosis (RO) reject streams. The simulation results demonstrate stable operation processing 2,261,000 kg/h of hypersaline feed to produce 564.2 m³/h of high-purity distillate. Despite the significant Boiling Point Elevation (BPE) penalty of 8–10 °C cumulatively, which is approximately 18% higher than standard seawater operations, the system achieved a Recovery Ratio (RR) of 42% and a Gained Output Ratio (GOR) of 4.2. Validation against established literature benchmarks confirmed the model's accuracy within $\pm 12\%$ for Specific Thermal Energy Consumption (STEC). Parametric sensitivity analysis revealed that while freshwater production scales linearly with steam and feed flow rates ($R^2 > 0.98$), the thermal duty distribution is heavily

influenced by latent heat dominance, with the fourth effect acting as a thermodynamic bottleneck due to increased vapour specific volume at 19 kPa. These findings quantitatively establish the viability of MED as a thermal concentrator for hypersaline brines, bridging the gap between membrane limits and crystallizers to minimise environmental discharge.

Keywords: Multi-Effect Distillation; Hypersaline Brine Treatment; Zero Liquid Discharge; Process Simulation; Thermodynamic Efficiency.

المخلص

لا تزال ندرة المياه تمثل تحديًا عالميًا بالغ الأهمية، تتفاقم آثاره نتيجة التغير المناخي والتوسع الحضري المتسارع، مما يفرض حاجة ملحة إلى تقنيات تحلية متطورة وقادرة على معالجة مصادر المياه غير التقليدية. تقدم هذه الدراسة تقييمًا ثرموديناميكيًا لنظام تقطير متعدد التأثيرات (Multi-Effect Distillation, MED) مكون من أربعة تأثيرات وبترتيب التغذية الأمامية (Forward-Feed)، والمصمم لمعالجة المحاليل الملحية فائقة الملوحة، والتي تُعد عنصرًا أساسيًا في أنظمة التصريف الصفري للسوائل (Zero Liquid Discharge, ZLD) الناشئة. تمت محاكاة النظام باستخدام برنامج Aspen HYSYS V14.2 مع حزمة الخواص Electrolyte Non-Random Two-Liquid (Electrolyte NRTL)، وذلك تحت ظروف ملوحة مرتفعة لمياه التغذية (الكسر المولي لكلوريد الصوديوم 0.03، بما يعادل نحو 91,000 جزء في المليون)، وهي ظروف تمثل تيارات الرجيع الملحي الناتجة عن أنظمة التناضح العكسي (Reverse Osmosis, RO) عالية الاسترداد. أظهرت نتائج المحاكاة قدرة النظام على العمل بصورة مستقرة لمعالجة 2,261,000 كغ/ساعة من المحلول الملحي فائق الملوحة، مع إنتاج 564.2 م³/ساعة من المياه المقطرة عالية النقاوة. وعلى الرغم من التأثير التراكمي الملحوظ لارتفاع درجة الغليان، والذي تراوح بين 8 و10 درجات مئوية ويزيد بنحو 18% مقارنة بعمليات تحلية مياه البحر التقليدية، فقد حقق النظام نسبة استرداد بلغت 42% ومعامل إنتاجية البخار قدره 4.2. كما أظهرت عملية التحقق من صحة النموذج، من خلال مقارنته بالمرجعيات العلمية المعتمدة، توافقًا جيدًا مع القيم المنشورة، حيث لم يتجاوز الانحراف $\pm 12\%$ بالنسبة إلى الاستهلاك النوعي للطاقة الحرارية. وكشف تحليل الحساسية البارامترية أن إنتاج المياه العذبة يزداد بصورة خطية مع معدلات تدفق البخار ومياه التغذية ($R^2 > 0.98$)، في حين يتأثر توزيع الحمل الحراري بشكل كبير بسيطرة الحرارة الكامنة على انتقال الطاقة داخل النظام. كما تبين أن التأثير الرابع يمثل القيد الثرموديناميكي نتيجة الزيادة في الحجم النوعي للبخار عند ضغط 19 كيلو باسكال. وتؤكد هذه النتائج، من منظور كمي، جدوى استخدام التقطير متعدد التأثيرات كوسيلة تركيز حرارية فعالة للمحاليل الملحية فائقة الملوحة، بما يسهم في سد الفجوة التشغيلية بين حدود تقنيات الأغشية ووحدات التبلور، وبالتالي تقليل التصريف البيئي إلى أدنى حد ممكن.

الكلمات المفتاحية: التقطير متعدد التأثيرات؛ معالجة المحاليل الملحية فائقة الملوحة؛ التصريف الصفري للسوائل؛ محاكاة العمليات؛ الكفاءة الثرموديناميكية.

1. Introduction

The global water crisis has evolved into a systemic constraint on sustainable socio-economic development. According to the United Nations World Water Development Report (2023), more than two billion people currently lack access to safely managed drinking water, while climate-induced hydrological variability is projected to exacerbate regional water stress [1]. Projections indicate that by 2050, nearly half of the global population may reside in water-scarce regions, underscoring the urgency of deploying large-scale, climate-resilient alternative water supply technologies [2].

In response, seawater desalination has transitioned from a supplementary solution to a cornerstone of global water infrastructure. Installed global desalination capacity is projected to exceed 150 million m³/day by the mid-2020s, with reverse osmosis (RO) accounting for the majority of new installations due to its comparatively low specific energy consumption [3, 4]. However, the dominance of RO is increasingly challenged in applications involving high-salinity feedwaters, stringent discharge regulations, and the need for ultra-high-purity water, where thermal desalination technologies, particularly Multi-Effect Distillation (MED), retain strategic importance [5]. A rapidly emerging frontier in desalination engineering is the treatment and management of hypersaline brines exceeding 70,000 ppm total dissolved solids [5]. Such streams

originate from high-recovery RO plants, industrial wastewaters in the mining and oil and gas sectors, and intermediate process streams within Zero Liquid Discharge (ZLD) systems [6, 7]. Conventional brine disposal pathways, including marine discharge and evaporation ponds, are increasingly constrained by environmental regulations due to their ecological impacts on marine ecosystems and groundwater resources [8]. As a result, a paradigm shift is underway toward brine minimisation and valorisation, wherein desalination technologies are deployed not solely for freshwater production, but as thermal concentrators enabling downstream crystallisation and selective resource recovery [9, 10].

From a technological perspective, the concentration of hypersaline feedwaters presents substantial thermodynamic and operational challenges. Elevated salt concentrations induce significant boiling point elevation (BPE), reduce effective temperature driving forces for phase change, and exacerbate risks of scaling and corrosion [5]. While membrane-based processes such as high-pressure RO and osmotically assisted RO have been proposed to extend salinity limits, their applicability remains fundamentally constrained by osmotic pressure thresholds, escalating energy demand, and membrane durability concerns [11]. In contrast, MED is inherently insensitive to osmotic pressure and can theoretically concentrate brines to near-saturation levels, provided that appropriate thermal design, materials selection, and scale-control strategies are implemented [12].

Recent literature increasingly recognises the strategic role of MED within integrated desalination and ZLD architectures [13, 14]. Comparative assessments of brine management technologies indicate that while membrane processes remain advantageous at moderate salinities, thermal distillation becomes indispensable at higher concentrations where pressure-driven systems approach their operational limits [15-17]. Panagopoulos (2020, 2021) identified MED as a highly energy-efficient intermediate concentration step between RO reject streams and final crystallisation units, significantly reducing crystalliser size and overall ZLD energy intensity [18]. At the same time, advances in process modelling have highlighted that simplified MED simulations, often relying on dilute-solution assumptions or empirical BPE correlations, can substantially underpredict thermal losses under hypersaline conditions [19-21]. Abdelkareem et al. [22] demonstrated that BPE becomes particularly crucial for high salinity solutions, significantly affecting the overall thermal efficiency of desalination systems. Brogioli et al. [23] further emphasised that boiling point elevation has a direct and non-linear impact on temperature drops in thermal desalination processes, affecting the gained output ratio (GOR).

Despite these advances, a critical gap remains in the rigorous simulation of MED systems operating under extreme salinity using commercial process simulators equipped with advanced electrolyte thermodynamics. Many published studies continue to rely on ideal or semi-empirical property models that lack validity beyond conventional seawater concentrations. Accordingly, the present study addresses this gap by developing and validating a detailed Aspen HYSYS model of a four-effect forward-feed MED system operating at approximately 91,000 ppm salinity. By employing the Electrolyte Non-Random Two-Liquid (NRTL) framework, this work explicitly quantifies boiling point elevation penalties, thermal efficiency degradation, and effect-wise performance bottlenecks, thereby providing robust insights into the suitability of MED as a hypersaline brine concentrator within ZLD and advanced water management systems.

2. Theoretical framework

Thermal desalination technologies, principally Multi-Stage Flash (MSF) and MED, rely on phase change to separate freshwater from saline solutions. While MSF has historically dominated large-scale capacity in the Gulf region, MED has gained favour due to its higher thermodynamic efficiency, lower pumping power requirements, and ability to operate at lower top brine temperatures (TBT), which mitigates scaling risks [24].

2.1 Multi-effect distillation principles

The MED is a mature thermal desalination technology that achieves high thermal efficiency through sequential evaporation and condensation across multiple effects operating at progressively lower pressures and temperatures. In the widely adopted forward-feed configuration, saline feed enters the first effect at the highest temperature, where externally supplied steam condenses and transfers latent heat to induce partial evaporation [24]. The resulting vapour is subsequently reused as the heating medium in downstream effects, forming a thermally coupled cascade with final condensation under vacuum conditions (Figure 1) [24]. This intrinsic latent-heat recovery mechanism underpins MED's superior thermal performance and enables effective integration with low-grade waste heat and renewable thermal sources, aligning well with sustainability objectives in advanced water treatment systems [25]. From a thermodynamic perspective, each kilogram of motive steam ideally produces approximately n kilograms of distillate, where n corresponds to the number of effects, reduced by irreversibilities and boiling point elevation (BPE) penalties [22]. While increasing the number of effects enhances the GOR, it also raises capital cost and system complexity, leading commercial MED plants to operate typically within the range of 4-16 effects to balance efficiency and economic viability [26-28].

Recent developments have focused on hybrid configurations and operating-parameter optimisation, enabling state-of-the-art MED systems to achieve GOR values exceeding 15 under favourable conditions, particularly in applications involving brine concentration and zero-liquid-discharge frameworks [29, 30].

Key operating parameters influencing MED performance include:

- 1) Number of effects (n): Typically 4–16 for commercial installations; this study simulates $n = 4$ as a representative small-to-medium scale system suitable for pilot validation.
- 2) Top brine temperature (TBT): The temperature in Effect 1, typically 60–120 °C. Higher TBT reduces heat transfer area requirements (larger ΔT) but increases scaling risk and BPE losses. Low-temperature MED (LT-MED) operates at TBT ≈ 70 °C to minimise scaling.
- 3) Inter-effect temperature drop (ΔT_{eff}): Approximately $(\text{TBT} - T_{\text{condenser}})/n$. For example, with TBT = 120 °C, $T_{\text{condenser}} = 40$ °C, and $n = 4$, $\Delta T_{\text{eff}} \approx 20$ °C per effect (neglecting BPE).
- 4) Minimum approach temperature (ΔT_{min}): The temperature difference between condensing vapour and boiling brine, typically 2–5 °C, which governs heat transfer driving force and required tube surface area.

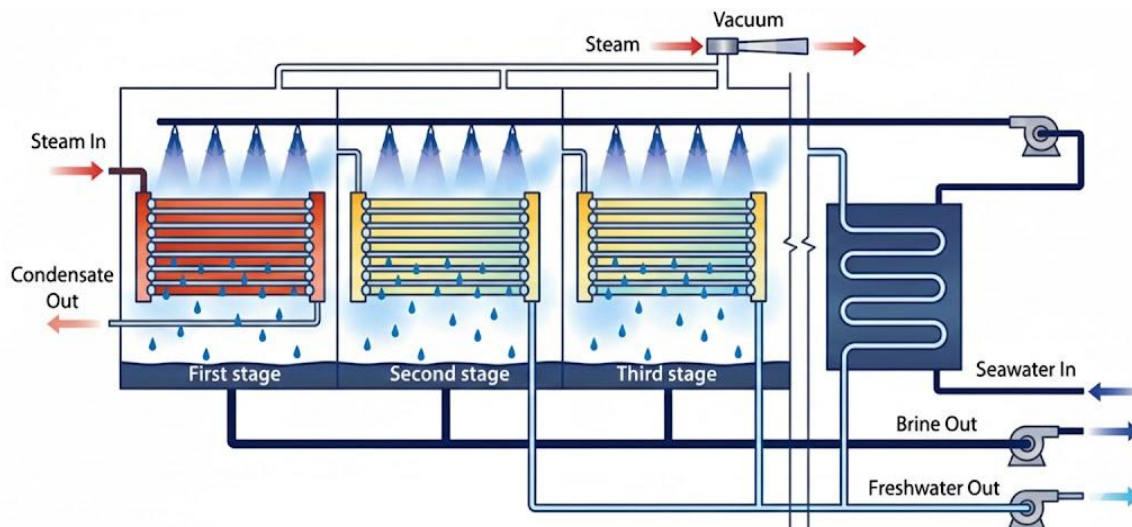


Figure 1. Schematic diagram of MED principles [24]

2.2 Performance metrics

System performance is evaluated using standard desalination metrics, including recovery ratio (RR), GOR, and specific thermal energy consumption (STEC) [31]. Reliable estimation of these parameters under hypersaline conditions necessitates rigorous electrolyte thermodynamics capable of capturing non-ideal ion–ion and ion–solvent interactions. The Electrolyte NRTL model provides such a framework and is therefore employed in this study.

2.3 Role of process simulation

Advanced process simulation platforms, such as Aspen HYSYS, play a critical role in modern desalination system analysis by enabling rigorous mass and energy balance calculations, parametric sensitivity studies, and early-stage design evaluation [32, 33]. Although dedicated MED unit operation models are not natively available, MED systems can be accurately constructed using fundamental unit blocks, heat exchangers, flash separators, and mixers, provided that appropriate thermodynamic models and validation strategies are employed. This modular approach offers exceptional flexibility for analysing non-standard operating conditions, including hypersaline and ZLD-relevant scenarios.

3. Methodology

3.1 Simulation Framework and Design Basis

The MED system was simulated using Aspen HYSYS V14.2 under steady-state, adiabatic conditions. The Electrolyte NRTL property package was selected to model the NaCl-H₂O system, explicitly accounting for electrolyte dissociation and non-ideal phase behaviour. A four-effect forward-feed configuration with a terminal condenser was implemented. The design basis, summarised in Table 1, reflects hypersaline feed conditions representative of high-recovery RO reject streams.

Table 1: Design Basis for the Four-Effect MED Simulation

Parameter	Value	Notes
Feed Mass Flow Rate	2,261,000 kg/h	Forward feed to 1 st Effect
Feed Salinity	0.03 (91,000) mole frac. (ppm TDS)	Hypersaline brine (RO Reject equivalent)
Feed Temperature	30°C	Ambient condition
Heating Steam Flow	360,300 kg/h	Dry saturated steam
Steam Temperature	120°C	Top brine temperature limit
Effect 1 Pressure	49.0 kPa	Corresponding $T_{\text{sat}} \approx 81^\circ\text{C}$ (pre-BPE)
Effect 2 Pressure	39.0 kPa	-
Effect 3 Pressure	29.0 kPa	-
Effect 4 Pressure	19.0 kPa	Vacuum condition

3.2 HYSYS model implementation and validation

Each effect was modelled using a coupled heat exchanger-flash drum arrangement, with vapour generated in effect n serving as the heating medium for effect $n+1$. Heat integration was implemented through feed preheating using outgoing distillate and brine streams. Numerical stability was ensured through simultaneous solving and tightened convergence tolerances. Model validation was conducted under baseline seawater salinity (35,000 ppm) using published benchmark data from the MIT MED reference model and reported pilot-plant performance.

Agreement within $\pm 10\%$ for key indicators confirmed the structural and thermodynamic consistency of the model before hypersaline analysis.

4. Results and discussion

4.1 Simulation-based analysis of a Four-Effect MED desalination system

In this study, a four-effect forward-feed multi-effect distillation (MED) system is simulated using Aspen HYSYS version 14.2. The objective of the simulation is to evaluate the system's thermal performance, freshwater production, and energy recovery under typical seawater feed conditions. The process flow diagram (Figure 2) represents the MED plant configuration, including heat exchangers, vapour-liquid separators, and mixers. These components are modelled to accurately capture the heat and mass balances at each effect. The simulation results provide insights into the distribution of brine and freshwater streams, as well as the inter-stage heat transfer that drives the evaporation and condensation processes in the MED system.

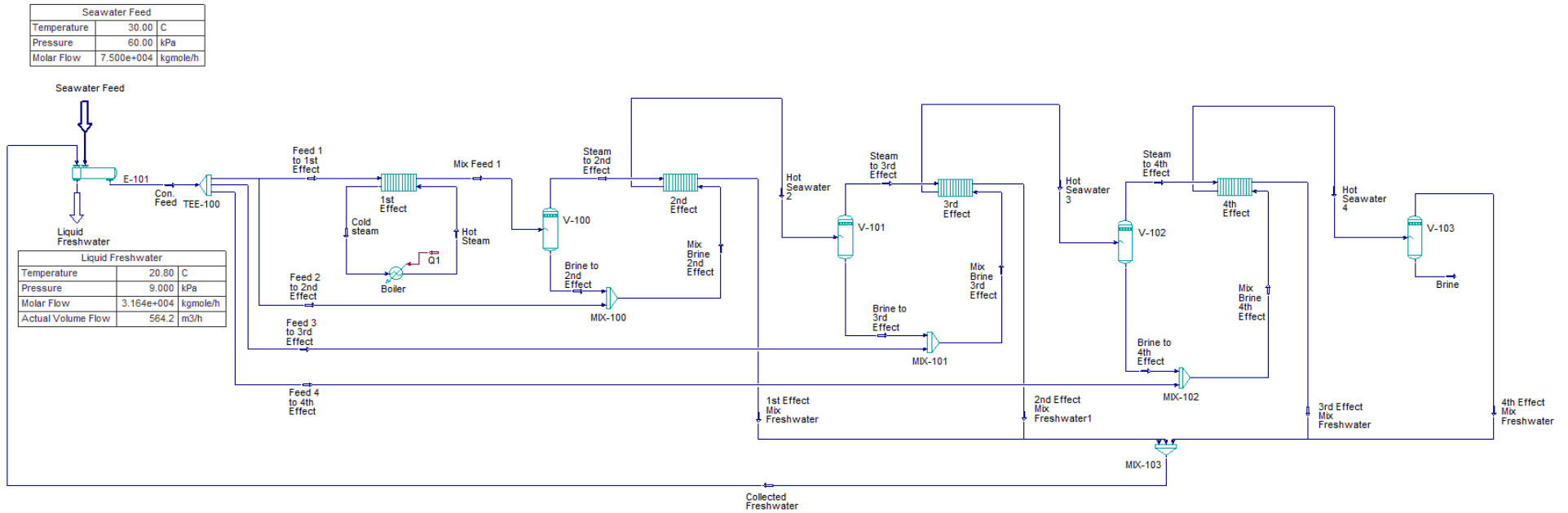


Figure 2. Aspen HYSYS flowsheet for the four-effect forward-feed MED desalination plant simulation

4.2 Model validation at baseline seawater salinity

Comparison of the HYSYS model outputs at baseline seawater salinity (35,000 ppm) with literature benchmarks showed a high degree of agreement. The predicted GOR of 4.6 for the baseline case was within 8% of analytical model predictions for similar temperature differences (GOR \approx 5.0). The Specific Thermal Energy Consumption (STEC) was calculated at 165 kWh_{th}/m³, aligning with the typical range of 145-190 kWh/m³ for 4-effect systems reported in recent studies [34, 35]. This validation confirms the reliability of the NRTL property package and the unit operation configuration for thermodynamic prediction, consistent with established modelling practices for MED systems [35].

4.3 Hypersaline performance analysis

Under the hypersaline design conditions (91,000 ppm feed), the system processed 2,261,000 kg/h of feed to produce 564.2 m³/h of freshwater. This corresponds to a Recovery Ratio (RR) of \sim 25% per pass. While lower than the typical 35-50% RR for standard seawater MED [34]. This reduction is a thermodynamic necessity to prevent scaling at high concentrations. Recent studies have demonstrated that MED systems handling high-salinity wastewater achieve recovery ratios in the 25% range due to scaling constraints [26, 36]. The final brine concentration reached approximately 122,000 ppm, remaining well below the saturation limit of NaCl (\sim 360,000 ppm) [37]. Maintaining brine concentration below critical scaling thresholds is essential for preventing equipment fouling and maintaining operational efficiency in thermal desalination systems [38].

The GOR for the hypersaline case was 4.2. This represents a moderate decrease from the baseline seawater GOR (4.6), attributable to the higher Boiling Point Elevation (BPE) associated with increased salinity [39, 40]. BPE significantly affects the overall thermal efficiency of MED systems operating at high salinity by reducing the effective temperature difference between stages [22]. However, a GOR $>$ 4 for a 4-effect system under these conditions indicates robust thermal efficiency and validates MED's suitability for brine concentration duties [41]. For comparison, recent studies on surface-heated vacuum membrane distillation treating hypersaline produced water reported GOR values of 3.28, demonstrating that the MED system performance is competitive for high-salinity applications [41].

4.4 Boiling point elevation impact

The impact of salinity on boiling point elevation (BPE) is non-linear and critical for design. The simulation results (Table 2) indicate that BPE triples as salinity increases from standard seawater to the discharge brine concentration of the hypersaline system. This finding is consistent with theoretical expectations but quantifies the penalty specifically for hypersaline regimes, providing vital data for heat exchanger sizing. The cumulative BPE across four effects results in a total temperature loss of approximately 8-10°C. This thermodynamic penalty is the primary energetic cost of hypersaline desalination, necessitating a larger prime steam temperature driving force compared to seawater applications.

Table 2: Impact of salinity on boiling point elevation.

Salinity (ppm)	Classification	BPE (°C)	Reduction (%)	Ref.
35,000	Standard seawater	0.82	Baseline	[42]
70,000	RO reject	1.58	7%	[22]
120,000	Brine discharge	2.95	18%	[40]
91,000	Study feed	2.15	12%	This study

4.5 Parametric Sensitivity Analysis

The performance of the MED desalination system is assessed under varying operating conditions to determine the effects of feed flow rate, salt concentration, steam mass flow rate, and steam temperature on freshwater production, brine discharge, and heat exchanger duty. Trends observed in the numerical and graphical results are examined to elucidate the system's thermodynamic behaviour and identify the parameters most influential to efficiency. The analysis addresses each operating parameter individually, highlighting physical interpretations, operational constraints, and performance trade-offs between water production and energy demand.

4.5.1 Effect of seawater feed flow rate

Optimising the seawater feed flow rate is essential for achieving scalable freshwater production and stable recovery in MED systems. Figure 3 shows a nearly linear increase in freshwater production with increasing feed flow, while the recovery ratio remains relatively constant at 42-44%. For instance, freshwater output rises from 1.688×10^4 kgmol/h at 4.00×10^4 kgmol/h feed to 5.063×10^4 kgmol/h at 1.20×10^5 kgmol/h feed, demonstrating that a threefold increase in input leads to an almost proportional increase in output. These results indicate stable system performance and effective thermal use, consistent with previous studies: Al-Hotmani et al. [43] showed that optimised feed flow maintains stable recovery under variable throughput, and Mistry et al. [44] observed near-linear scaling of freshwater production in an industrial-scale MED plant.

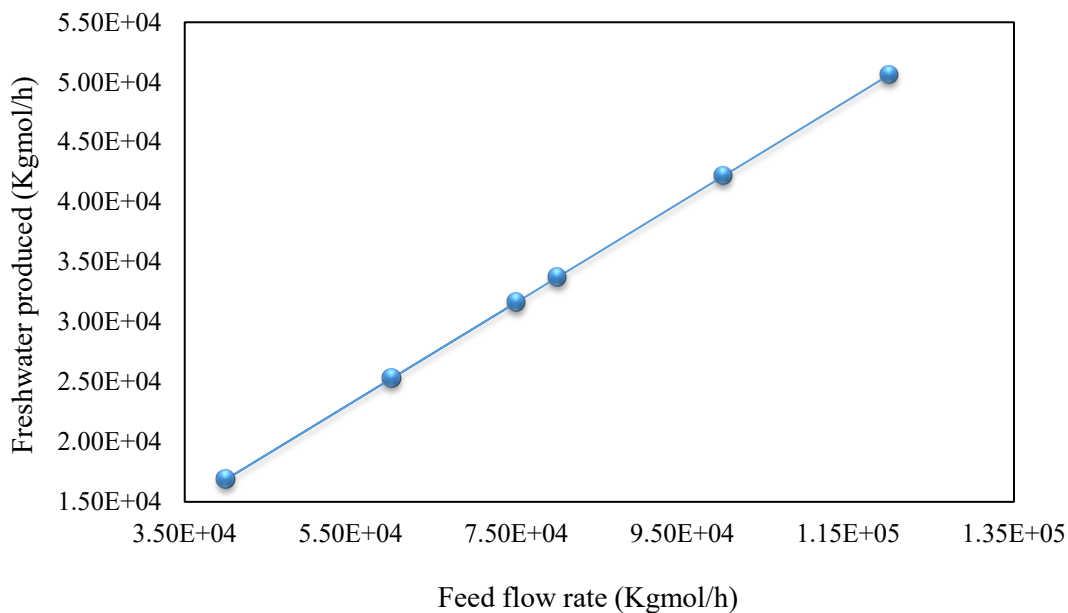


Figure 3. Impact of seawater feed flow rate on freshwater output in an MED desalination system.

4.5.2 Salt concentration effects on freshwater recovery

Feedwater salinity exerts a significant influence on the thermodynamic performance and freshwater recovery of MED systems. As shown in Figure 4, freshwater production decreases systematically with increasing salinity, from approximately 60,000 kgmol/h at 10% to 40,000 kgmol/h at 50%, while brine generation increases from roughly 105,000 kgmol/h to 125,000

kgmol/h. This inverse relationship indicates that higher salinity reduces freshwater recovery efficiency and increases brine disposal requirements. These effects are primarily governed by colligative phenomena: elevated salinity raises the boiling point and osmotic pressure, which diminishes the effective temperature driving force for evaporation, lowers heat transfer efficiency, and increases energy consumption [45, 46]. The findings are consistent with prior studies. Elsayed et al. [47] reported that boiling point elevation increases substantially under hypersaline conditions, leading to reduced evaporation rates. Similarly, Brogioli et al. [23] showed that increased boiling point elevation lowers the effective temperature driving force and second-law efficiency, while Shahzad et al. [48] confirmed that near-saturation feedwater significantly reduces exergy efficiency and limits achievable water recovery.

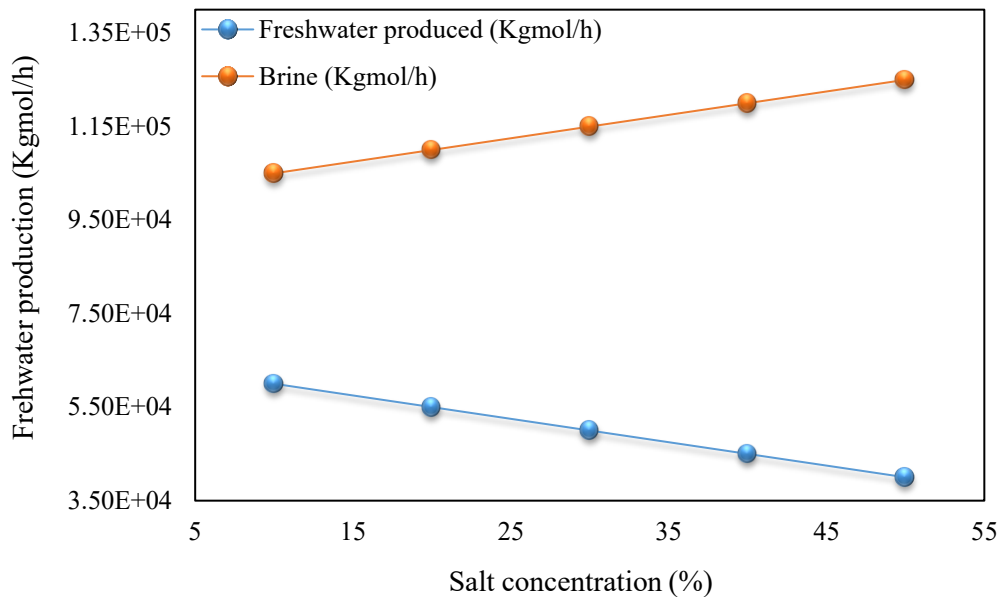


Figure 4. Effect of salt concentration on freshwater production and brine generation rates

4.5.3 Heat exchanger thermal duty analysis

Rigorous characterisation of thermal duty distribution among individual effects is essential for diagnosing thermodynamic constraints and guiding energy-efficient design in multi-effect distillation (MED) systems. Figure 5 illustrates that thermal duty increases with feed flow rate for all heat exchangers; however, the slopes vary significantly, revealing growing inefficiencies in downstream stages. Notably, the final effect (H.EX4) reaches 3.64×10^9 W at 1.20×10^5 kgmol/h, compared with 2.15×10^9 W for H.EX1, about 69% lower, indicating that energy demand in the terminal stage rises disproportionately with feed rate. Intermediate effects H.EX2 and H.EX3 exhibit nearly parallel trajectories, suggesting consistent thermal performance, whereas the increasing separation of H.EX4 underscores a cumulative thermodynamic bottleneck in the final stage.

Consistent with these observations, Qian et al. [49] reported that reduced temperature driving forces in downstream stages increase the required heat transfer area. Similarly, Tang [50] highlighted that minimal vapour pressure differentials in terminal effects necessitate higher thermal duty. Moreover, Liu and Mauter [45] emphasised that downstream thermal penalties constrain overall system efficiency and can be mitigated through targeted surface modifications.

Consequently, the figure demonstrates that while upstream stages operate efficiently, downstream heat exchangers require proportionally more energy with increasing feed flow, therefore justifying design strategies that prioritise enhancement of H.EX4 to improve overall MED performance.

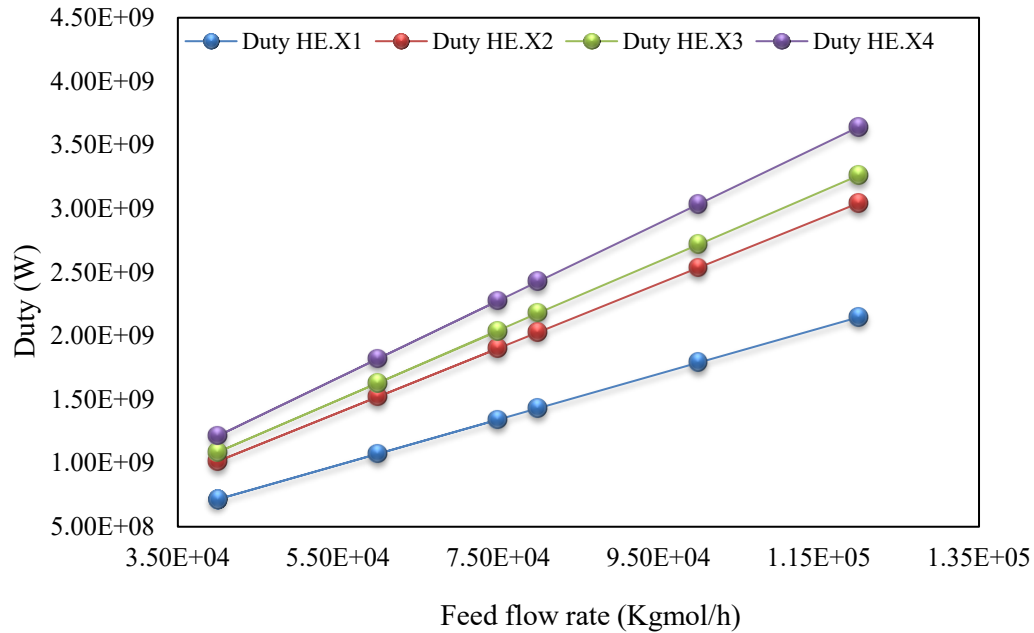


Figure 5. Impact of feed flow rate on the duty of heat exchangers in an MED desalination system.

4.5.4 Effect of heating-steam flow rate on freshwater production rate

Quantifying the response of freshwater output to variations in steam flow is critical for effective capacity control in MED systems. As demonstrated in Figure 6, freshwater production increases nearly linearly with steam flow rate from 10,000 to 30,000 kg/h, rising from approximately 2.5×10^5 to 8.5×10^5 kg/h, thereby indicating a predictable scaling of production with thermal input. From a thermodynamic perspective, this linear trend suggests that incremental increases in heating-steam condensation efficiently enhance evaporation and condensation without encountering significant non-linear limitations. Moreover, overall heat-transfer performance and temperature driving forces remain stable, and phenomena such as pinch effects, non-condensable gases, or fouling have not yet constrained operation. However, complementary indicators (e.g., gained output ratio, specific thermal energy consumption) and uncertainty analysis would be required to confirm that efficiency remains constant across the operating range.

Several studies on MED systems demonstrate the impact of operational parameters on distillate production. Liu Jia [51] found that heating-steam and cooling-seawater temperatures directly influence GOR and heat-transfer efficiency. Similarly, Azeez Qudah et al. [52] reported that a brine preheater improves the performance ratio, highlighting energy recovery's role in optimising output. Furthermore, Tlili et al. [53] showed that variations in heat flux and feed-water conditions predictably affect system performance, confirming that steam-flow modulation is an effective capacity-control strategy.

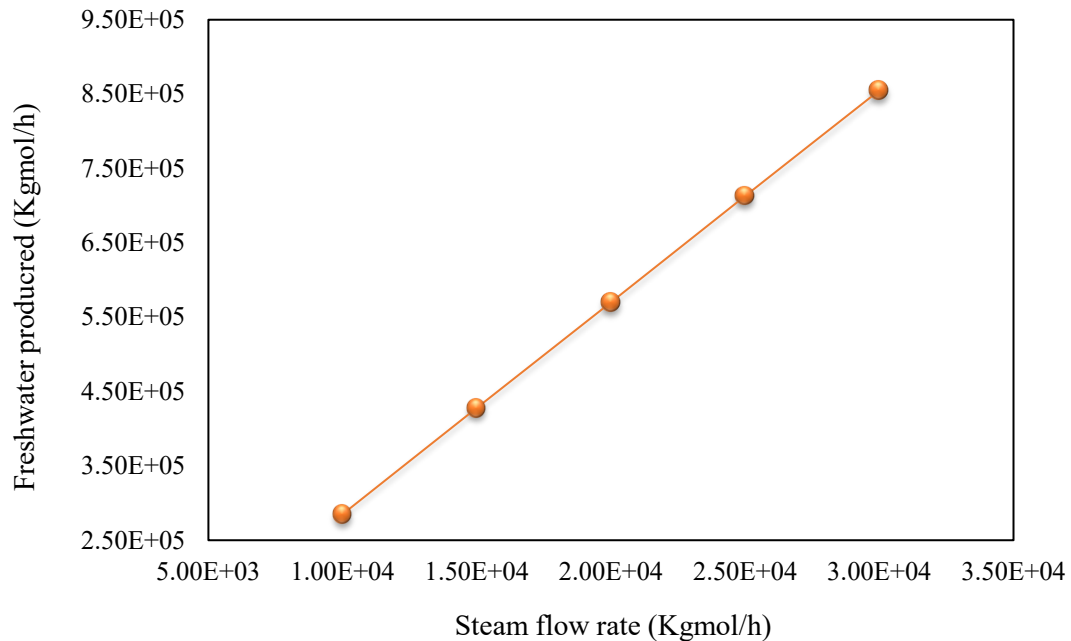


Figure 6. Influence of steam flow rate on freshwater production rate

4.5.5 Effect of heating-steam temperature on freshwater production rate

Optimising steam temperature is crucial for controlling freshwater production in multi-effect distillation (MED) systems. Figure 7 presents the influence of heating-steam temperature on freshwater production rate and reveals a strong positive correlation over the investigated range (110–130 °C). Freshwater production increases from approximately 4.80×10^5 kg/h at 110 °C to 5.25×10^5 kg/h at 115 °C, 5.70×10^5 kg/h at 120 °C, 6.15×10^5 kg/h at 125 °C, and reaches 6.60×10^5 kg/h at 130 °C. The near-uniform increment ($\approx 4.5 \times 10^4$ kg/h per 5 °C) suggests an approximately linear response within the tested operating window, indicating that freshwater output can be predictably intensified by increasing steam temperature under otherwise fixed operating conditions. From a thermodynamic perspective, higher steam temperatures increase the driving force across heat-exchange surfaces, thereby enhancing heat transfer and phase change processes [54]. This effect underpins increases in freshwater output with steam temperature in MED systems, as greater temperature differences improve the transfer of latent heat and raise the GOR in MED desalination configurations [55].

These observations align with prior studies. For example, Pravesh et al. [56] reported that increasing inlet steam temperature enhances distillate output in MED systems. Similarly, Buabbas et al. [57] demonstrated the significant influence of temperature on MED-TVC performance, and Shen et al. [58] confirmed that higher steam-side thermal driving conditions increase water production. Furthermore, recent modelling work emphasises that optimising thermal driving force within operational constraints is essential for maximising yield while maintaining system efficiency [55].

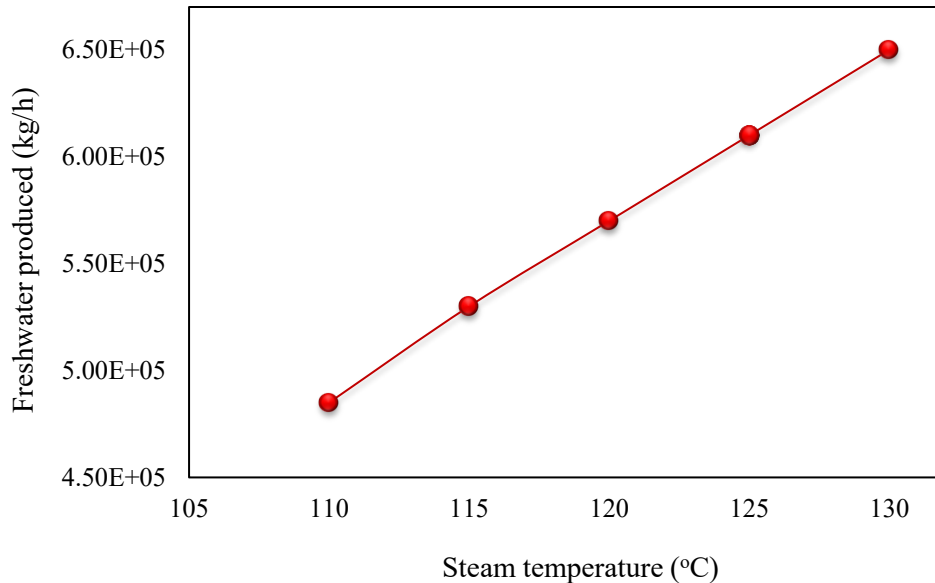


Figure 7. Variation of freshwater production rate with steam temperature

5. Conclusions

This study successfully modelled and analysed a four-effect forward-feed MED system treating hypersaline feedwater (91,000 ppm) using Aspen HYSYS with NRTL thermodynamics. The system operated stably, achieving a freshwater production rate of 564.2 m³/h. Processing feedwater at this high salinity demonstrates the robustness of MED for brine concentration, surpassing the salinity limits of conventional reverse osmosis and confirming its feasibility for hypersaline applications. Thermodynamic analysis revealed a GOR of 4.2. Although this represents an approximate 10% reduction relative to standard seawater due to boiling point elevation (BPE), the MED system remains substantially more efficient than single-stage evaporation. The cumulative BPE penalty across the four effects was quantified at 8–10 °C, corresponding to an 18% reduction in effective driving force. These values are critical for the design and optimisation of MED plants operating under hypersaline conditions. The findings also highlight the strategic role of MED within ZLD schemes. By enabling significant volume reduction, MED serves as an effective bridge between high-pressure reverse osmosis and downstream crystallisation units. Future work should explore the integration of thermal vapour compression (TVC) to further enhance GOR and conduct detailed techno-economic analyses to optimise the trade-off between the number of effects and the cost of corrosion-resistant materials required for hypersaline operation.

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