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Exergy and thermo-economic analysis of solar thermal cycles powered multi-stage flash desalination process

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ABSTRACT

Solar thermal power cycles assisted multi-stage flash brine recycle (MSF-BR) distillation process are thermo-economically analyzed and evaluated. In this work, the analyses are compared according to three different configurations via two techniques of solar thermal power cycles. The first technique is considered for only desalination process; however, the second is considered for desalination and electric power generation via organic Rankine cycle. Solar parabolic trough concentrator (PTC) field is considered to dominate sufficient thermal power for MSF plant. Water steam working fluid is used for a direct vapor generation (DVG); however, Therminol-VP1 working substance is used for an indirect vapor generation (IDVG) through the PTC field. Moreover, the optimized configuration from the first technique is compared with the power generation and desalination (the second technique). The comparisons are proceeding for the MSF-BR desalination plant with total productivity in the range of 5,000m^3/d which the gain ratio is increased up to 12 with 40 stages. The thermo-economic results reveal that first technique achieves remarkable results related to the PTC area, the SPC, kWh/m^3, and the thermo-economic product cost, $/GJ.

Keywords: Solar organic Rankine cycle; Thermo-economic; MSF-BR

1. Introduction

The water problem in the Mediterranean region is not limited to the shortage but is being extended to the low quality of water and its conversion to non-consumption purposes for specific reasons. These countries usually have abundant seawater resources and a good level of solar radiation, which could be used to produce drinking water from seawater. Although everybody recognizes the strong potential of solar thermal energy to seawater desalination, the process is not yet developed at the commercial level [1]. Cost-effective desalination, and particularly solar-powered desalination technology, can play an important role toward helping to solve the water supply problems of this region and other regions of the world [2]. Among different kinds of thermal desalination processes, multi-stage flash (MSF) evaporation process is the powerhouse of the desalination industry. MSF process has also a possibility for use with solar thermal power. Operating conditions of multi-stage flash distillation systems allow the use of different solar collectors in solar powered plants [3]. The solar MSF desalination system tested in Kuwait [4] with a

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capacity of a 10 m^3/d consisted of a 220 m^2 parabolic trough collector, and a 12-stage MSF desalination system. The thermal storage system was used to level off the variation of thermal energy supply and allowed the production of fresh water to continue during periods of low radiation and night-time. The output of the system is reported to be over ten times the output of solar stills for the same solar collection area (about 40 kg/m^2). Sharaf et al. [5,6] examined a small unit for water desalination by solar energy and flash evaporation process. The system was built to produce an amount of 20 kg of distillate water during the daylight by the using of solar flat plate collector (FPC). Garcia-Rodriguez [7] concluded that the use of solar energy could compete with a conventional energy supply in MSF distillation processes in some climatic conditions.

Moreover, the possible effect of future parabolic trough concentrator (PTC) cost reductions and conventional energy cost increasing in the competitiveness of solar energy in MSF plants is remarkable. Results obtained in Garcia-Rodriguez [7] work were useful in competitiveness evaluations of solar vs. conventional energies in MSF plants. Furthermore; several low-capacity plants for MSF desalination using solar energy have recently been implemented. Block [8] found that solar-powered MSF plants can produce 6–60 kg/m^2/day, in comparison with the 3–4 kg/m^2/day typical of solar stills. MSF could become the most widely used desalination process with solar energy in terms of capacity. This is due to the simplicity of the process, performance characteristics, and scale control [9].

Top brine temperature range makes the MSF relatively unsuitable for solar energy applications unless a storage tank is used for thermal buffering [9]. Table 1 shows the indirect solar desalination pilot plants that implemented at different locations. It is clear from the literature that the possibility of utilizing solar energy with different types of distillation processes such as MSF already exists. However; such combination is with a market share about 6% compared against Photovoltaic-Reverse Osmosis (PV-RO 32%) [10].

Moreover, the implemented configurations are performed for low capacities. In this work, exergy and thermo-economic analyses are performed for powering MSF-BR configuration with a capacity of 5,000 m^3/d using solar energy. The analysis is presented in order to give a clear decision-based exergy and cost about the feasibility of combining between the MSF thermal process and the solar thermal power cycles-assisted large-scale MSF desalination process. Two different techniques are compared and thermo-economically analyzed in this work: The 1st technique utilizes the solar energy with the help of the parabolic trough concentrator (PTC). The 1st technique itself has two different configurations concluded as the direct vapor generation (DVG) via water-steam working fluid and indirect vapor generation (IDVG) which uses the Therminol-VP1 working fluid via boiler heat exchanger (BHX) intermediate unit between the solar field and the brine heater (BH). The 2nd technique is to combine the MSF brine heater with solar organic Rankine cycle (SORC) in order to generate electricity via the turbine to the main grid thence the exhaust steam would power the MSF. The aim of this work may be concluded into the following points:

- SDS [16] software package is utilized in this study in order to give the data results related to the proposed cycles.
- Exergy and thermo-economic analyses are presented for such combination between solar thermal power cycles and MSF thermal desalination process.
- Investigations are performed for large-scale MSF-BR (5,000 m^3/day).
- Optimization on desalination part comes first in order to save costs for the solar part. Therefore, a new characteristic of the MSF-BR section is maintained to increase the gain ratio of the system thence reducing the whole system thermo-economic and unit product costs ($/GJ and $/$m^3$).

Table 1
Some of indirect solar desalination pilot plants implemented at different locations

Desalination process type	Location	Capacity	Type of power	Reference
MSF	Safat, Kuwait	10 m^3/day	Solar collectors	[11]
MSF	Berken, Germany	10 m^3/day	–	[12]
MSF	Gran Canaria, Spain	10 m^3/day	Low concentration solar collectors	[13]
MSF	Lampedusa Island, Italy	0.3 m^3/day	Low concentration solar collectors	[13]
MSF	La Paz, Mexico	10 m^3/day	Parabolic trough collectors	[14]
MSF	Kuwait	100 m^3/day	Parabolic trough collectors	[15]

2. Overview of the REDS-SDS package

REDS is a software package for renewable desalination systems. Solar desalination systems (SDS) are a library part of the REDS software package that has been created and developed by Sharaf [16–20]. SDS library contains two main categories: (a) Solar thermal powered desalination; and (b) Solar electrical powered membranes. For thermal section, the library contains different types of solar collectors such as CST, PTC, CPC, and FPC. Also, it contains pumps, storages, and heat exchangers. Furthermore, SORC and solar combined cycle (SCC) take an important part through the thermal section. Therefore, condensers, boiler heat exchangers (BHX), pumps, and expanders are modeled, stored and simulated. Thermal section of the SDS library is approved for many configurations as introduced by Sharaf et al. [16–21]. Moreover, the solar field is modeled for many configurations such as direct and indirect vapor generations with the utilization of many of working fluids (toluene, molten salt, steam, oils, Freon's, etc.). For solar electrical section, a PV system is modeled and introduced.

It is proposed that by identifying the output power from the system application (example of reverse osmosis desalination plant); the design limits would be calculated. The PV application is modeled for membrane reverse osmosis (RO) and the calculations of solar building loads. Fig. 1 shows the library browser of the SDS library under MatLab/SimuLink program. The library is embedded in the SimuLink/MatLab tool box. User can easily open a new model browser window, drag and drop the selected unit, and then double clicking on the unit in order to specify some input parameters (related to design a type of simulation). Also, the designer or the user has the ability to construct any proposed system by dragging the needed units, thence using the ultimate stream allowance by the use of SimuLink tool box to connect all units together. The user has the ability to run out all physical properties (temperatures, pressures, enthalpies, entropies, etc.) and all data types such as energy, exergy, cost and thermo-economic. SDS-REDS library has some features such as:

- Including a visual library of several and different models thermal units used for CSP power generation.
- Thermal desalination plants (MSF, MED, MED-TVC, MED-MVC) are thermo-economically modeled and stored as a ready model for any designer to use with friendly interface.
- The PV power system is modeled for membrane RO desalination plants.

In this work, SDS-thermal part is utilized for the proposed techniques and configurations. MSF-BR type, pumps, condensers, PTC, BHX, and Rankine cycle components are dragged from the REDS-SDS

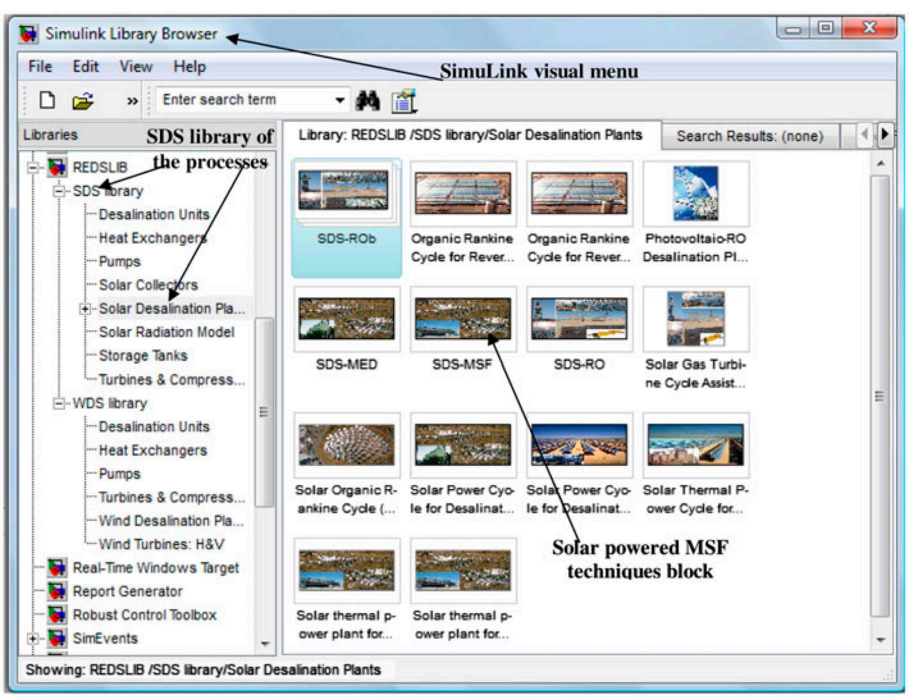

Fig. 1. The library browser of SDS software package under MatLab/SimuLink program as a part of REDS package.

library to run out the considered techniques. Moreover, different working fluids are used throughout this study.

3. Solar thermal power for MSF-BR (techniques and process description)

In this part, solar energy is assisted MSF-BR based on two proposals techniques; the 1st is to utilize solar thermal power from the solar field directly to the brine heater unit (DVG). Water steam is used as a main working fluid through the solar field. The 2nd is to utilize the solar thermal power to operate the MSF-BR via heat exchanger unit as a pre step before the brine heater unit (IDVG). In such case, Therminol-VP1 is used as heat transfer fluid through the solar field. The following subsections present the process description and the design points for MSF process, solar power cycle and design considerations for each technique.

3.1. MSF-BR process considerations

Success of MSF is mainly due to its simple layout and reliable performance over the years. Although the MSF process as well as the MED process consumes a larger amount of energy than the RO process, however, the reliable performance of the thermal desalination processes MSF and MED made highly competitive against the RO process [22]. Current commercial installations are designed with 10–30 stages (2˚C temperature drop per stage). Before coupling with solar power cycle, MSF improvements should be studied well. Previous studies indicated that the parametric analyses showed that MSF processes could be improved towards high performance and gain ratios by increasing the top brine temperature, number of stages and the specific heat transfer area. First, the role of the number of stages in the performance of the plant has been analyzed by Rosso [23]. As expected, increasing the number of stages yields an improvement in process performance. However, it is worth noticing that this improvement is due to the simultaneous increase of the product distillate flow rate and decrease of the steam flow rate. It is evident that while designing an MSF plant, the number of stages must be chosen as a compromise between fixed costs, which increase when increasing the number of stages, and variable costs, which decrease when increasing the number of stages. One of the most important parameters in desalination process control is the temperature of the heating steam. Moreover, the brine heater effectiveness should be maintained at reasonable values almost not less than 30–40%. In this work, the process is studied for 5,000 m^3/d desalination plant with a change in total number of stages (increased up to 40 stages) with an increasing in TBT ˚C from normal value (110˚C) to become 130˚C. During winter operation, it is expected that the brine blow down from the last stage reaches around 30–35˚C while the sea water temperature is in the range of 20–27˚C. The main plant characteristics and design points are illustrated in Table 2.

3.2. Solar thermal power cycle techniques

3.2.1. Solar desalination without power (DVG & IDVG)

In this part, there are three possible configurations that are mentioned in this work. Configuration (a) includes solar field (PTC), Brine heater (BH), MSF-BR, and pump unit. Saturated steam is directly generated from the solar field toward the BH which will raise the seawater temperature to TBT. The condensed steam (saturated liquid) will pumped again through the solar field. The pump unit is introduced to overcome the pressure losses across the solar field. This

Table 2
Main specifications for MSF-BR desalination plant (5,000 m^3/d)

Design point	New characteristics	Eoun Mousa [24]
Top brine temperature (TBT), ˚C	90–135	110
Brine blow down temperature, ˚C	34.5	40
Feed seawater temperature, ˚C	28.67	27
Cooling water splitter ratio	0.42	0.42
Sea water salinity, ppm	47,300	48,620
Tube outside diameter (brine heater), m	0.02199	0.02199
Tube outside diameter (heat recovery), m	0.01299	0.01299
No. of stages	40 (37/3)	20 (17/3)
Recirculation pump efficiency, %	75	–

type of operation is named as direct vapor generation (DVG). The specifications for configuration (a) are summarized as follows:

- Direct normal irradiance under winter operating conditions is assumed for Egypt and Mediterranean countries. It is estimated that the daily average global radiation in a typical day in the winter would be in the range of 21–22 MJ/m^2. To dominate long operation along the daylight, the solar radiation would be estimated and fixed at 352 W/m^2 (21.4 MJ/m^2 ≈ 503.7 W/m^2 hourly average ≈252–352 W/m^2 daily average) [17,18]. However, under summer conditions, it will be expected that there is an excessive energy due to the large field area and it might be handled through bypassing some loops in the solar field for maintenance operation.
- Collector outlet temperature is fixed as 135˚C (upper than TBT by 5–6˚C) putting into consideration the brine heater (BH) effectiveness.
- Pump efficiency is assigned as 75%.
- Water working fluid is used through the solar field.
- MSF-BR characteristics are presented in Table 2.
- PTC configuration and design specifications are adjusted according to the LS-3 type [17,25].
- Fig. 2(a) shows a schematic diagram of the configuration (a).

For IDVG of operation, Therminol-VP1 heat transfer oil (HTO) is used through the solar field. Boiler heat exchanger unit (BHX) is used as a previous step before the brine heater unit. The HTO is a transfer medium to transfer the thermal power for the brine heater. One of the advantages of using the HTO is the stability range of operation; furthermore, it works as the liquidized medium avoiding the steam problems. Moreover, HTO is considered a storage medium for power generation during sundown's operation. The specifications for this configuration (b) are summarized as follows:

- Solar radiation is adjusted at 352 W/m^2 (see reference [17,18]) as a typical daily average value for winter operation in Egypt and the ambient temperature is about 20˚C.
- Collector outlet temperature is fixed at 350˚C.
- Brine heater top steam temperature is maintained at 135˚C (upper than TBT by 5˚C).
- Pump efficiency is assigned as 75%.
- Water steam working fluid is used through the BHX and BH units.
- MSF-BR characteristics are presented in Table 2.
- PTC configuration and design specifications are adjusted according to the LS-3 type [17,25].
- Fig. 2(b) shows a schematic diagram of the configuration (b).

3.2.2. Solar desalination and power (IDVG)

This technique consists of pumps for circulation and pressure drops, solar collector field (PTC), BHX unit, turbine expander unit, condenser BH unit, and MSF-BR unit. Fig. 3 shows a schematic diagram of the process units for the 2nd technique (solar Rankine cycle). The specifications for this technique are summarized as follows:

- The operating conditions are set and considered as the same as the previous technique.
- Collector outlet temperature is fixed at 350˚C.
- Brine heater top steam temperature is maintained at 135˚C (upper than TBT by 5˚C).
- The inlet turbine condition is set as 300˚C.
- Pumps and recuperator efficiencies are assigned as 75 and 80%, respectively.

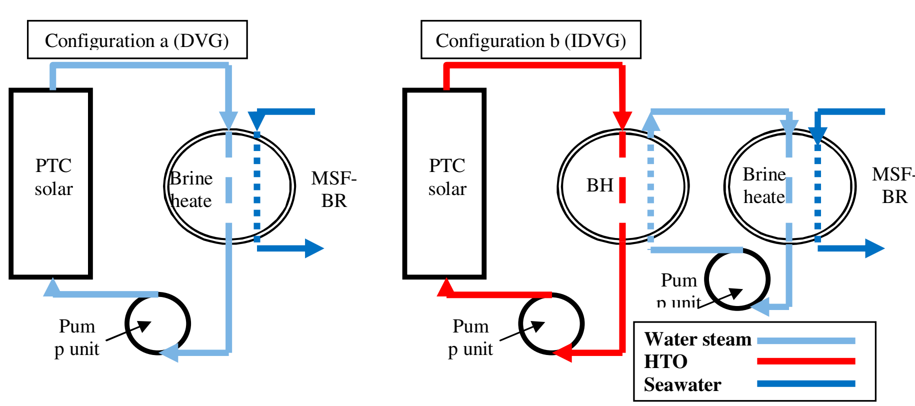

Fig. 2. The 1st technique with different configurations of solar assisted MSF-BR desalination plant: (a) DVG with water steam, (b) IDVG with HTO and water via BHX unit.

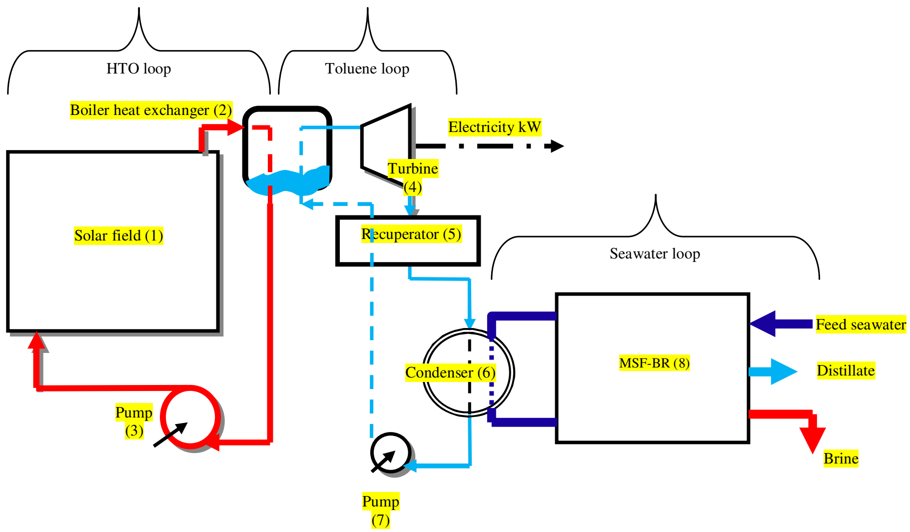

Fig. 3. A schematic diagram of solar Rankine with MSF-BR components: (1) Solar field, (2) boiler heat exchanger, (3) HTO pump, (4) turbine, (5) recuperator, (6) condenser, (7) pump and (8) MSF-BR.

- Toluene is used in the Rankine cycle with recuperator unit [21].
- MSF-BR characteristics are presented in Table 2.
- PTC configuration and design specifications are adjusted according to the LS-3 type [17,25].

4.1. Exergy analysis

The exergy destruction rate (kW) in solar collector is obtained from [26] as;

$$\dot{I}_{collector} = A_{col} \times G_b \times \left(1 + \frac{1}{3}\left(\frac{T_{amb}}{T_{sun}}\right)^4 - \frac{4}{3}\left(\frac{T_{amb}}{T_{sun}}\right)\right) + \dot{m}_{col}[h_i - h_o - T_{amb}(s_i - s_o)] \quad (1)$$

Bejan [27] has recommended $T_{sun} = 6{,}000\,\text{K}$ and this value is used in this study.

$$\dot{I}_{BHX,BH} = \dot{m}_{hot}[\Delta h_{i-o} - T_{amb} \times \Delta S_{i-o}]_{hot} + \dot{m}_{cold}[\Delta h_{i-o} - T_{amb} \times \Delta S_{i-o}]_{cold} \quad (2)$$

$$\dot{I}_{pump} = \dot{m}[\Delta h_{i=0} - T_{amb} \times \Delta S_{i=0}] + \dot{W}_{pump} \quad (3)$$

$$\dot{I}_{MSF} \Delta \dot{Ex}_{steam} + \dot{W}_{pump} + \dot{Ex}_f - \dot{Ex}_b - \dot{Ex}_d \quad (4)$$

where $\dot{Ex}_f$ represents the chemical and physical exergy of seawater feed stream to the MSF effects, $\dot{Ex}_b$ is the exergy stream associated with brine and neglected as loss stream, while $\dot{Ex}_b$ is the chemical and physical exergy stream of distillate product, and $\Delta\dot{Ex}_{steam}$ is the exergy stream of steam conditions based on inlet and outlet cases. Exergy of saline streams is obtained based on physical and chemical components. In physical part, the exergy streams to feed, brine, and distillate are functions of h_f, h_b, and h_d which are calculated based on seawater-specific heat capacity C_p, salinity s, and feed seawater temperature for each stream [28] where

$$h_{f,d,b} = h_o + (A \times T + B/2 \times T^2 + C/3 \times T^3 + D/4 \times T^4 \quad (5)$$

where $h_o = 9.6296 \times s - 0.4312402 \times s^2$ and;

$$A = 4206.8 - 6.6197 \times S + 1.2288 \times 10^{-2} \times S^2$$

$$B = -1.1262 + 5.4178 \times 10^{-2} \times S - 2.2719 \times 10^{-4} \times S^2$$

$$C = 1.2026 - 5.3566 \times 10^{-4} \times S + 1.8906 \times 10^{-6} \times S^2$$

$$D = 6.8774 \times 10^{-7} + 1.517 \times 10^{-6} \times S - 4.4268 \times 10^{-9} \times S^2$$

Therefore, the physical exergy equation (kg/s) for any saline stream is obtained as:

$$\dot{Ex}_{ph} = \dot{m}\left(C_p(T,S) \times (T - T_o) \times C_p(T,S)\log\frac{T}{T_o}\right), \quad (T_o = \text{reference temperature}) \quad (6)$$

For chemical part, the exergy stream (kg/s) should be calculated according to the following relation:

$$Ex^{\cdot}_{ch} = m^{\cdot}(N_{mol}(S, M_w, M_s) \times 10^{-3} \times 8.314 \times T_o\{-X_w \times \log X_w - X_s \times \log X_w\}) \quad (7)$$

And the total stream exergy rate is then calculated,

$$Ex^{\cdot}_{total} = Ex^{\cdot}_{ph} + Ex^{\cdot}_{ch} \quad (8)$$

where

$$X_w = N_{pure}(S, M_w)/N_{mol}(S, M_w, M_s) \quad (9)$$

$$X_s = N_{salt}(S, M_w)/N_{mol}(S, M_w, M_s) \quad (10)$$

$$N_{pure} = (1{,}000 - S)/M_w \quad (11)$$

$$N_{salt} = S/M_s \quad (12)$$

$N_{mol} = N_{pure} + N_{salt}$ is the number of particles, and X_w, X_s is the fraction of water and salt (mol), and the molar weight $M_{w,s}$ for water and salt is 18 g and 58.5 g respectively.

4.2. Cost and thermo-economic analyses

In this part, investment and operating and maintenance cost analyses are performed for each component, solar field, condensers (brine heaters), boiler heat exchanger (BHX), and pump units. The interest rate is set at 5%, and the LT_p is the plant lifetime and set as 20 years. Tables 3 and 4 illustrate the *ICC* and *O&M* costs for the cyclical components. For the MSF part, cost analyses are estimated based on direct capital costs (*DCC*) and the total capital costs (*TCC*). Thermo-economic is the branch of engineering that combines exergy analysis and economic principles to provide the system designer or operator with information not available through conventional energy analysis and economic evaluations but crucial to the design and operation of a cost effective system [29]. In a conventional economic analysis, a cost balance is usually formulated for the overall system operating at steady state as follows [29];

$$\sum_{out} C^{\cdot} = \sum_{in} C^{\cdot} + Z^{IC\&OM} \quad (13)$$

Table 3
ICC and *O&M* costs for solar cycle components

Parameter:	ICC, $	O&M, $	TCC, $/y	$Z^{IC\&OM}$, $/h	Ref.
Solar field	$150 \times (A_{col})^{0.95}$	$15\% \times ICC_{col}$	$A_f \times (ICC + O\&M)_{col}$	$TCC_{col}/8{,}760$	[31]
Condensers	$150 \times (A_{cond})^{0.8}$	$25\% \times ICC_{cond}$	$A_f \times (ICC + O\&M)_{cond}$	$TCC_{cond}/8{,}760$	[31]
Pumps	$3{,}500 \times (W_p)^{0.47}$	$25\% \times ICC_p$	$A_f \times (ICC + O\&M)_p$	$TCC_p/8{,}760$	[31]

Table 4
Cost parameters for MSF desalination plant

Parameter	Correlation	Ref.
Interest rate,%	5	[30]
Plant life time, y	20	
Amortization factor, 1/y	$A_f = \frac{i \times (1+i)^{LTp}}{(1+i)^{LTp} - 1}$	
Direct capital costs, $	$DCC = 10 \times 10^6$	
Annual fixed charges, $/y	$AFC = A_f \times DCC$	
Annual heating steam costs, $/y	$AHSC = \frac{SHC \times L_s \times LF \times M_d \times 365}{1{,}000 \times PR}, SHC = \frac{1.466\$}{MkJ}$	
Annual electric power cost, $/y	$AEPC = SEC \times SPC \times LF \times M_d \times 365, SEC = 0.06\$/kWh$	
Annual chemical cost, $/y	$ACC = SCC \times LF \times M_d \times 365, SCC = 0.025\$/\mathrm{m}^3$	
Annual labor cost, $/y	$ALC = SLC \times LF \times M_d \times 365, SLC = 0.1\$/\mathrm{m}^3$	
Total annual cost, $/y	$TAC_{MSF} = AFC + AHSC + AEPC + ACC + ALC$	
Operating and maintenance costs, $	$OMC_{MSF} = 0.02 \times DCC$	
Hourly operating & maintenance cost in $/h	$Z^{IC\&OM}_{MSF} = \frac{OMC_{MSF} \times A_f + AFC}{8{,}760}$	
The total plant costs, $/y	$TPC = TCC_{col} + TCC_{cond} + TCC_p + \ldots + TAC_{MSF}$	
Total water price $/m^3	$TWP = TPC/(D_p \times 365 \times LF)$	

where $C^{\cdot}$ the cost rate, according to inlet and outlet streams, and $Z^{IC\&OM}$ is the hourly investment & operating and maintenance costs. In exergio-economic, the cost is associated with each exergy stream. Thus, for inlet and outlet streams of matter with associated rates of exergy transfer $E_{i,o}$, power W, and the exergy transfer rate associated with heat transfer $E_{q,}$ it can write as

$$C^{\cdot}_{i,o} = c_{i,o}E^{\cdot}_{i,o}, \quad C^{\cdot}_{w} = c_{w}W^{\cdot} \quad \text{and} \quad C^{\cdot}_{q} = c_{q}E^{\cdot}_{q}$$

where $c_{i,o,w,q}$ denote average costs per unit of exergy in \$/kJ for inlet (i), outlet (o), power (w), and energy (q), respectively. For turbo machinery units, the cost of electric power is assigned based on the price of the electricity 0.06 \$/kWh [30]. Therefore, the specific thermal power cost would be converted to become 0.06/3,600 \$/kJ. The cost equation for the pump unit stream toward the solar collector should become as

$$C_{pump-col} = C_{w} + C_{bhx-pump} + Z^{IC\&OM}_{pump} \tag{14}$$

For solar collector, the relation should become

$$C_{col-bhx} = C_{q} + C_{pump-col} + Z^{IC\&OM}_{col} \tag{15}$$

Thermo-economic balance for boiler heat exchanger (BHX) unit is performed as;

$$C_{bhx-bh} + C_{bhx-pump} = C_{col-bhx} + C_{pump-bhx} + Z^{IC\&OM}_{bhx} \tag{16}$$

For BH unit;

$$C_{bh-pump} + C_{bh-msf} = C_{msf-bh} + C_{bhx-bh} + Z^{IC\&OM}_{bh} \tag{17}$$

For MSF process streams;

$$C_{p} + C_{brine} + C_{steam-pump} = C_{steam-msf} + C_{fi} + Z^{IC\&OM}_{msf} \tag{18}$$

where C_p is the distillate product cost \$/h, C_{brine} is the brine blow down cost and is specified as zero cost, and C_{fi} is the feed stream cost. The thermo-economic streams are presented in each unit in the Appendix-A.

5. Results and comments

Using the design input data assigned in Table 5, SDS package was used to find out iteratively the rest of needed design data such as areas, solar field dimensions, pressure losses, pumps power consumption, number of heat exchanger tubes, tube length, storage capacity (volume and mass), flow rates, operating conditions, physical properties, cost and thermo-economic streams, etc. The input design data that the SDS assumed and assigned are concluded as follows:

- Weather and environmental conditions.
- Tubes diameters for condensers and heat exchangers.
- Productivity and salinity values.
- Top brine, sea water and blow down temperatures.
- Top cycle temperature (solar collector high temperature).
- Mechanical efficiencies of turbo machinery units.
- Solar field characteristics.

5.1. Results of MSF-BR

The results obtained for the MSF-BR (5,000 m^3/d) are analyzed in the relevant figures. The results show that the gain ratio (M_d/M_s) has increased from 5

Table 5
Design input data for all process units

General	
Productivity, m^3/d	5,000
Ambient temperature, ℃	20
Solar radiation (winter), W/m^2	300
MSF-BR (5,000 m^3/d)	
Splitter ratio	0.4203
Seawater salinity, ppm	47,300
Brine blow down salinity, ppm	70,900
TBT, ℃	90–130
Blow down temperature, ℃	34.4
Seawater temperature, ℃	28.67
Number of stages (recovery/rejection)	37/3
Chamber load, kg/s m	180
Vapor velocity, m/s	6
Condenser flow velocity, m/s	2.5
Orifice discharge coefficient	0.5
Heat recovery inner/outer tube diameter, m	0.0127/0.01299
Heat rejection inner/outer tube diameter, m	0.0229/0.0239
Pumps efficiency,%	75
Pumps	
Efficiency,%	75
Cost of power, \$/kJ	0.06/3,600
Brine heater/condenser	
Flow velocity, m/s	2
Inner tube diameter, m	0.021
Outer tube diameter, m	0.02199
Solar field (PTC)	
Width, m	5.67
Length, m	100
Glass envelope diameter, m	0.1
Absorber tube inner diameter, m	0.0655
BHX	
Effectiveness	0.8
Inner tube diameter, m	0.0127
Outer tube diameter, m	0.0129

(20 stages) to become 11.32 (40 stages). And that explains clearly the advantage of increasing the number of stages, although this will increase the total heat transfer area (extra initial costs) but also would decrease the specific unit productivity cost for all systems.

The vapor temperature considered little bit lower than the brine temperature due to the decreasing of temperature drop across the stages. And this is considered an another reason to explain the increase in gain ratio according to the increase in the number of stages. Increasing the gain ratio (GR) would affect on the PTC total area, thence, decreasing the total and specific costs of the systems at all.

The seawater feed flow rate would become 413.6 kg/s, the makeup feed flow rate is about 173.9 kg/s, the feed loss of the 1st splitter is about 239.8 kg/s, the brine blow down from the 2nd splitter is 116 kg/s, the recycle feed water flow rate is 361.5 kg/s, and the brine salinity of the recycle stream is 59,550 ppm. The brine 2nd splitter ratio would become 0.618 with a brine mass flow rate for the mixer unit 187.7 kg/s with total brine about 303.7 kg/s.

The condenser total heat transfer area for MSF-BR stages is about $1.7265 \times 10^4\,m^2$. Fig. 4 shows the profile of data results according to the number of stages for 5,000 m^3/day case study. It is revealed from Fig. 4(d) that the increase in the number of stages will increase the gain ratio, thence the all system performance. To achieve minimum solar field area, the MSF plant should be optimized first. Top brine temperature (TBT) and number of stages have a great influence on the gain ratio.

Fig. 5 shows the effect of TBT and number of stages on the gain ratio of the MSF-BR process. Itis obvious from Fig. 5 that the optimized point related to the GR is at TBT = 90℃ and the number of stages around 40 stages. At this point ($X = 40$, $Y = 90$, $Z = 12.32$) located on the figure, gain ratio is resulted as 12.32. Therefore, it is becoming essential for the solar part to operate the MSF-BR plant at operating conditions of TBT = 90℃ and Nstg = 40.

Moreover, it is evident from Fig. 5 that the TBT effect on the GR is not remarkable enough compared against the Nstg effect. For example; at Nstg = 40, the difference between GR values for 90℃ and 130℃ weren not exceeding over one value compared with the Nstg effect at 90℃ (GR = 12 @40 stages vs. 2 @10 stages).

5.2. Results of solar power cycles

The solar part of the proposed technique is highly proportional to the MSF partial. As a normal effect by the TBT, Nstg and GR, the data results show that by increasing of GR the thermo-economic product cost will decrease according to the considered configurations (DVG and IDVG). Fig. 6 shows the data results comparisons for the proposed techniques. Based on area results, DVG gives lower PTC area value (48,486.47 m^2) than the IDVG (50,620 m^2). The difference in PTC area is considered quite little (4% difference) giving nearly the same hourly cost consumption for the two cases (about $Z_{col}^{IC\&OM} = 45\ \$/h$ for both). Less area means less costs, maintenances and controlling issues. For BH units, the area was the same

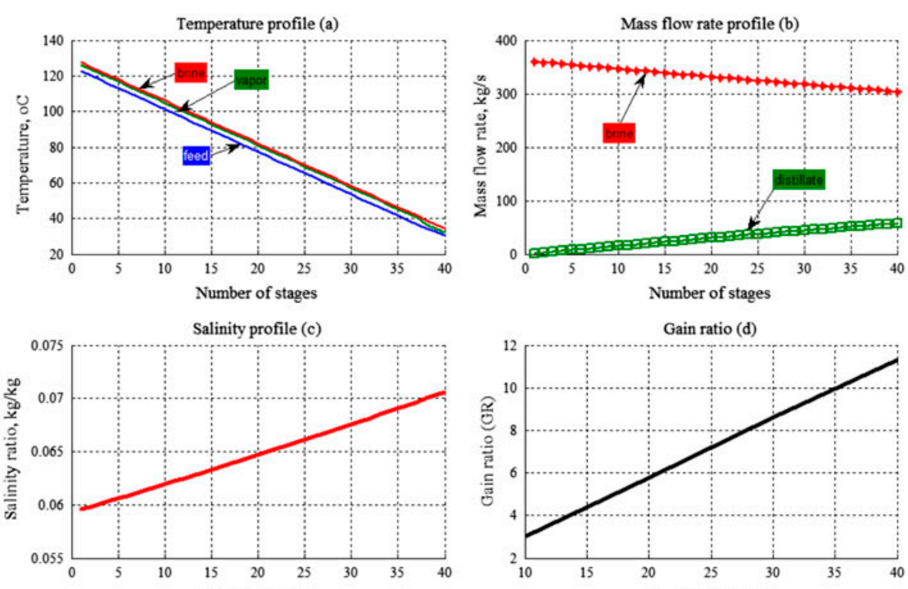

Fig. 4. Profile curves of temperatures, mass flow rates, salinity, and gain ratio of 5,000 m^3/day MSF-BR process.

because of the same thermal load in both cases (DVG and/or IDVG). Furthermore; the same behavior exists in the condenser area on the MSF side.

The exergy destruction rate ($\dot{I}$) kW is quite high for MSF side because of massive thermal losses in fluid flow and higher mass flow rate in fluid streams. However; it is noticed lower in solar field with the advantage of the second configuration (IDVG). That's because of the physical properties of the HTO through the solar field ($Cp_{HTO} \approx 2$ kJ/kg °C *vs.* $Cp_{water} \approx$ 4.18 kJ/kg °C). Thermo-economic distillate cost $/GJ is noticed higher in DVG than IDVG (about 13.5% difference). That's because of the effect some parameters such as exergy flow rate across the system, and solar field top temperature. The effect of PTC high temperature is shown in

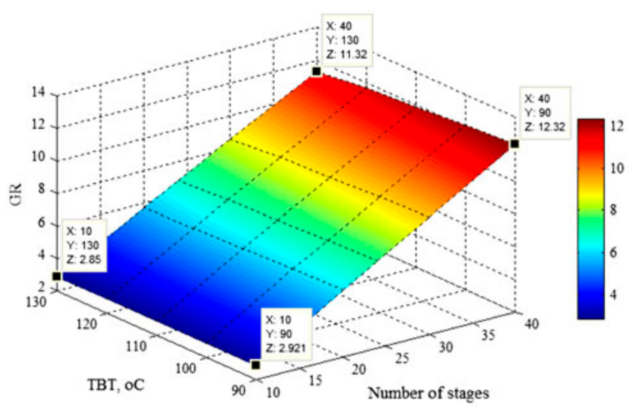

Fig. 5. Effect of TBT, ℃ and number of stages on the GR of the 5,000 m^3/day MSF-BR desalination process.

Fig. 7. The increasing of PTC high temperature would decrease the specific thermo-economic distillate cost (c_p, $/GJ) for the IDVG case. However; this effect would slightly increase the c_p, $/GJ for the DVG. Increasing the PTC high temperature in case of DVG may cause a high severe stresses on the absorber tube because of the operation of water steam.

Fig. 8 shows the effect of PTC high temperature on the saturated pressure in both cases (DVG with water) and (IDVG with HTO). It becomes very clear to distinguish between the two cases however; the IDVG case is quite suitable for the operation with thermal desalination processes according to some issues:

- Lower specific heat capacities of the HTO (around 2 kJ/kg℃) at high ranges of temperatures leading to lower exergy destruction rates. Moreover; lower specific heat capacity means less time to transfer the thermal power.
- The oil properties permit to store the thermal power heat related to its molecular weight, viscosity, and density.
- Operation with high ranges of temperature can easily be operated (at 350℃ $p = 5.5$ bar) without any pressure problems on the envelope or the absorber tubes.

5.3. Data comparison for power & desalination techniques

Fig. 9 shows the results obtained for the power and desalination technique (PSDMSF) and only solar desalination technique (SDMSF-presented in the previous section). The comparison is performed according

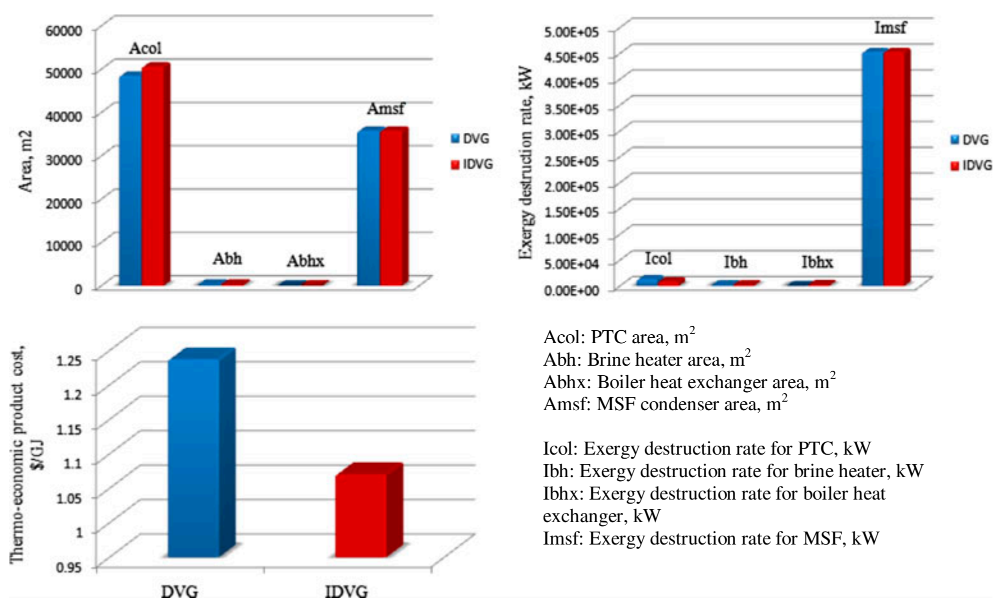

Fig. 6. Data results comparisons for DVG vs. IDVG according to area m^2, exergy destruction rate kW, and thermo-economic product cost $/GJ.

to some terms such as SPC, kWh/m^3, specific thermo-economic product cost, c_p, $/GJ, total solar field area A_{col}, m^2, and the gain ratio (GR). The effect of TBT and Nstg is quite clearly related to the results obtained. For the SPC, kWh/m^3, increasing the TBT would decrease the SPC, kWh/m^3 for both techniques. However, the first technique gives significant results considered lower against the second. Moreover, increasing the Nstg would decrease the SPC; however, the great influence on the SPC, kWh/m^3 is caused by the TBT, against the increasing of the Nstg of the MSF-BR. The same influence is noticed by the TBT and the Nstg on the c_p, $/GJ. By increasing the TBT and the Nstg, as a target, the c_p, $/GJ would significantly decrease. However, the first technique would result lower significant values against the second one. The existence of turbine unit would increase the outlet exergy rate. At the same time; it would increase the hourly costs causing an increase in the final product cost in $/GJ. Increasing the TBT would exceed the solar field area. That is referring to the increasing the thermal load demand by the solar field via the brine heater unit. At the same time,

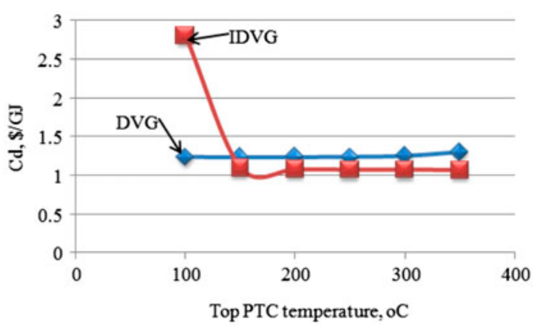

Fig. 7. Effect of PTC high temperature on the thermo-economic distillate cost.

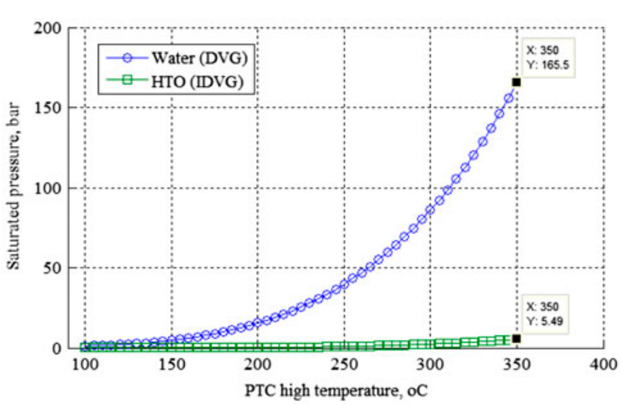

Fig. 8. Effect of PTC high temperature on the saturated pressure for both cases (DVG with water steam) and (IDVG with HTO).

increasing the Nstg would reduce the solar field area. Therefore, the designer has to compromise between the TBT and the Nstg in order to achieve the best fit regarding to the product cost parameter. The solar field area is considered a vital parameter to judge the system cost performance. In most cases, land area could be limited; therefore, the lower solar field area is complimentary. To achieve minimum solar field area related to the first technique, the TBT should be operated at 90°C and Nstg = 40 stages. Related to the second technique, increasing the TBT would decrease the solar field area. This is quite dominated by the ORC effect. To achieve minimum solar field area related to the second technique, TBT would be maintained at 120°C with the operation of Nstg = 40. Nstg is the main parameter that would affect on the GR. For both techniques, increasing the Nstg would increase the GR. However, the first technique significantly achieves higher remarkable results than the second. This is because of the effect of latent heat of vaporization of water steam (in the 1st technique) and toluene (in the 2nd technique). The values of 120°C and 40 are assigned for the TBT and Nstg, respectively, regarding to the second technique. For field design, especially with large capacities, it is recommended to ensure that the Reynolds number value is between 1 and 9×10^4 [25]. In the case of 1st technique, the solar field area results as 61,680 m^2 with cycle flow rate about 24.45 kg/s leading to 110 collectors for 8 loops. This exhibits a field width with 76 m. The 2nd technique gives a larger area compared with the 1st due to higher operating temperatures (120 vs. 90°C). Moreover, the existence of turbine unit needs high and sufficient collector operating temperature according to the high molecular weight of the toluene substance. Because of increasing the outlet collector temperature will permit to increase the evaporator temperature too. The 2nd technique consumes about 93,050 m^2, with a cycle mass flow rate about 43.2 kg/s, the field width is about 50 m with total 18 loops design, and Reynolds number equal 9.2×10^4 with 167 collectors. In case of the 2nd technique, the larger solar field area will be available under summer condition and that will cause an excessive thermal power of the organic turbine. Therefore, nearly about 51% of the winter field area would be out of service during summer conditions for maintenance operations. However, in the 1st technique, there is no need for this operation, because there is no turbine unit in this technique. The first technique has an advantage based on evaporation pressure through the absorber tube (2.2 bar) against the 2nd technique (32 bar). Since higher values may cause severe stresses on the absorber tube. The gain ratio for the 1st technique is

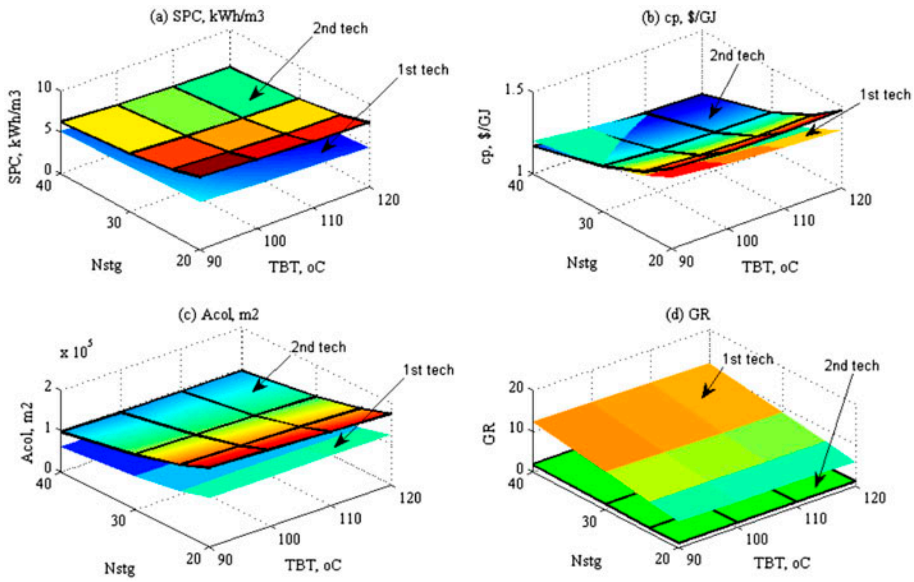

Fig. 9. Effect of TBT and N_{stg} on: (a) SPC, kWh/m^3, (b) C_p, \$/GJ, (c) A_{col}, m^2, (d) GR.

massively greater than the 2nd technique (11–12 vs. 1–2). And that is because the 2nd technique achieves a higher mass flow rate due to higher outlet operating conditions of the collector (outlet field temperature). Exergy analysis considered not far in values for both techniques with an advantage in the 2nd based on overall exergy efficiency and exergy inlet to the cycle. This is because the exergy inlet is directly affected by the solar field and larger solar field area surly remarkable in the 2nd technique. At the same time, larger area gives larger exergy destruction and larger exergy income rates. Therefore, exergy efficiency is a useful tool to judge the system performance. However, hourly operating and maintenance parameter ($/h) is noticed larger in the 2nd technique instead of the 1st due to two main reasons: the existence of turbine unit and the effect of the solar field area. Specific total water price considered little bit lower for 1st technique instead of the 2nd due to the largest solar field area exhibited by the 2nd technique. Also the thermoeconomic unit product cost considered the same (ranged between 1 and 1.1 and $/GJ); however, there is a little bit advantage to the 2nd technique due the cost of power that developed from the turbine work (4 MW). It is becoming clear from the related comparison that only desalination without power generation constitutes lower (means favorable) in the following:

- Solar collector field area (almost half) meaning with this decreasing maintenance issue and increasing the possibility to control the solar field.
- Pumping power issues and requirements which are leading to less electricity demands and it could be recovered from diesel engines or adding some panels of Photo Voltaic (PV) collectors.
- Exergy destruction rate and this is a very important term in the comparison because increasing the rate of irreversibility will cause a significant decrease in total exergy efficiency. Although turbine unit would increase the exergetic efficiency of the power technique but its destruction rate is also in the scope.
- Total plant cost value which is noticed lower; however, there is not a large deviation. This deviation might be larger while comparing based on larger capacities (up to 5,000–10,000m^3/day).

Increasing the power generated from the turbine unit is combined with the increasing of desalinating plant capacity. The example of MSF-BR with a capacity of 30,000 m^3/day would harvest about 612,604 m^2 of the solar field area to generate about

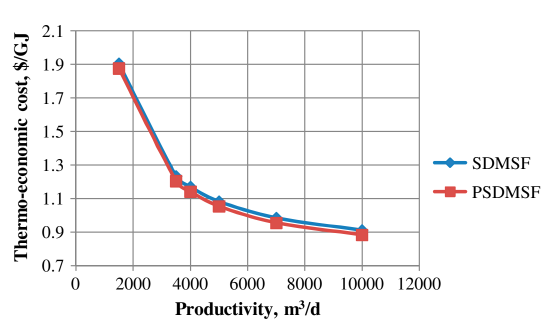

Fig. 10. The daily productivity effect on the thermo-economic product cost for both techniques (SDMSF & PSDMSF).

45MWe with overall exergy efficiency about 13.5%. This is indicated with larger irreversibility and excessive work of control and maintenance issues. Therefore, solar large capacities operation demands more economical considerations putting in the minds the existence of energy storage and/or energy backup system. Fig. 10 shows the effect of daily productivity on the thermo-economic product cost. It is clear from the figure that the thermo-economic product cost is decreased by the increasing of the plant productivity for both techniques. The product exergy stream is considered the main cause of the area increase. The exergy rate of the product stream is considered an important indication to the overall system performance. Thence, it would cause a decrease in the overall system product cost. Also, the effect of productivity (m^3/d) on the rated power is clarified in Fig. 11. Increasing the productivity would increase the power rate and this may serve to develop the excess power to the public grid. Table 6 shows the data comparison related to the proposed techniques in this study. Fig. 12 shows the data comparison between the proposed techniques related to the total water price (TWP, \$/m^3) parameter. It is clear from the figure that the first technique gives lower remarkable results against the second related to the TWP, \$/m^3. That is a normal reflection regarding to the existence of turbine unit in the second technique. It would be favorable for the second technique to produce more power in order to compete with the first one.

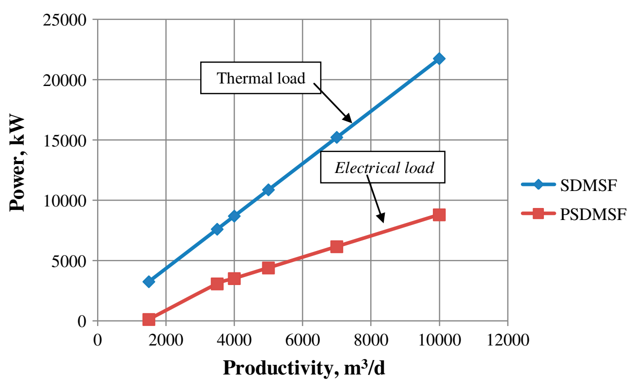

Fig. 11. The effect of productivity on the developed power for both techniques (SDMSF & PSDMSF).

Table 6
Data results for 1st and 2nd techniques operated by water and toluene fluids

Parameter:	SDMSF (Water)	PSDMSF (toluene)
Evaporation pressure, bar	2.25	32.75
Total solar field area, m^2	61,680	93,050
Solar field flow rate, kg/s	24.45	43.2
Solar field R_e number	9.45×10^4	9.24×10^4
No. of collectors (LS-3)/no. of loops	110/8	167/18
Solar field width, m	76	50
Solar collector thermal efficiency,%	69.7	69.7
Boiler HEX area, m^2	35	91.5
Outlet HTO temperature, ℃	145	178
Boiler HEX mass flow rate, kg/s	24.45	43.2
Brine heater effectiveness,%	66.6	30
Brine heater area, m^2	436	492
Organic cycle mass flow rate, kg/s	4.96	29.46
GR	11.67	1.96
Turbine power, MW	–	4.407
Total exergy destruction, MW	414.28	421
Total exergy efficiency, %	14.67	14.46
Total operating & maintenance cost, \$/h	270	320
Total water price, \$/m^3	1.36	1.58
Thermo-economic unit product cost, \$/GJ	1.103	1.1
SPC, kWh/m^3	4.09	5

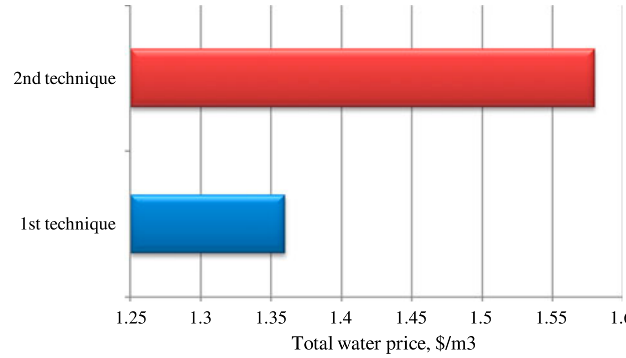

Fig. 12. TWP, \$/m^3 comparison related to the proposed techniques.

6. Conclusion

It is clear from the literatures that MSF distillation process could be powered by solar thermal concentrated power instead of fossil fuel; however, the techniques studied in this field are still under development. In this work, suggestions are pinpointed to combine between solar filed (PTC solar collectors) and MSF-BR desalination plant (capacity of 5,000 m^3/d). The combination is introduced based on two techniques; the first concerns about the transfer the useful energy from the sun collected by solar collector to the brine heater unit via two different configurations without any existence of storage medium. The second is concerned about utilizing a SORC with the MSF-BR. Water is used for DVG configuration; however, Therminol-VP1 heat transfer oil is the organic fluid that is chosen to operate PTC collector (LS-3 type) in case of IDVG. The cycle is compared with the proposed techniques according to the terms of exergy, thermo-economic and cost analysis. Based on the analysis performed in this work, the following conclusions can be drawn:

(1) Technical limitations for MSF-BR concluded in an increasing number of stages up to 40 stages and increasing the TBT in the range of 90–130°C. This may increase the gain ratio; moreover, its effect on total water price is negligible.
(2) Lowering the TBT down to 90°C may increase the GR; however, the massive effect of increasing the GR was made by the increasing of number of stages.
(3) Both technique's operation gives nearly the same results with a little bit advantage to IDVG technique based on thermo-economic distillate cost $/GJ. Lower solar field area means lower in maintenance and control issues.
(4) The operation of HTO is considered favorable based on liquid state through the field, and minimum pressure requirements for the solar field.
(5) Using water steam directly can cause severe stresses on the absorber tube of the PTC collector. Moreover; the top temperature cannot be exceeded than 150–200°C according to pressure issues.

Nomenclature

A	—	area, m^2
A_{col}	—	solar collector area, m^2
A_f	—	amortization factor, y^{-1}
BH	—	brine heater unit
BHX	—	boiler heat exchanger
C	—	cost, $
c_p	—	thermo-economic product cost, $/GJ
C_p	—	specific heat capacity at constant pressure, kJ/kg°C
DCC	—	direct capital cost, $
DVG	—	direct vapor generation
Ex	—	exergy rate, kW
Ex_b	—	brine blow down exergy rate, kW
Ex_{ch}	—	chemical exergy rate, kW
Ex_d	—	distillate exergy rate, kW
Ex_f	—	flow exergy rate, kW
Ex_{in}	—	exergy in, kW
Ex_{ph}	—	physical exergy rate, kW
Ex_q	—	exergy transfer, kW
Ex_{out}	—	exergy out, kW
Ex_w	—	exergy of work, kW
GR	—	gain ratio, M_d/M_s
G_b	—	global solar radiation, W/m^2
HTO	—	heat transfer oil
h	—	enthalpy, kJ/kg
I	—	exergy destruction rate, kW
ICC	—	investment capital costs, $
$IDCC$	—	indirect capital cost, $
$IDVG$	—	indirect vapor generation
i	—	interest,%
LF	—	load factor
LT	—	life time, year
$MSF\text{-}BR$	—	multi stage flash brine recycle technique
$M^{\cdot}$	—	mass flow rate, kg/s
M_b	—	brine mass flow rate, kg/s
M_d	—	distillate mass flow rate, kg/s
M_s	—	steam mass flow rate, kg/s
$Nstg$	—	number of stages
N_{pure}	—	number of moles of pure water, gmol
N_{salt}	—	number of moles of salt, gmol
OC	—	operating cost, $
P	—	pressure, kPa
$PSDMSF$	—	power and solar desalination for MSF
S	—	salinity ratio, g/kg (ppm)
S_b	—	brine blow down salinity ratio, g/kg
S_f	—	feed seawater salinity ratio, g/kg
SCC	—	specific chemical cost, $/m^3
$SDMSF$	—	solar desalination for MSF
SEC	—	specific electrical cost, $/kWh
SHC	—	specific heating steam cost, $/MkJ
SLC	—	specific labor cost, $/m^3
SPC	—	specific power consumption, kWh/m^3
s	—	specific entropy, kJ/kg°C
T	—	temperature, °C
TBT	—	top brine temperature, °C
T_{sun}	—	sun temperature, 6000K
TCC	—	total capital cost, $
TWP	—	total water price, $/m^3
W_{pump}	—	pump power, kW
$X_{w,s}$	—	fraction of water and salt contents
$Z^{IC\&OM}$	—	hourly investment and operating and maintenance cost, $/h

Subscripts

$_{amb}$	—	ambient
$_{av}$	—	average
$_{b}$	—	brine
$_{chm}$	—	chemical
$_{col}$	—	collector
$_{cond}$	—	condenser

d	—	distillate product
f	—	feed
i	—	in
o	—	out
ORC	—	organic Rankine cycle
p, pump	—	pump
s	—	salt, steam
st	—	steam turbine
steam	—	steam phase
v	—	vapor
w	—	water

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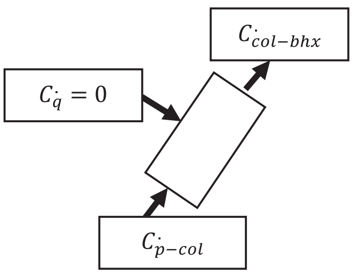
Appendix

Appendix A

This part introduce the thermo-economic analysis for each unit according to the proposed systems presented in Figs. 2 and 3. The units are: PTC, BHX, Pumps, Turbine, Recuperator, Condenser brine heater (BH), and the MSF-BR.

A-1: The PTC field: thermo-economic analysis

The streams



The equations

$\sum_{out} \dot{C}_{col} = \sum_{in} \dot{C}_{col} + Z^{IC\&OM}$

$\dot{C}_{col-bhx} = \dot{C}_q + \dot{C}_{p-col} + Z^{IC\&OM}_{col}$

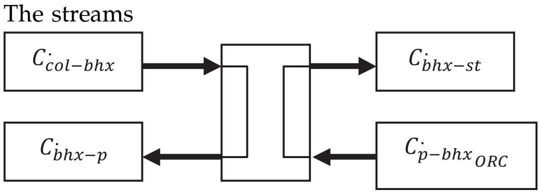
$\dot{C}_{i,o} = c_{i=o} E_{i,o}, \dot{C}_q = 0$

$c_{col-bhx} = \frac{c_{p-col} \times Ex_i + Z_{col}/3,600}{Ex_o}$

$Ex_{i,o} = f(T, s, = \dot{m}\Delta h - \dot{m} T \Delta s)$

A-2: The BHX unit: thermo-economic analysis

The streams



The equations

$\sum_{out} \dot{C}_{bhx} = \sum_{in} \dot{C}_{bhx} + Z^{IC\&OM}$

$\dot{C}_{bhx-st} + \dot{C}_{bhx-p} = \dot{C}_{col-bhx} + |C_{rec-bhxORC} + Z^{IC\&OM}_{bhx}$

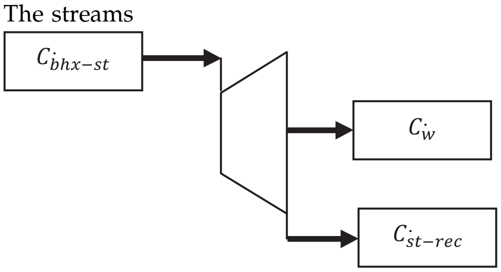
$\dot{C}_{i,o} = c_{i=o} E_{i,o},\ and\ c_{bhx-p} = \dot{c}_{col-bhx}$

$c_{bhx-st} = \frac{|c_{rec-bhx} \times Ex_{iORC} + c_{col-bhx} \times (Ex_i - Ex_o) + (Z_{bhx}/3,600))}{|Ex_{bhxORC}}$

$Ex_{i,o} = f(T, s, = \dot{m}\Delta h - \dot{m} T \Delta s)$

A-3: The steam organic Rankine turbine unit: thermo-economic analysis

The streams



The equations

$\sum_{out} \dot{C}_{st} = \sum_{in} \dot{C}_{st} + Z^{IC\&OM}$

$\dot{C}_{st-rec} + \dot{C}_w = \dot{C}_{bhx-st} + Z^{IC\&OM}_{st}$

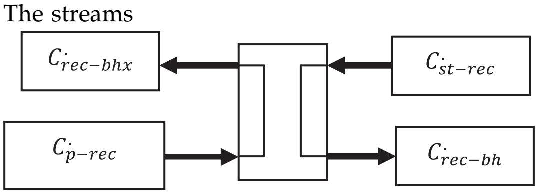
$\dot{C}_{i,o} = c_{i=o} E_{i,o},\ and\ c_{bhx-p} = \dot{c}_{col-bhx}$

$c_w = \frac{c_{bhx-st} \times (Ex_i - Ex_o) + Z_{st}/3,600}{\mathbf{kW_e}}$

$Ex_{i,o} = f(T, s, = \dot{m}\Delta h - \dot{m} T \Delta s)$

A-4: The recuperator unit: thermo-economic analysis

The streams



The equations

$\sum_{out} \dot{C}_{rec} = \sum_{in} \dot{C}_{rec} + Z^{IC\&OM}$

$\dot{C}_{rec-bhx} + \dot{C}_{rec-bh} = \dot{C}_{st-rec} + \dot{C}_{p-rec} + Z^{IC\&OM}_{rec}$

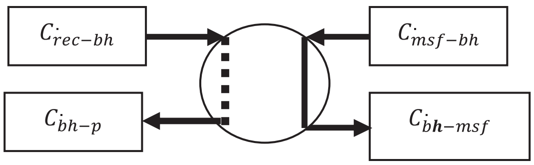
$\dot{C}_{i,o} = c_{i,o} E_{i,o},\ and\ c_{rec-bh} = c_{st-rec}$

$c_{rec-bhx} = \frac{c_{p-rec} \times \Delta Ex_{p-rec} + c_{st-rec} \times \Delta Ex_{i,o} + (Z_{rec}/3,600))}{Ex_{rec-bhx}}$

$Ex_{i,o} = f(T, s, = \dot{m}\Delta h - \dot{m} T \Delta s)$

A-5: The condenser BH unit: thermo-economic analysis

The streams



The equations

$\sum_{out} \dot{C}_{bh} = \sum_{in} \dot{C}_{bh} + Z^{IC\&OM}$

$\dot{C}_{bh-p} + \dot{C}_{bh-msf} = \dot{C}_{rec-bh} + \dot{C}_{msf-bh} + Z_{bh}^{IC\&OM}$

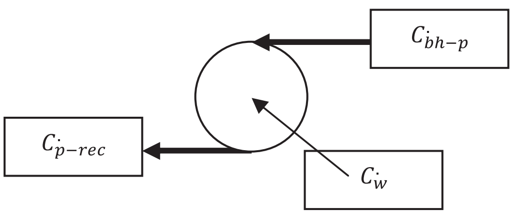
$\dot{C}_{i,o} = c_{i,o}\dot{E}_{i,o},\ and\ c_{bh-p} = c_{rec-bh}, c_f = feed\ cost$

$c_{bh-msf} = \frac{c_{rec-bh} \times \Delta Ex_{i,o} + c_f/3{,}600 + (Z_{bh}/3{,}600))}{Ex_{bh-msf}}$

$Ex_{i,o} = f(T, s, = m^{\cdot}\Delta h - m^{\cdot}T\Delta s)$

A-6: The organic Rankine pump unit: thermo-economic analysis

The streams:



The equations

$\sum_{out} \dot{C}_p = \sum_{in} \dot{C}_p + Z^{IC\&OM}$

$\dot{C}_{p-rec} + \dot{C}_{bhx-p} + \dot{C}_w + Z_p^{IC\&OM}$

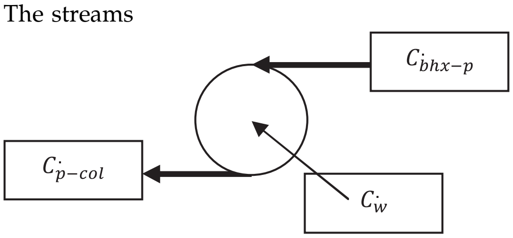
$\dot{C}_{i,o} = c_{i,o}E_{i,o}$

$c_p = \frac{c_w \times \mathbf{kW_e} + c_{bhx-p} \times Ex_{bhx-p} + Z_p/3{,}600}{Ex_{p-col}}$

$Ex_{i,o} = f(T, s, = m^{\cdot}\Delta h - m^{\cdot}T\Delta s)$

A-7: The PTC pump unit: thermo-economic analysis

The streams



The equations

$\sum_{out} \dot{C}_p = \sum_{in} \dot{C}_p + Z^{IC\&OM}$

$\dot{C}_{p-col} = \dot{C}_{bhx-p} + \dot{C}_w + Z_p^{IC\&OM}$

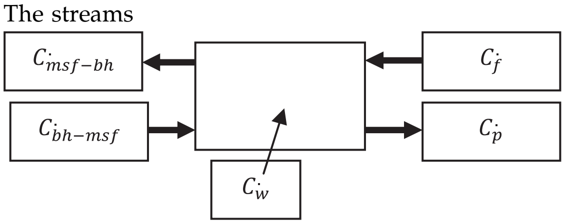
$\dot{C}_{i,o} = c_{i,o}E_{i,o}$

$c_{p-col} = \frac{c_w \times \mathbf{kW_e} + c_{bhx-p} \times Ex_{bhx-p} + Z_p/3{,}600}{Ex_{p-col}}$

$Ex_{i,o} = f(T, s, = m^{\cdot}\Delta h - m^{\cdot}T\Delta s).$

A-8: The MSF-BR unit: thermo-economic analysis

The streams



The equations

$\sum_{out} \dot{C}_{msf} = \sum_{in} \dot{C}_{msf} + Z^{IC\&OM}$

$\dot{C}_{msf-bh} + \dot{C}_p = \dot{C}_f + \dot{C}_{bh-msf} + \dot{C}_w + Z_{msf}^{IC\&OM}.$

$\dot{C}_{i,o} = c_{i,o}\dot{E}_{i,o}C_{msf-bh} = c_f, c_b = 0$

$c_p = \frac{c_w \times \mathbf{kW_{e,pumps}} + c_{bh-msf} \times Ex_{bh-msf} + Z_{msf}/3{,}600}{Ex_p}.$

$Ex_{i,o} = f(T, s, = m^{\cdot}\Delta h - m^{\cdot}T\Delta s)$

Appendix B

The schematic diagram of the MSF-BR process with new characteristics that presented in Table 2. By the aid of SDS, user should assign the following parameters:

(1) Sea water temperature ˚C.
(2) Top brine temperature ˚C.
(3) Brine blow down temperature ˚C.
(4) Feed seawater splitter ratio.
(5) Seawater and brine blow down salinity ratios kg/kg.
(6) Number of stages.
(7) Tubes diameter for each section m.
(8) Pumps efficiency.

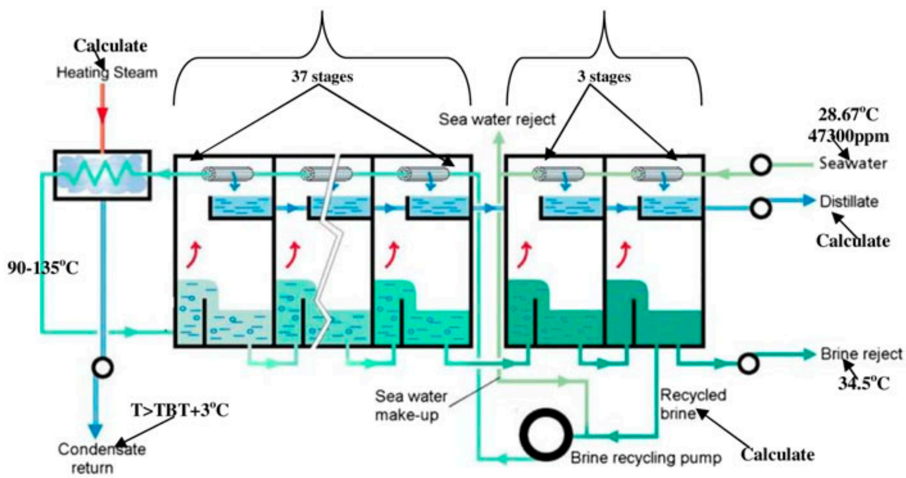


Fig. B1. Schematic diagram of the MSF-BR with new characteristics presented in Table 2.