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Energy and Exergy Analysis of Hybrid RO-freeze Desalination Integrated with an Evaporation Pond

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ABSTRACT

As international desalination capacities have increased, brine from desalination plants has become an environmental danger to ecosystems. Thus, it is essential to treat such hypersaline brines. This case study uses a hybrid RO-freeze desalination system and an evaporation pond to treat desalination brine. A thermodynamic analysis based on the mass and energy balances is initially performed for the proposed system. Then, RO-freeze Desalination and Reverse Osmosis desalination have been compared from the viewpoint of energy consumption and the amount of brine discharge. The effects of temperature and salinity in the feedwater and the F_s factor on energy consumption and the quantity of brine discharge are under investigation. The results show a 30% increase in recovery in RO-FD compared to reverse osmosis desalination, while SEC has only a 40% increase. The specific energy consumption, second-law efficiency, and evaporation pond area are 6–12 kWh/m^3, 7–12 %, and 20000-52000 m^2, respectively. It is coupled with a CO_2 cooling system that freezes seawater in a crystallizer and melts ice in a chamber. The evident rise in water product and decreased residual brine amount create an exceptionally appealing desalination process.

KEYWORDS

Reverse Osmosis, Freeze Desalination, Hybrid Desalination, Evaporation Pond, Carbone Dioxide

INTRODUCTION

Water is recognized as one of the most vital natural resources; however, it is fast depleting owing to human activity. A growing number of countries, particularly in arid areas, have reached a level where sustainable water delivery is difficult. Several desalination techniques have been invented in recent decades to reduce water shortage [1]. High amounts of concentrated brine from conventional desalination plants with a total soluble solid content in high salinity are an essential problem in many desalination processes. Brine has at least 1.6 times more total dissolved solids (TDS) than seawater. Because of the high concentration of the desalination brine, the choice of a second-stage desalination unit is limited [2, 3]. Brine treatment technologies must significantly decrease brine quantities while dealing with high contaminants. Conventional desalination is ineffective for treating high-salinity waters. As a result, excessive salinity is frequently the underlying cause of brine treatment challenges, resulting in fouling/scaling and high energy demand [4]. One of the treatment methods for this concentrated brine is freeze desalination (FD), which is getting popular progressively [5]. For many years, freeze technology has been recognized for its ability to purify and concentrate liquids [6]. Freezing desalination processes mainly depend on a saline water phase change from liquid to solid "ice." Most ice crystals are theoretically composed of pure water [7]. The main reason for developing a freezing desalination plant is the low enthalpy of phase change for water freezing, compared to water evaporation. Its other features include its small size, no corrosion, and no necessity for pre-treatment [8].

Hybrid desalination technologies are among the strategies to offset the drawbacks of typical desalination. Hybridization means combining two or more valuable forms of primary energy, increasing efficiency and reducing atmospheric emissions [9,10]. The main disadvantage of freeze desalination is operational costs during the ice separation. According to various analyses, combining the freezing process with other desalination methods improves performance. Salajeghe et al. [11] proposed a RO-MED-FD hybrid desalination system. This study examined the impacts of the inlet water temperature, salt concentration in inlet water, and the FD system recovery ratio on system energy consumption using mathematical modeling.

Furthermore, in order to power this hybrid system, the potential of new energies was evaluated. Much research has been carried out numerically on multi-effect freeze desalination. The evaluation of single-effect and multi-effect freeze desalination reveals that the latter uses less energy than the former [12].

Evaporation ponds (EP) are the most prevalent waste management alternative for the hypersaline brine formed in water treatment plants. Evaporation ponds are a form of brine disposal that consists of shallow, walled earthen basins in which brine slowly evaporates due to direct sunlight. Once the freshwater evaporates, the minerals in the brine precipitate into salt crystals at the basin's bottom. Since wastewater disposal costs are determined by volume rather than concentration, it is more cost-efficient to dispose of a small volume of very saline water than a large volume of slightly saline water (used primarily in semi-arid areas with low land costs [13, 14].

Due to the green characteristics of CO_2, a carbon dioxide refrigeration cycle has been chosen for freezing. CO_2 is chemically inert and non-toxic [15].

The high concentration of the RO brine is a significant issue in many desalination processes, so in the past, the combination of freeze desalination and reverse osmosis (RO) has been executed. But the combination of two effects freeze desalination and reverse osmosis has been proposed for the first time.

However, the present research marks the first instance of an exergy analysis of freeze desalination being conducted and the hybrid RO-FD system is coupled with an evaporation pond to increase sustainability desalination. In the past, the analysis of freeze desalination has been done using the characteristics of freons, which is limited due to environmental issues. But in this analysis, carbon dioxide has been used for the first time. The hybrid RO-FD system is intricately linked with a cooling CO_2 system, where the evaporator serves as the ice freezer, and the initial condenser functions as the ice melter. This cooling CO_2 cycle operates below the critical point (CO_2). Notably, one of the key advantages of this hybrid system is its potential to reduce energy consumption and discharge of brine while simultaneously increasing desalination recovery rates. To address environmental concerns, the brine produced by this hybrid desalination system is directed toward an evaporation pond. This strategic approach mitigates groundwater pollution by reducing the amount of brine discharge and facilitates the conversion of the brine into potable salt crystals. This research aims to present the idea and Performance analysis of RO-FD desalination by Considering the effects of operating parameters such as variation of solid ice fraction, salinity of RO brine and salt concentration have changed. These parameter variations are critical to determine the working design parameters effects on the overall hybrid system performance. Work of Compressor, SEC, exergy efficiency, area of evaporation pond and brine salinity will be investigated in this work.

SYSTEM DESCRIPTION

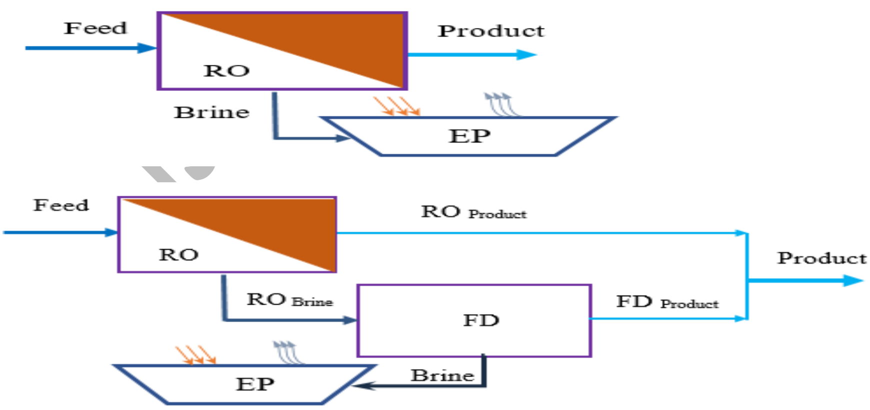
The proposed hybrid system comprises a cooling CO_2 system and a hybrid desalination system.

This part uses reverse osmosis desalination and two hybrid configurations to reduce discharge brine and energy consumption. All are shown schematically in Fig. 1.

A reverse osmosis desalination system (RO) is considered in the first configuration.

In configuration II, a hybrid RO-FD desalination plant is explored, in which the concentrated brine of the RO is used as feed for the freeze desalination system. Therefore, before entering the crystallizer, the concentrated brine is first pre-cooled by a heat exchanger, in which approximately pure ice crystals are produced and separated from the brine in the separator.

In configuration III, a hybrid RO-2EFD desalination plant is explored to reduce the brine of hybrid desalination.



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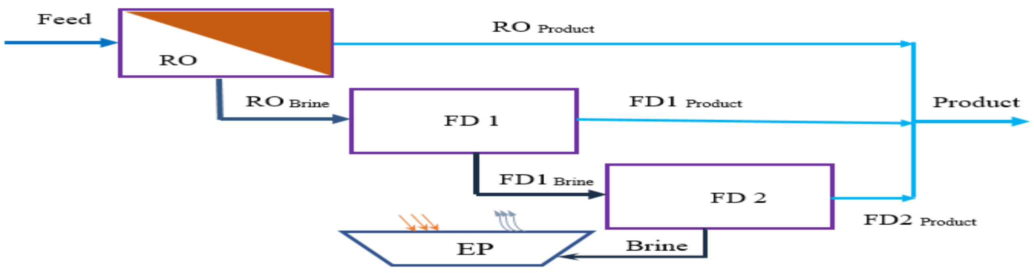

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Fig.1 Simplified block diagram of (a) RO, (b) RO-FD, (c) RO-2EFD

The hybrid RO-FD and CO_2 cooling system (configuration II) is illustrated in Fig. 2. Seawater is fed to a RO unit (w0). The concentrated brine of the RO is used as the feed for the FD unit (w1). The evaporator of the CO_2 cooling system works as the crystallizer of the FD system. The heat exchanger is intended to recycle heat from two distinct cold streams, namely rejected brine (w8) and melted ice crystal (w7), while also lowering the temperature of the incoming feed (w2). Thus, ice crystals form inside the crystallizer (w3). The ice slurry, which includes ice crystals and rejects brine, is delivered to the separation unit and divided into two streams (w4, w6). The washing can be accomplished by losing only 5% of the total product water. Clean ice crystals melt due to indirect contact with the refrigerant pumped to the first condenser by the primary compressor (w5). A melter absorbs the waste heat from the first condenser (melter). This technique must be precisely devised and implemented to decrease environmental concerns about groundwater pollution. The saline brine of hybrid desalination is sent through the evaporation pond. It is one of the reliable methods and requires a small amount of technical equipment.

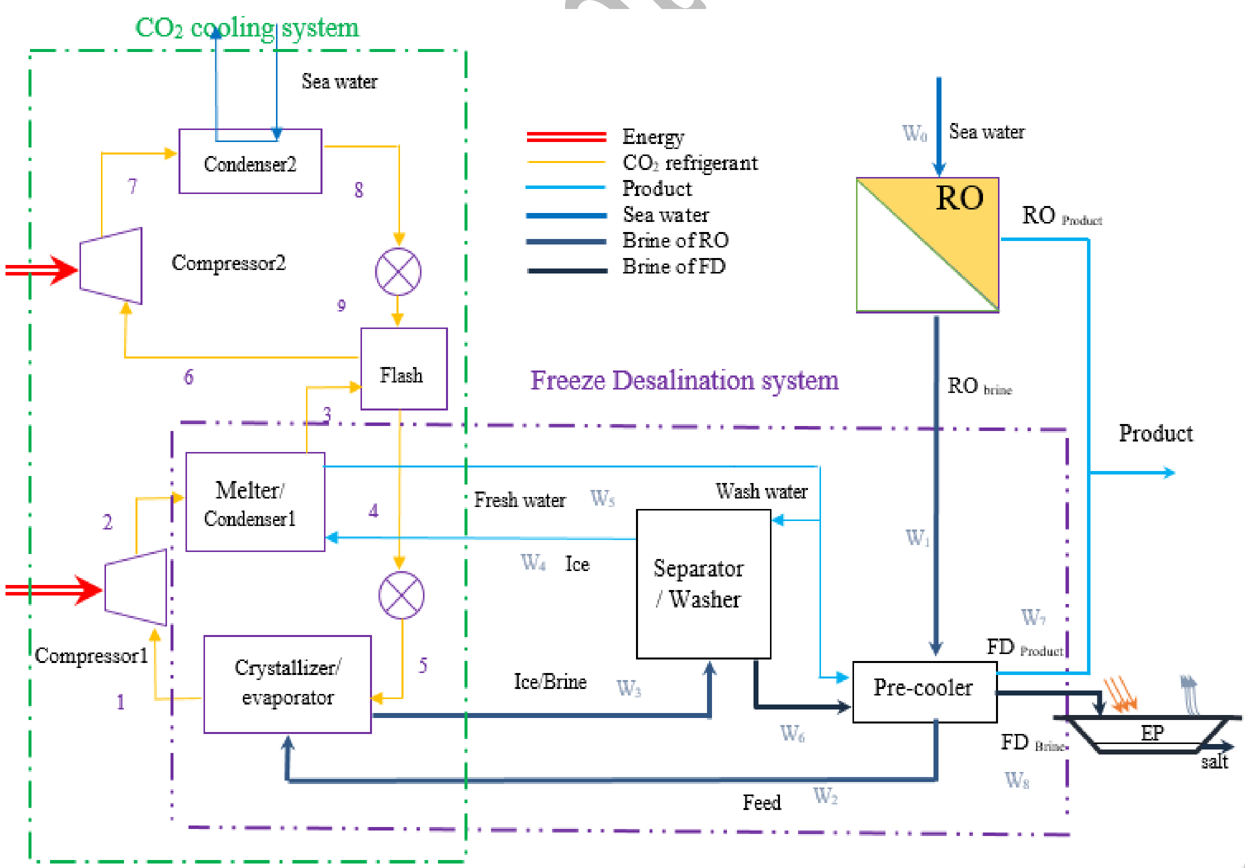


Fig. 2 Schematic layout of RO-FD-EP integrated with CO_2 cooling system

SYSTEM ANALYSIS

The governing equations and thermodynamic relations are provided to analyze the hybrid system. The following assumptions are made in order to simplify the system analysis:

- The system runs in a steady state;
- In heat exchangers and pipes, pressure drops and heat transfer loss are ignored;
- The expansion valve throttling process is isenthalpic;
- Heat transfers in compression processes are negligible;
- The dead state was taken as the environmental conditions (with ambient temperature of T_o = 25 °C and pressure of P_o = 1 bar).
- The evaporator temperature of each effect is 5°C lower than the feed water freezing point of that FD effect;
- The temperature of condenser I and II are 5°C higher than the melting temperature in the melter and seawater temperature.
- Full refrigerant condensation at the condenser exit and complete evaporation at the evaporator exit
- Neglect tubing pressure drops between the components.
- The constant density applies to saline water, salt, and freshwater.

Based on the above assumptions, the system is developed based on the steady-state mass and energy balances for solving state point parameters in the cycle. The general forms of conservation principles for each component are as follows [16, 17]:

Table 1 provides the guiding equations of the CO_2 cooling cycle.

Table1. Thermodynamic equation utilized in cooling CO_2 system

$\mathbf{Q_{eva}} = \dot{\mathbf{m}}_{\mathbf{co_2}}(\mathbf{h_{in}} - \mathbf{h_o})$	**The equation of energy balance for evaporators**	**(4)**
$\mathbf{W_{com.ID}} = \dot{\mathbf{m}}_{\mathbf{co_2}}(\mathbf{h_{ID.o}} - \mathbf{h_{in}})$ $\boldsymbol{\eta}_{\mathbf{com,is}} = \mathbf{0.93 - 0.44 * PR}$ $\boldsymbol{\eta}_{\mathbf{com}} = \frac{\mathbf{W_{com.ID}}}{\mathbf{W_{com}}}$	**The equation of energy balance for compressors [17]**	**(5)**
$\dot{\mathbf{m}}_{\mathbf{co_2}}(\mathbf{h_{in,1}} - \mathbf{h_{o,1}}) = \dot{\mathbf{m}}_{\mathbf{2.co_2}}(\mathbf{h_{in,2}} - \mathbf{h_{o,2}})$	**The equation of energy balance for the flash tanks**	**(6)**
$\mathbf{h_{in}} = \mathbf{h_o}$	**The equation of energy balance for expansion valves**	**(7)**
$\mathbf{Q_{cond}} = \dot{\mathbf{m}}_{\mathbf{co_2}}(\mathbf{h_{in}} - \mathbf{h_o})$	**The equation of energy balance for condensers**	**(8)**

The governing equations of the RO desalination are given in Table 2.

Table2. Equations governing the RO desalination

$\boldsymbol{\pi} = \frac{\boldsymbol{vRTX_s}}{\boldsymbol{v_w}}$	***The osmotic Pressure***	***(9)***
$\boldsymbol{J_w} = \boldsymbol{A} \times (\Delta\boldsymbol{P} - \Delta\pi)$	***Water Flux***	***(10)***

$E = \frac{v\Delta P}{\eta_p}$	***Pump Efficiency***	***(11)***

Mass and energy conservation equations are utilized to evaluate the performance characteristics of freeze desalination; the controlling equations are provided in Table 3.

Table 3. Thermodynamic relations in freeze desalination

$\mathbf{D_F = D_{CRY} + D_{F.C}}$ $\mathbf{X_F D_F = X_{CRY} D_{CRY} + X_{F.C} D_{F.C}}$	**The equations of mass balance in the crystallizer**	**(12)**
$\mathbf{Q_C = D_{fF} C_{p.F}(T_{C1} - T_{F.P}) + D_{CRY}\Delta H_F}$ $\mathbf{Q_C = Q_{sensible} + Q_{latent}}$ $\mathbf{D_{CRY} = F_s D_F}$	**Heat amount to be removed from the crystallizer**	**(13)**
$\mathbf{\Delta T_F = -9.66E^{-2} C_L - 5.2E^{-6} C_L}$ $\mathbf{S = 1.8147 C_L}$	**The freezing point depression [18]**	**(14)**
$\mathbf{X_{CRY} D_{CRY} + X_{F.C} D_{F.C} + X_{Wash} D_{Wash} = X_P D_P + X_B D_B}$ $\mathbf{D_{Wash} = 0.5 D_P}$	**The equations of mass balance in the separation column**	**(15)**
$\mathbf{D_P = D_{CRY} + D_{IMP}}$ $\mathbf{X_P D_P = X_{CRY} D_{CRY} + X_{IMB} D_{IMB}}$	**The equations of mass balance in the melting chamber**	**(16)**
$\mathbf{Q_{melt} = D_{IMB} C_{IMB}(T_{melt} - T_C) + D_{CRY}\Delta H_F}$	**The heat amount to be melted**	**(17)**
$\mathbf{D_F C_{P.F}(T_{F.P} - T_F) + D_B C_{P.B}(T_P - T_C) + D_P C_{P.B}(T_P - T_{Cmelt}) = 0}$	**The equations of mass balance in the pre-cooling heat exchanger**	**(18)**
$\mathbf{W_{ADD} = 0.15 W_{comp}}$ $\mathbf{W_{total} = W_{comp} + W_{ADD}}$	**Additional power [4]**	**(19)**

Hypersaline brine from the hybrid desalination is sent to an evaporation pond to convert the brine to potable salt crystals. Evaporation ponds work by converting the water in the pond into vapor in the atmosphere just above. The larger the surface area, the greater the evaporation rate. The evaporation rate from the pond determines the size of the evaporation pond size. E_v represents the water evaporation flux, which depends on the difference between the water surface's vapor pressure and the water vapor's partial pressure in the air (Δp_{EP}). Salinity negatively affects the evaporation rate. The salinity factor determines the evaporation rate from saline water (Esal). The area of the evaporation pond was calculated based on the law of conservation of mass in the pond so that the amount of brine entering the pond is equal to the evaporation of water. Relations are presented in Table 4.

Table4. Equations governing the solar evaporation pond

$E_v = (232.5 + 101V_w)\Delta P_{EP}$	***Evaporation rate of freshwater [19]***	***(20)***
$FE = 1.025 - .0246e^{.00879*X}$ $FE = \frac{E_{sal}}{E_v}$	***Salinity factor [20]***	***(21)***

This study's results regarding specific energy consumption (SEC) based on water production are presented. While the first law focuses on the quantity of energy, the second law analysis (exergy analysis) introduces quality and quantity [22]. The exergy efficiency (η_{exe}), on the other hand, provides more detailed thermodynamic insights. In a specific state, the exergy efficiency of the system represents the maximum work that can be extracted through interactions with its surroundings to attain thermal, mechanical, and chemical equilibrium. The condition wherein the system achieves equilibrium with its surroundings is called the dead state (Table 5) [23]. Relations are presented in Table 5.

Table 5. Equations applied for the optimization model

$SEC = \frac{W_{total}}{D_{product}}$	***The SEC of the desalination system***	***(22)***
$\eta_{exe} = \frac{E_p}{E_F} * 100$ $E_p = m_p e_p$ $E_F = w_{tot} + m_F\, e_F$	***The exergy efficiency of hybrid desalination***	***(23)***

THE MODEL VALIDATION

Since the proposed hybrid system of this study has not been simulated before, to validate the simulation and the results, a freeze desalination system was used for comparison. The outcomes of the freeze desalination system are compared to Ref. [24] to guarantee the correct operation and calculation in this study. Elrahman et al. [24] proposed exergy analysis for different operational parameters of a freeze desalination cycle; the proposed system gave higher thermal efficiency than alternative desalination systems such as reverse osmosis. The studied system and the system presented by [24] are compared; the effect of F_s on Brine salinity is illustrated in Fig. 3, and reverse osmosis desalination was not considered since only freeze desalination was studied. They assume that the ice fraction (F_s) varies between 0.3 and 0.8. Brine salinity is a function of F_s and the salt concentration in the feed water. The brine salinity parabolically increases as Fs rise; good agreements between the compared systems are observed.

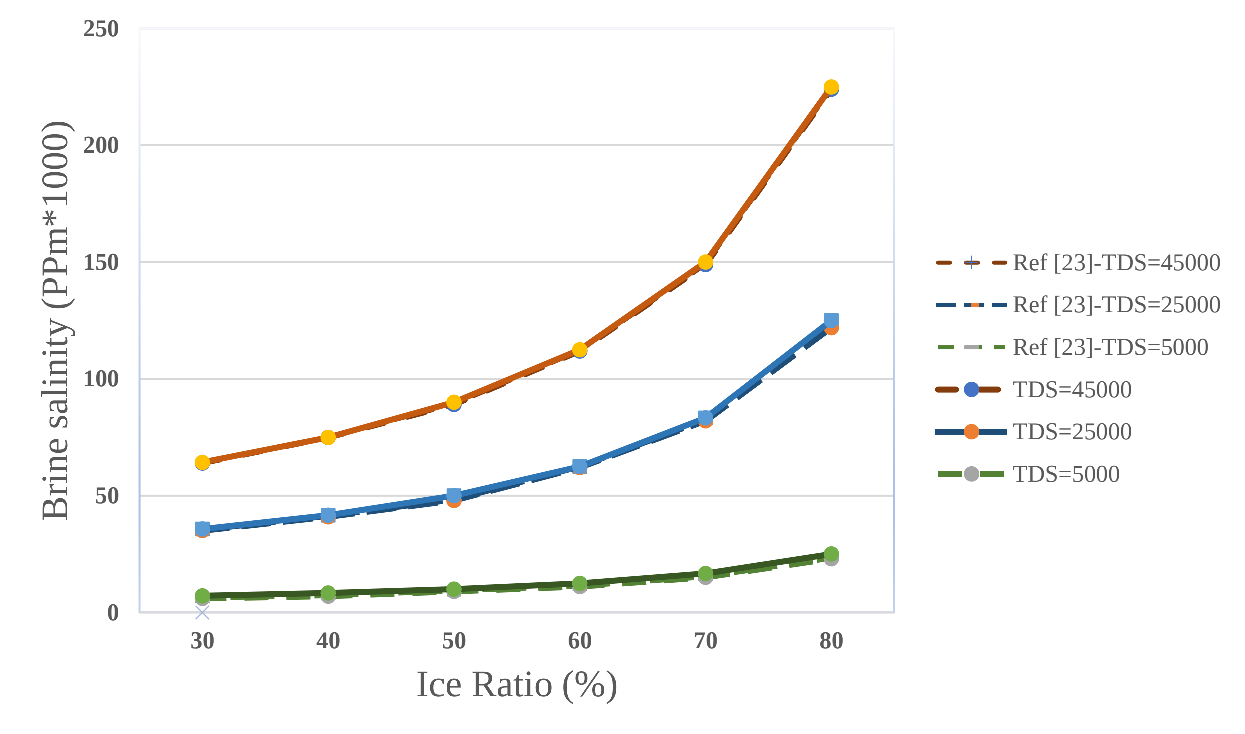


Fig.3 The effect of F_s on the brine salinity in reference [23] and the present research

RESULTS AND DISCUTIONS

The conditions applied in hybrid desalination are listed in Table 6. For thermodynamic analysis of the system, EES software was utilized for solving a set of equations for various operating conditions.

Table 6. Basic operating parameters

Operating value	*value*	*Operating value*	*value*
Seawater salinity (ppm)	*35000*	*Capacity (m^3/d)*	*700*
Seawater temperature (ºC)	*20*	*FD product salinity (ppm)*	*220*
Ambient temperature (ºC)	*25*	*Product temperature (˚C)*	*20*
Pressure difference (kPa) [24]	*5*	*Wind velocity (m/s) [24]*	*2*

A comparison analysis of hybrid desalination and reverse osmosis desalination configurations is presented in Table 7. According to the data, the RO-FD performance improvement is more significant compared to the other configurations in decreasing energy consumption; also, the results show that the exergy efficiency of the RO-FD system is maximum. Further, the SEC of RO-FD is higher than the conventional RO system; this could be explained by increased consumption work. When the recovery ratio rises, the minimum energy of desalination systems gets higher. Since the amount of discharge brine has decreased and the salt concentration in the brine has increased, evaporation ponds can be used for this hypersaline brine. The hybrid RO-FD could decrease the quantity of rejected concentrated brine from current RO brackish water plants by more than 70% (recovery ratio of 50%). Further, the area of the evaporation pond of RO-FD decreases by 58% compared to RO alone.

Examination of the data in Table 5 shows that RO-2EFD system, although increases the recovery and decreases the volume of brine, but increased the energy required and decrease exergy efficiency, which is not desirable.

Table 7. Comparison analysis of hybrid desalination configurations

Configurations	***Recovery (%)***	***Brine salinity (ppm)***	***SEC (kWh/m³)***	η_{exe} ***(%)***	***Area of evaporation pond (m²)***
RO	***50***	***69000***	***4.9***	***15.7***	***78000***
RO-FD	***70***	***116000***	***7.57***	***10.9***	***34000***
RO-2EFD	***82***	***194000***	***15.44***	***5.02***	***31000***

Given that the hybrid RO-FD system performs better, the effect of solid ice fraction in a crystallizer, feed water temperature and RO brine salinity on the critical parameters of the RO-FD desalination system and evaporation pond is investigated.

Solid Ice Fraction Effect

Assuming that the solid ice fraction (F_s) varies between 0.2 and 0.6. Fig. 4a illustrates the impact of F_s on the crystallizer's brine salinity and freezing temperature. The brine salinity proportionately increases as F_s rises, while the freezing temperature reduces by increasing Fs because the salinity in the remaining solution increases, reducing the freezing temperature. Fig. 4b shows that with the increase of F_s, the quantity of ice made in the crystallization rises, and the removed heat from the crystallizer (Q_{eva}) increases; that is because as F_s increases, the latent heat term increases while the sensible heat term remains constant. Thus, the whole quantity of heat released increases, causing an increase in W_{com}, possibly because more feed must be treated in the crystallizer when the Fs is higher.

Also, with the increase of F_s, according to Fig. 4a, the temperature of the evaporator decreases, which increases the pressure ratio in the compressor, which increases the W_{com}. Fig. 4c shows the SEC and η_{exe} variation with the F_S in the crystallizer; by increasing F_s, SEC increases and η_{exe} reduces. The increase in SEC is due to the increase in the power consumption of the compressor. The exergy efficiency rises with a lower F_s, even though the amount of product water is marginally affected by the F_s; this is exergy output. The exergy consumption (the denominator of equation 22) consists of two parts: feed exergy (m_f*e_f) is constant, and W_{com} is higher at a higher F_s, translating into further exergy consumption that is more than exergy output. A higher F_s translates into less exergy efficiency for the hybrid system. Fig. 4d shows the effect of the F_s on the evaporation rate and the area of the evaporation pond; by increasing Fs, the salinity of brine increases, thus decreasing the evaporation rate (relation 21). As F_s rises, the amount of brine of hybrid desalination decreases, thus decreasing the area of the evaporation pond.

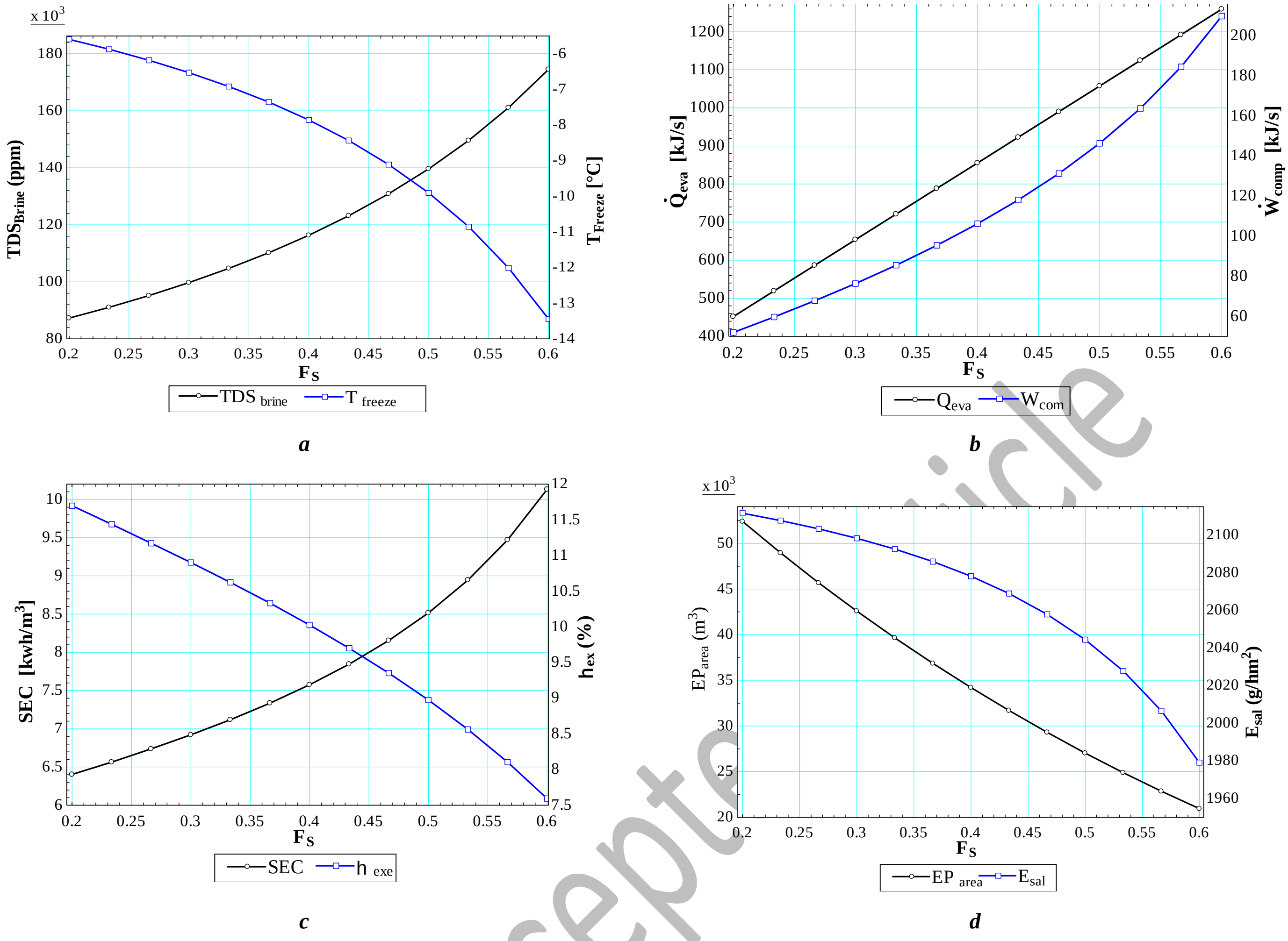


Fig. 4 The effect of F_s on a) brine per feed and brine salinity, b) Q_{eva} and W_{com}, c) SEC, d) η_{exe}

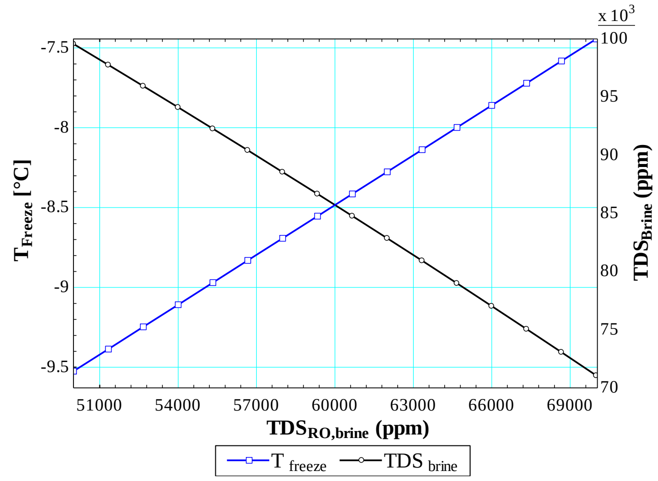
Effect of RO Brine Salinity

Assume that the salinity of RO brine (feed of FD) varies between 50000 and 70000ppm. Fig. 5a shows the effect of the RO brine salinity on freezing temperature and brine salinity of hybrid desalination. It indicates that the freezing temperature falls once the salt concentration rises (according to relation 14). The hybrid RO-FD's brine salinity increases as RO brine salinity increases due to the same recovery.

As seen in Fig. 5b, heat consumption in the crystallizer (Q_{eva}) increases with an increase in the feed concentration of FD. That is because as the salinity of RO brine increases, the freezing temperature in the crystallizer increases, resulting in latent heat term increases. Thus, the whole quantity of heat released increases with the feed concentration of FD.

Also, as the salinity of freeze desalination (RO brine) feed water increases, the freezing temperature decreases, increasing the required work by the compressor. A lower freezing temperature raises the PR value in the compressor, which raises its required work.

Fig. 5c shows the effect of RO brine salinity on SEC and η_{exe}, indicating that increasing the compressor's required work (a deduction in the SEC formula) increases the SEC. The exergy efficacy is higher in a lower RO brine salinity. This is because W_{com} is lower in a lower feed salinity, translating into less exergy consumption. Fig. 5d shows the effect of the salinity of RO brine on the evaporation rate and evaporation pond area. Increasing RO brine's salinity increases hybrid desalination's brine salinity (according to Fig. 5a). Thus, the evaporation rate decreases according to the salinity factor; the evaporation rate is negatively affected by TDS. As the evaporation rate decreases, with the same amount of brine, the area of the evaporation pond rises.



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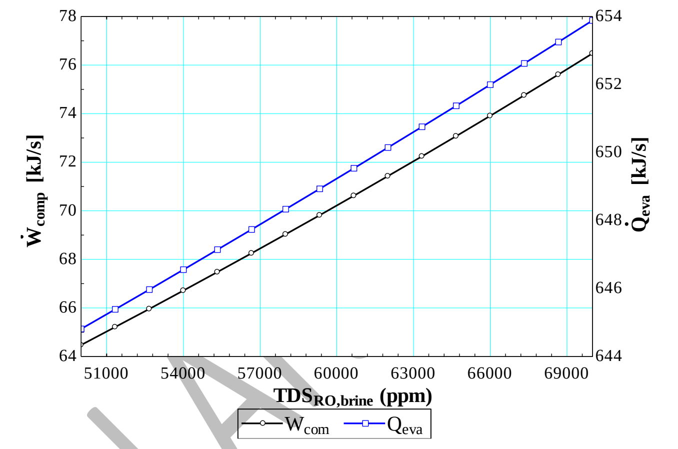

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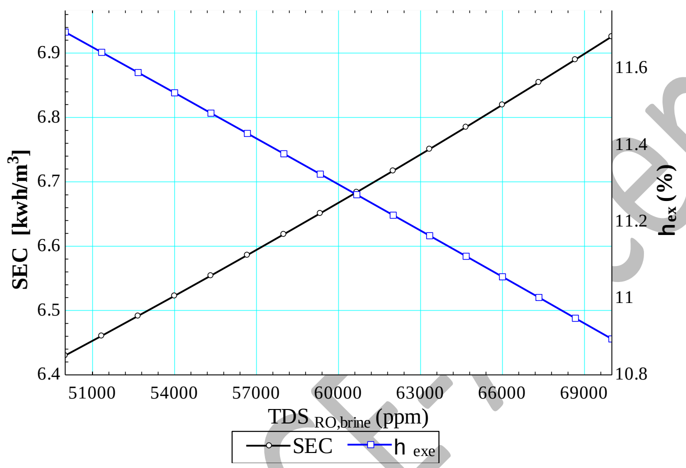

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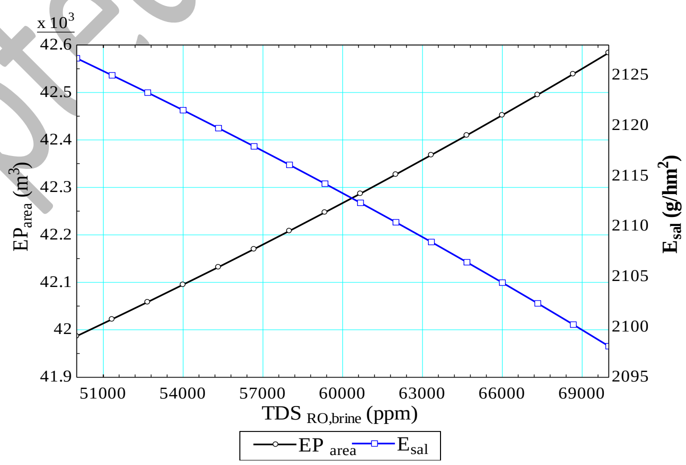

d

Fig. 5 The effect of salinity of RO brine on the a) T_{freeze} and brine salinity, b) Q_{eva} and W_{com}, c) SEC and η_{exe}, d) EP_{area} and E_{sal} ppm*10^3

Feed Water Temperature Effect

The feed temperature effect on the required work by the compressor is illustrated in Fig. 6a. Increasing the feed water temperature increases the needed work by the primary compressor, and the required work by the second compressor rises owing to the rise in heat recovery temperature in the secondary condenser. As seen in Fig. 6b, as the temperature of the feed water rises, The COP decreases because heat removed from the crystallizer (Q_{eva}) rises, as well as the required work of the compressor, leading to a decrease in COP; on the other hand, at any F_s, the temperature of the feed water has a noticeable effect on the energy consumed as it increases the sensible heat required to reduce the supply water temperature up to the freezing point with the constant ice latent heat. Thus, when increasing water temperature, the total amount of heat removed increases directly.

The effect of feed temperature on the SEC is shown in Fig. 6c. Increasing the feed water temperature increases the SEC by increasing the energy needed in the evaporator (the sensible heat required) and raising the work needed by the second compressor. With the increase in feed temperature, the temperature of the second condenser decreases, which increases the pressure ratio in the second compressor, which increases the W_{com}. Thus, the SEC increases with increasing the feed temperature.

The effect of feed temperature on the η_{exe} is shown in Fig. 6d; η_{exe} is higher under a lower T_{feed}. This is because the exergy consumption (W_{com}+ m_f e_f) is higher at a higher T_{feed}, translating into further exergy consumption. A higher T_{feed} translates into less exergy efficiency for the hybrid system.

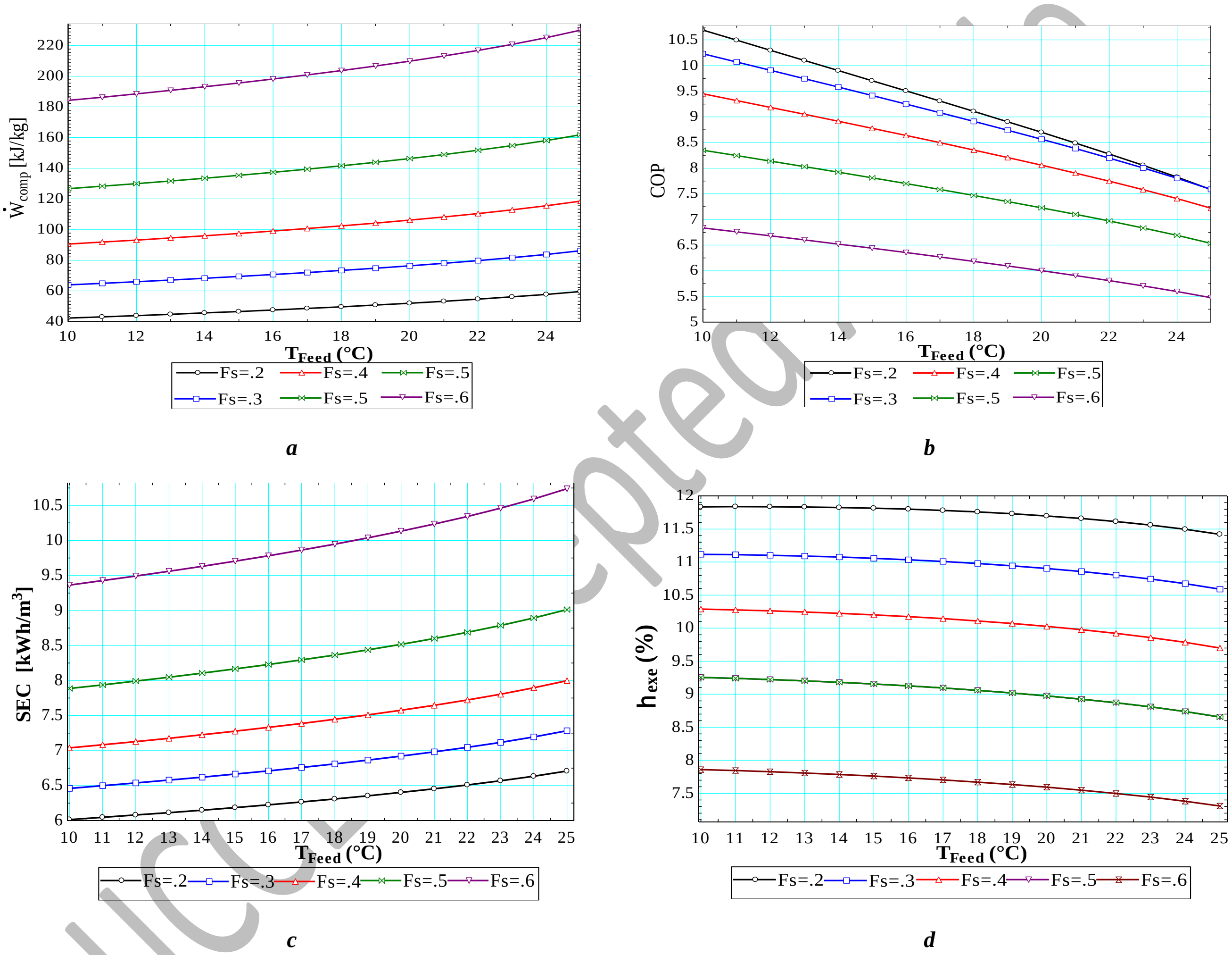

Fig. 6 The effect of T_{feed} on the a) W_{com}, b) COP, c) SEC, d) η_{exe}

The resolution of mass and energy balance equations of hybrid RO-FD gives results summarized in Table 8. This table represents flows, salinity, temperatures, and heat quantity.

Table 8. Results of mass and energy balances calculation related to the RO-FD system

Rate of flow (m^3/d)		***Salinity (ppm)***		***Temperature (˚C)***		***Heat quantity (MJ/m^3)***	
$D_{F,RO}$	**1000**	$X_{F,RO}$	**35000**				
$D_{P,RO}$	**500**	$X_{B,RO}$	**69000**	T_F	**20**		
$D_{B,RO}$	**500**	$X_{P,RO}$	**140**	T_C	**-4**	Q_C	**102**
$D_{F,FD}$	**500**	$X_{F,FD}$	**69000**	T_{melt}	**0**	Q_{melt}	**95**
$D_{P,FD}$	**200**	$X_{P,FD}$	**220**	T_P	**20**		
$D_{B,FD}$	**300**	$X_{B,FD}$	**116000**				

CONCLUSION

The hypersaline brine originating from conventional desalination is a primary environmental concern. The present research proposes a hybrid desalination system and a freezing desalination system is used for treating RO brine. Hypersaline brine from the hybrid desalination is sent to an evaporation pond to be converted to potable salt crystals. Three configurations of desalination systems involving RO, RO-FD, and RO-2EFD are compared. The data show that the SEC and second-law efficiency of the RO-FD system, respectively, is lower and higher than the two other hybrid desalination systems. Thermodynamic analysis show that the hybrid RO-FD decreases the amount of hypersaline brine and the area of evaporation, respectively, by approximately 40% and 45% and can increase recovery by about 30% compared with RO alone. The hybrid RO-FD process's specific energy consumption and Second-law efficiency are 6–12 kWh/m^3 and 7–12 %. For the further scope of the work, the economic analysis of the system is suggested.

NOMENCLATURES

B	— Brine	T	— Temperature, ˚C
F	— Feed	p	—Pressure, kpa
Cry	—Crystallizer	C_p	—Specific heat, kJ/kgK
P	— Product	h	—Specific enthalpy, kJ/kg
F, C	— Non-crystallized	in	—Input
F, P	— Feed out of pre-cooler	o	—Out
Imb	—Imbibitions	PR	—Pressure ratio of the compressor

Sens	—Sensible	Q	— Heat quantity, kW
lat	—Latent	W	—Power, kW
F_s	—Solid ice fraction	Melt	—Melter
C_l	—Chlorinity of seawater	Cond	— Condenser
x	—Salinity, g/l	Eva	—Evaporator
S	—Salinity percentage %	Com	—Compressor
m	—Mass flow rate, kg/s	η	—Efficiency
ppm	—Particle per million	ex	—Exergy
FD	—Freeze desalination	E_D	—Exergy destruction
RO	—Reverse osmosis	VW	—Wind velocity,m/s
ΔP	—Transmembrane pressure, kpa	FE	—Salinity factor
Δπ	—Transmembrane osmosis pressure, kpa	TDS	—Total dissolved solids
J	—Mass flux through the membrane in RO	E_v	—Rate of evaporation of freshwater
COP	—Coefficient of performance of the cooling cycle	E_{sal}	—Rate of evaporation of saline water
SEC	—The specific energy consumption, kJ/kg	ΔP_{EP}	—Pressure difference on the surface of the evaporation pond, kpa

DECLARATIONS

Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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