

This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

<http://www.elsevier.com/copyright>



Contents lists available at ScienceDirect

## Desalination

journal homepage: [www.elsevier.com/locate/desal](http://www.elsevier.com/locate/desal)

# Exergy and thermo-economic analyses of a combined solar organic cycle with multi effect distillation (MED) desalination process

M.A. Sharaf<sup>a,\*</sup>, A.S. Nafey<sup>a</sup>, Lourdes García-Rodríguez<sup>b,1</sup><sup>a</sup> Department of Engineering Science, Faculty of Petroleum & Mining Engineering, Suez Canal University, Egypt<sup>b</sup> Departamento Ingeniería Energetica, Universidad de Sevilla, Spain

## ARTICLE INFO

## Article history:

Received 24 September 2010

Received in revised form 26 December 2010

Accepted 4 January 2011

Available online 1 February 2011

## Keywords:

Thermo-economic

Multi effect distillation

Solar organic cycles

SDS package

## ABSTRACT

Solar energy with different configurations of multi-effect distillation process is thermo-economically evaluated. In this work, two different combined solar cycles with different configurations of multi effect distillation (MED) processes are considered. In the first technique, the solar energy is directly utilized from the solar collector field via evaporator heat exchanger to the first effect of the MED process. This technique produces only potable water. In the second technique, the exhausted energy from the organic Rankine cycle (ORC) turbine is used in the first effect of the MED process. The second technique produces power electricity and desalted water. The comparison is implemented according to the operation of Parabolic Trough Collector (PTC) with toluene organic oil and water working fluids. Therminol-VP1 Heat Transfer Oil (HTO) is considered for indirect vapor generation operation across the solar field and evaporator heat exchanger. The comparisons are manipulated according to 100 m<sup>3</sup>/day of distillate product as a case study. As a result, only desalination technique is considered more attractive than desalination and power technique due to higher gain ratio and lower solar field area needed. Parallel feed configuration is dominated against the forward feed with feed heater configuration while increasing the number of effects to more than 12 effects.

© 2011 Elsevier B.V. All rights reserved.

## 1. Introduction

A shortage of fresh water is a very important problem that is continuously increasing, due to population growth and changes in weather conditions, and affects many countries in the world. Most of these countries 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 commercial level. The main reason for this is that the existing technology, although already demonstrated as technically feasible cannot presently compete, on produced water cost basis, with conventional thermal distillation and reverse osmosis technologies.

Nevertheless, it is also recognized that there is still important room to improve desalination systems based on solar thermal energy [1]. Solar desalination systems are classified into two categories: direct and indirect collection systems. As their name implies, direct collection systems use solar energy to produce distillate directly in

the solar collector, whereas in indirect collection systems, two sub-systems are employed (one for solar energy collection and the other one for desalination). Among the several options to connect a seawater desalination system with a solar power plant the combination of a thermal desalination system such as a multi effect distillation (MED) and a solar trough field as the heat source is one of the most promising [2]. The race for the second generation of the seawater desalination systems has been settled with Reverse Osmosis (RO) and low temperature MED of horizontal tube evaporators. Both systems are characterized by their low energy consumption as compared to the Multi Stage Flash (MSF) system [3].

Conventional MED desalting system uses about half of the MSF pumping energy, and almost the same amount of thermal energy used by the MSF, if both have the same gain ratio [4]. However, a recent trend of using low-temperature MED allows the use of low temperature (in the range of 70 °C) steam as heat source, and consequently of low exergy and low equivalent work. This can bring the MED consumed equivalent mechanical energy close to that consumed by the efficient RO system. Recent construction in Abu Dhabi of an MED plant with a 240,000 m<sup>3</sup>/day capacity shows a breakthrough in large-scale MED plants [2].

During the past years, several indirect solar desalination pilot plants have been designed and implemented using Parabolic Trough Concentrator (PTC), flat-plate and evacuated-tube solar collectors [5]. During the nineties, an experiment in solar seawater desalination at the Plataforma Solar de Almería (PSA) coupled a parabolic-trough

\* Corresponding author. Tel.: +20 122748717.

E-mail addresses: [swazy20@hotmail.com](mailto:swazy20@hotmail.com) (M.A. Sharaf), [lourdesg@esi.us.es](mailto:lourdesg@esi.us.es) (L. García-Rodríguez).<sup>1</sup> Fax: +34 954487233.

solar field with a conventional MED distillation unit was constructed [2]. For large capacity, an MED plant with a capacity of 6000 m<sup>3</sup>/day driven by parabolic trough collectors is designed and constructed in Arabian Gulf [6].

For lower capacities, an MED-14 effect plant with a capacity of 40 m<sup>3</sup>/day driven by evacuated tube collectors is constructed in La Desirée Island, French Caribbean [7]. Also a 16 effect-MED (plant capacity, 16 m<sup>3</sup>/day; solar collectors, flat plate) is constructed in Takami Island, Japan [8]. It is clear from literature that the possibility of utilizing reliable solar thermal power with different types of distillation processes such as MED already exists. However, the technique of such utilization, mathematical model representing the process, examining different techniques of solar concentrated power with different working fluids needs more investigations.

Second law analysis computations allow engineers to distribute energy resources at the boundary of the system of interest to each part of the system. Thermo-economics distribute the expenses on the plant boundary in each unit stream based on the exergy not energy. The exergy destruction was estimated by Spiegler et al. [9] for specific operating conditions of MEE unit and MSF stage. The results showed that the exergy destruction of the MEE effect is lower than that of the flash chamber. Nafey et al. [10] thermo-economically investigated a hybrid MED–MSF desalination plant. Thermo-economic analysis of the hybrid (MEE–MSF) system showed that the running cost decreases with increasing the module number, however the capital cost increases.

Piacentino and Cardona [11] analyzed from the site of thermo-economic approach the MED desalination process. They investigated the possibility to optimize 6-effects of MED as a case study. Sayyaadi et al. [12] thermo-economically optimized a MED desalination system with thermo-vapor compressor (TVC). Sayyaadi's [12] approach was applied to minimize the cost of the system product (fresh water). According to the available literature, solar assisted MED processes (based on thermo-economic) are often few. It is very important to investigate different techniques of solar assisted MED processes to give a clear standpoint about the second law efficiency in such processes.

In this work, investigation analyses are performed for different configurations of MED with low capacity (100 m<sup>3</sup>/day) by using solar power technology. Two different techniques are thermo-economically studied in this work: The first technique utilizes the solar power by using the concentrator (PTC) to deliver thermal power via heat exchanger boiler to drive on MED directly, and the second technique utilizes the rest of the exhaust energy from solar Rankine organic cycle turbine unit to drive on the MED process. The first effect for both techniques works as a brine heater/steam generator for MED plant. Both techniques use Therminol-VP1 [13] heat transfer oil (HTO) for indirect vapor generation via heat exchanger boiler. The MED introduced in this work has a capacity of about 100 m<sup>3</sup>/day. The analyses are introduced based on thermo-economic mathematical approaches. The comparison is made to evaluate the most economical and reliable MED-configuration to be implemented with solar energy.

Solar Desalination Systems (SDS) software package [14] is used to design and simulate the process units of the considered techniques. Using the developed Solar Desalination Systems (SDS) package [14], different types and configurations of solar thermal desalination plants can be easily designed and simulated based on thermo-economic approach. The aim of this work may be concluded into these points:

- Investigating and analyzing the design limitations of utilizing different techniques of solar power with different configurations of MED process.
- Electing the most reliable MED configuration based on energy, exergy, cost and thermo-economic analyses putting in mind the number of MED effects.

- Comparisons are introduced versus conventional operation (water working fluid). The design points are summarized according to typical winter operating conditions due to the high demanded thermal load for such types of desalination processes (MED or MSF).

## 2. Solar thermal power for MED process (techniques and process description)

### 2.1. MED process configurations

MED plants utilize horizontal tube, falling-film evaporative condensers in a serial arrangement, to produce through repetitive steps of evaporation and condensation, each at a lower temperature and pressure, a multiple quantity of distillate from a given quantity of low grade input steam. Technically the number of effects is limited only by the temperature difference between the steam and seawater inlet temperatures (defining the hot and cold ends of the unit) and the minimum temperature differential allowed on each effect [15]. The low temperature operation aided by a comprehensive multi-disciplinary development and design approach has made possible the utilization of economical and durable materials of construction such as aluminum alloy for heat transfer tubes, plastic process piping and epoxy-painted carbon steel shells which show a better resistance against corrosion when matched with aluminum alloy or titanium.

Also, the significant increase in heat transfer area, in addition to the thermodynamic superiority of MED over the MSF process, results in a very low temperature drop per effect (1.5–2.5 °C), enabling the incorporation of a large number of effects (10–16) even with a maximum brine temperature of as low as 70 °C, consequently resulting in very high gain ratio (product to steam flow rates) leading to cost minimization. There are different schemes for supplying the feed seawater to the evaporators, mainly forward, backward, parallel, and mixed feed systems [16]. In the forward feed (MED-FF) arrangement, the feed water (after leaving the bottom condenser) is supplied to the first effect of the highest temperature. In the backward feed (MED-BF) arrangement, the feed water is directed from the end condenser to the last effect (of the lowest temperature), and the brine leaving the first effect is blown down to the sea. Thus, the feed and vapor entering the effects have opposite flow directions. In the parallel feed (MED-PF) arrangement, the feed leaving the condenser is divided and distributed almost equally to each effect. The choice of any of these feed arrangements affects the design and performance of the MED desalting system, e.g. the evaporator arrangements, the required heat transfer areas of the effects, the amount of vapor generated in each effect (evaporator), the amounts of vapor generated by boiling and by flashing, the pumping energy, the gain ratio (distillate to heating steam ratio), and the cooling water to distillate ratio. For forward feed with feed heaters (MED-FFH), cooling water enters an end condenser to condense (last effect vapor output) and part of the leaving cooling water is pre-treated and becomes feed water, and is heated successively as it flows in the feed heaters before entering the first effect (for more details, see ref [16]).

In this work, all the mentioned feed arrangements (see Appendix-A) are considered and compared to pin point the most reliable configuration. Moreover, the number of 16 effects is offered to ensure minimum temperature drop between effects. Top steam temperature is maintained based on the type of technique presented (solar desalination and/or power and solar desalination). The design limits for MED are maintained under winter operating conditions to dominate stable operation along summer period. Dealing with solar energy is concerned with sun availability during summer and winter periods. Table 1 illustrates the specifications and design limits that are considered for different MED configurations under winter operating conditions.

**Table 1**

Specifications of MED (100 m<sup>3</sup>/day capacity) different configurations under winter operating conditions.

Design point	MED-(BF, FF, FFH, PF)
Ambient temperature, °C	20
Seawater temperature, °C	25
Brine blow down temperature, °C	40
Top steam temperature (TST), °C	Depends on each technique
Sea water salinity, ppm	42,000
Brine blow down salinity, ppm	70,000
Condenser effectiveness	0.8
Condenser inner tube diameter, m	0.039
Condenser outer tube diameter, m	0.04
Number of effects	16
Number of feed heaters (in case of MED-FFH)	15
Effect inner tube diameter, m	0.0295
Effect outer tube diameter, m	0.03
Productivity, m <sup>3</sup> /day	100
Brine mass flow rate, kg/s	Calculated
Distillate profile mass flow rate, kg/s	Calculated
Feed mass flow rate, kg/s	Calculated
Cooling water mass flow rate, kg/s	Calculated
Steam mass flow rate, kg/s	Calculated
Vapor temperature through the effects, °C	Calculated
Brine temperature through the effects, °C	Calculated
Effects area, m <sup>2</sup>	Calculated
Feed heaters area, m <sup>2</sup>	Calculated
Condenser area, m <sup>2</sup>	Calculated
Gain ratio	Calculated

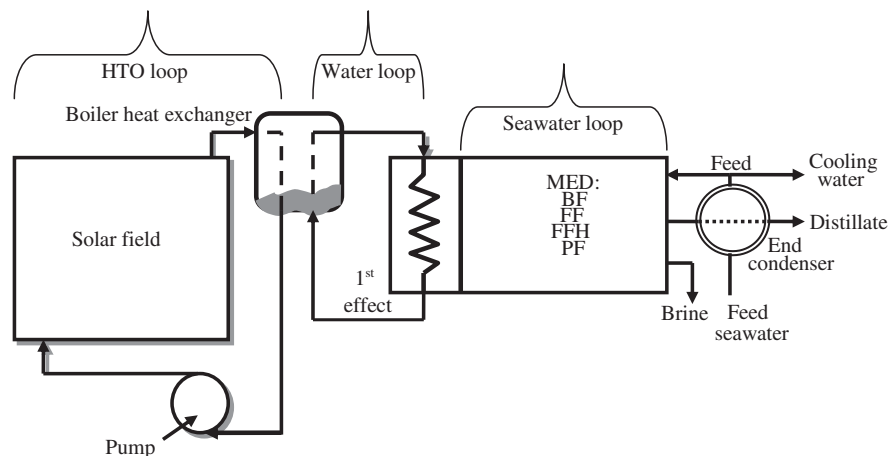
## 2.2. Solar power cycle configurations

Operating conditions (TBT) of MED allow the use of Parabolic Trough Collector (PTC) in solar power plants. Conventional PTC uses heat transfer oil as heat transfer fluid and the hot oil is stored in an insulated tank [17]. In solar PTC application to desalination, the heated oil could be sent to a boiler, which would generate the steam required by a conventional MED plant. In this work, boiler unit with heat transfer oil is used in the analysis. The analysis of the storage element is not investigated in this work. There are two methods of combining solar thermal power cycle with MED plants. The first is direct contact of PTC field to the first MED effect, and the second is utilizing solar Rankine cycle for desalination and electricity production by means of using the exhausted steam from the turbine to operate the first effect.

### 2.2.1. Solar desalination with MED (SDMED)

Fig. 1 shows a schematic diagram of the process units for the first technique. This technique consists of a pump unit to overcome the pressure losses, solar collector field (PTC-LS-3 type [18]) for thermal power delivering, boiler heat exchanger for vapor release and MED with 16 effects. The organic HTO across the PTC would transfer its thermal power to the fluid (water) across the boiler heat exchanger unit. The generated top steam temperature (TST) would raise the preheated seawater brine to the desired top temperature (TBT) then it would be condensed again to the boiler heat exchanger unit. Fig. 1 shows a schematic diagram of the process units for the 1st technique. Based on previous studies by the authors [18,19], Therminol-VP1 [13] is selected as a working fluid for PTC. Table 2 shows and summarizes the design points for this technique. The specifications and assumptions related to this technique are pin pointed as follows:

- Direct normal irradiance under winter operating conditions is assumed for Egypt-Suez Gulf region (latitude: 30°N; longitude: 32.55°E). It is estimated by reference [20] that the daily average global radiation in a typical day in winter would be in the range of 21–22 MJ/m<sup>2</sup>. To dominate long operation along the day light (11 h), the solar radiation would be estimated and fixed at 503 W/m<sup>2</sup> (21.4 MJ/m<sup>2</sup> ≈ 503.7 W/m<sup>2</sup>). For all day operation (24 h), the daily average is estimated as 252 W/m<sup>2</sup>. Fig. 2 shows the variations of solar radiation on the specified location in 21st of January. Also, Table 2 illustrates some of the data results of the solar model according to the location of operation. Designing the solar field based on lower values of solar radiation such as winter conditions gives the allowance to collect huge amount of solar radiation based on larger expected area. Although the PTC operates at 850 W/m<sup>2</sup> this value could cause the very need for storage element (extra costs) during winter or may also not be able to power on the plant based on lower operation area service against the demanded productivity. However, under summer conditions it will be expected that there is an excessive power due to large solar field area and it might be handled through bypassing some loops in the solar field for maintenance and cleaning operations.
- The inlet feed seawater conditions to produce an amount of 100 m<sup>3</sup>/day of fresh water are 25 °C and 42,000 ppm. The outlet brine stream temperature is kept constant at 40 °C and the number of effects is fixed at 16 effects.
- The outlet PTC collector temperature would be fixed at 350 °C [21] due to the design limits of the PTC and the mass flow rate through the field. Increasing the top PTC temperature would slightly



**Fig. 1.** A schematic diagram of solar MED components for desalination: solar field, boiler heat exchanger, pump, MED.



**Table 2**  
Data results for solar radiation model based on the specified location of operation.

Parameter	Data results
Location	Suez Gulf region
Longitude	Longitude: 32.55°E
Latitude	latitude: 30°N
Equation of time, min	−11.25
Day hours	10.37
Declination-angle	−20.138
Daily average solar radiation, MJ/m <sup>2</sup>	21.76
Monthly average of daily total radiation, MJ/m <sup>2</sup>	15.623
Extraterrestrial intensity, W/m <sup>2</sup>	1409.19
Sun temperature, K	5833.11
Sun rise time	6.814
Sun set time	17.19
Julian day	21st of January

decrease the mass flow rate through the field thence, keeping the Reynolds number in the range of  $1 \times 10^4$ – $9 \times 10^4$ . The boiler heat exchanger (BHX) top temperature will be maintained at 75 °C putting into consideration the 1st effect effectiveness thence achieving higher gain ratio.

- The efficiency of the positive displacement pumps is assumed to be at 75%.
- PTC configuration and design specifications are adjusted according to LS-3 type [18,22].

### 2.2.2. Power and solar desalination with MED (PSDMED)

This technique consists of two pumps for circulation and pressure drop, solar collector field (PTC), boiler heat exchanger (BHX), turbine expander unit, recuperator for regeneration and de-superheating, and MED with 16 effects. This technique is similar to the previous; however, turbine and recuperator units are added for electricity and power regeneration. Moreover, the first effect would operate as a brine heater for MED and a condenser unit for the Rankine cycle. Fig. 3 shows a schematic diagram of the process units for the second technique. Table 3 shows and summarizes the design points for this technique. The specifications and design parameters for this technique are pin pointed as follows:

- Solar radiation and ambient temperature would be fixed as the previous technique (252 W/m<sup>2</sup> and 20 °C).

- The distillate product is fixed at 100 m<sup>3</sup>/day, and the inlet seawater feed temperature stream is fixed at 25 °C with salinity of about 42,000 ppm. The outlet brine stream temperature is adjusted as 40 °C and the number of effects is fixed as 16 effects. The brine blow down salinity is assumed as 70,000 ppm.
- Due to the operating conditions (TBT) of MED and boiler heat exchanger effectiveness, the collector outlet temperature is maintained at 350 °C the same as the previous technique to dominate the saturated vapor (Toluene) that enters the turbine unit first stage in the range of 200 °C [21].
- To obtain TST at 75 °C, the condensed steam temperature should be maintained at 70 °C.
- The efficiency of turbine, generator, recuperator and pump units is fixed at 85%, 95%, 80% and 75% respectively.
- PTC configuration and design specifications are adjusted according to LS-3 type [18,22].

### 3. Exergy, cost, and thermo-economic considerations

Exergy and thermo-economic analyses that are presented in Appendix-B are performed according to the embedded equations in the SDS software package [14] and [23,24]. The exergy analysis is based on thermodynamic potential exergy, which takes into account the energy as well as its potential use (quality). In outline, the exergy analysis of the proposed processes will be implemented based on the following terms:

- The processes are in steady state condition.
- Chemical and physical exergy components are performed for each stream in desalination plant.
- The negative exergy rate of blow-down represents the potential use of rejected chemical exergy with respect to seawater. Commonly, this potential use is wasted in desalination facilities where rejected brine is merely returned to the sea. Then, this loss of exergy represents the impact of waste on the surroundings.

For cost analysis, investment and operating and maintenance costs' analyses are performed for each component, solar field, steam turbine, recuperator, boiler heat exchanger (BHX), and pump unit. The main assumptions for cost analysis are outlined as follows:

- The interest rate is set as 5%.
- $LT_p$  is the plant lifetime and set as 20 years.

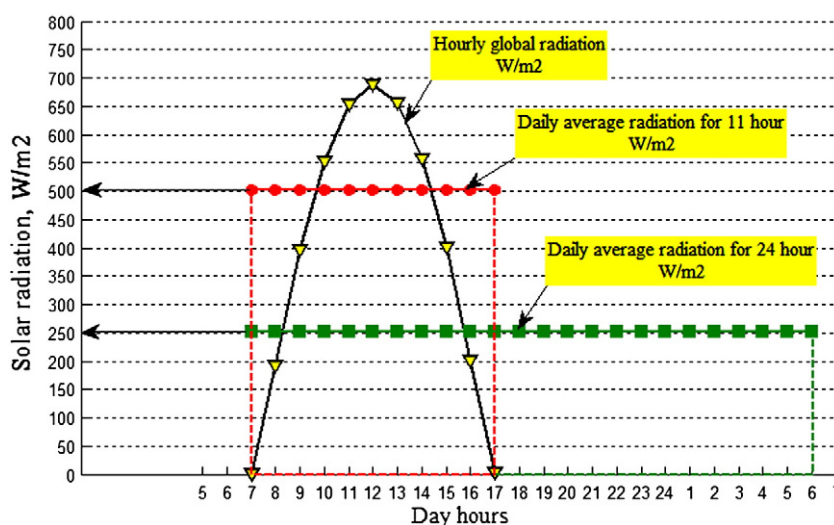


Fig. 2. Global solar radiation data results based on hourly, daily average (11 h), and daily average (24 h) variations.

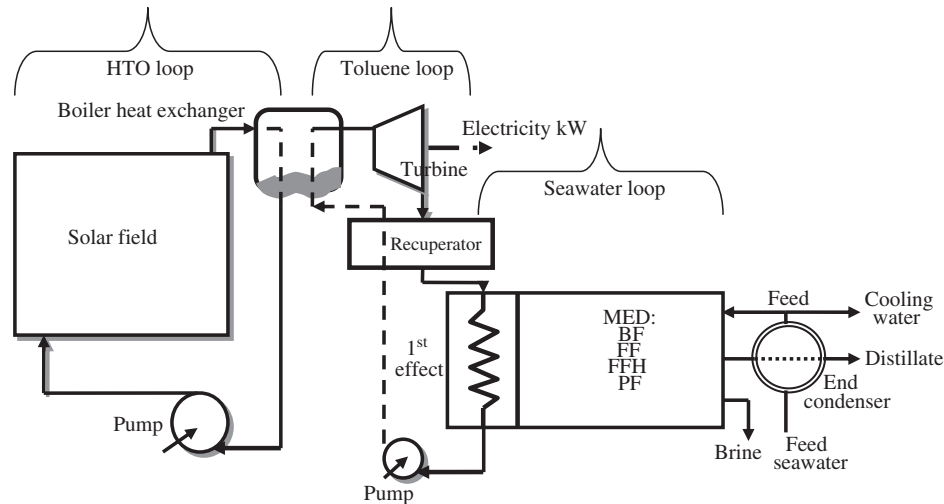


Fig. 3. A schematic diagram of solar MED components for desalination and power generation: solar field, boiler heat exchanger, pump, turbine, recuperator, MED.

- Tables in Appendix-B illustrate the ICC and O&M costs for the cycle components.
- Cost of brine blow-downstream is set as zero costs [27].

Thermo-economic is the branch of engineering that combines exergy analysis and cost principles to provide the system designer or operator with information not available through conventional energy analysis and economic evaluations [25]. Thermo-economic balance for any unit is performed based on exergy and cost balances. In a conventional economic analysis, a cost balance is usually formulated for the overall system operating at steady state as follows [25]:

$$\sum_{out} C^* = \sum_{in} C^* + Z^{IC\&OM} \quad (1)$$

where  $C^*$  is the cost rate according to inlet and outlet streams, and  $Z^{IC\&OM}$  is the capital investment and operating and maintenance costs. In exergy costing a 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 follows;

$$C_{i,o}^* = c_{i,o} E_{i,o}^* \quad (2)$$

$$C_w^* = c_w W^* \quad (3)$$

$$C_q^* = c_q E_q^* \quad (4)$$

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. Thermo-economic main terms based on [14,24] are assigned as follows:

- The cost of power is assigned based on the price of the electricity 0.06\$/kWh [26]. Therefore the specific power cost would become 0.06/3600\$/kJ.
- Thermo-economic power stream from the sun is set as zero costs.
- Feed stream cost is set as 0.3284\$/h for both techniques.
- The brine blow-down stream is a useless outlet flow and it has zero exergy cost [27].

Table 3

Design points considered for MED according to the 1st and the 2nd techniques.

Design point:	1st technique (SDMED)	2nd technique (PSDMED)
$G_b$ , W/m <sup>2</sup>	252	252
$T_{amb}$ , °C	20	20
$T_{co}$ , °C	350	350
$\eta_{lt}$ , %	–	85
$\eta_{lt}$ , %	–	95
$\eta_{lp}$ , %	75	75
Seawater end condenser effectiveness	0.8	0.8
ORC recuperator effectiveness	0.8	0.8
Boiler heat exchanger effectiveness	0.8	0.8
Boiler inner tube diameter, m	0.0127	0.0127
Boiler outer tube diameter, m	0.0129	0.0129
$T_{sea}$ , °C	25	25
$T_{steam}$ from boiler, °C	75	200
$T_b$ , °C	40	40
TST to the MED, °C	75	75
Feed salinity, ppm	42,000	42,000
Brine blow down salinity, ppm	70,000	70,000
No. of effects	16	16
Product mass flow rate, kg/s	1.157	1.157
Solar field mass flow rate per loop, kg/s	1	1
Plant life time, year	20	20
Power generation cost, \$/kWh	0.06	0.06

## 4. Results and discussions

In this section, detailed comparison for different MED configurations based on each solar desalination technique is pin pointed and highlighted. Results for each technique are illustrated in Tables 4 and 5.

### 4.1. Results of SDMED technique

As indicated earlier, this technique is performed to desalinate seawater regardless of the method of power consumption and/or generation. Therefore, the system mainly contains solar collector field (PTC LS-3 [18,22]), boiler heat exchanger (BHX), pump, and MED desalination plant. Thence, turbine unit is not present in this technique as long as the electricity production is not important. Therminol-VP1 HTO (hot saturated liquid) is required to deliver the converted thermal power from the sun via PTC to the BHX unit; however, pure water (dry saturated steam) is required to generate steam from BHX to power on the first effect of the MED process. In general, it is clear from Table 4 that the MED-PF configuration has given very promising results compared to other configurations. MED-FFH and MED-BF respectively come next after the MED-PF

**Table 4**

Data results for the 1st technique operated by water and HTO fluids.

Parameter	MED-BF	MED-FF	MED-FFH	MED-PF
<i>Solar collector field</i>				
Total solar field area $A_{col}$ , m <sup>2</sup>	1545	3408	1096	1005
Solar field flow rate $m_{col}$ , kg/s	0.572	1.262	0.406	0.372
Solar field $R_e$ number	$1.1 \times 10^4$	$2.75 \times 10^4$	$1.073 \times 10^4$	7980
No. of collectors (LS-3)/no. of loops	2/1	6/1	1/1	1/1
Solar field width $w_{col}$ , m	11	27	10.5	8
Solar collector thermal efficiency $\eta_{col}$ , %	69.7	69.7	69.7	69.7
Solar collector thermal power, kW	271	598	192.5	176.5
Exergy destruction rate, kW	244.5	540	173.5	159
Exergy inlet rate, kW	370.2	816.3	262.6	240.7
Cost stream to BHX, \$/GJ	3.837	3.677	3.911	3.931
<i>Boiler heat exchanger unit</i>				
Area $A_{BHX}$ , m <sup>2</sup>	0.575	1.268	0.408	0.374
Outlet HTO temperature, °C	130	130	130	130
$M_s$ , kg/s	0.1171	0.2583	0.083	0.076
Exergy destruction rate, kW	82.5	182	58.5	53.6
Cost stream to MED, \$/GJ	$5.65 \times 10^{-3}$	$4.82 \times 10^{-3}$	$6.05 \times 10^{-3}$	$6.16 \times 10^{-3}$
Cost stream to pump, \$/GJ	3.837	3.677	3.911	3.931
<i>HTO pump unit</i>				
Power, kW	0.428	0.95	0.304	0.278
Mass flow rate, kg/s	0.572	1.262	0.406	0.372
Exergy destruction rate, kW	0.212	0.4764	0.1507	0.138
Cost stream to PTC, \$/GJ	4.289	4.058	4.406	4.437
<i>MED section (16 effects)</i>				
$M_d$ , kg/s	1.157	1.157	1.157	1.157
$M_f$ , kg/s	2.894	2.894	2.894	2.894
$M_{cw}$ , kg/s	0.702	0.702	0.702	0.702
$M_s$ , kg/s	0.1171	0.2583	0.083	0.076
$T_f$ , °C	36.38	36.38	36.38	36.38
$T_d$ , °C	27.85	27.85	27.85	27.85
TBT, °C	73.53	73.53	73.53	73.53
TVT, °C	72.76	72.76	72.76	72.76
TFT, °C	36.38	36.38	69.92	36.38
Condenser area $A_{cond}$ , m <sup>2</sup>	13	13	13	13
Total effects' area $A_{eff}$ , m <sup>2</sup>	1135.4	2486	800	835
Total feed heaters' area $A_{fh}$ , m <sup>2</sup>	–	–	53	–
Gain ratio (GR) = $M_d/M_s$	9.88	4.48	13.93	15.2
Exergy destruction rate, kW	5136	5168	5135	5134
Cost stream to BHX, \$/GJ	$5.65 \times 10^{-3}$	$4.82 \times 10^{-3}$	$6.05 \times 10^{-3}$	$6.16 \times 10^{-3}$
Product cost stream $c_d$ , \$/GJ	1.756	1.82	1.73	1.72
<i>Performance and cost</i>				
STPC, kWh/m <sup>3</sup>	65.2	143.8	46.25	42.4
$Z^{ICOM}$ , \$/h	10.5	12.75	9.94	9.8
Total plant cost, \$/y	$2.345 \times 10^5$	$4.226 \times 10^5$	$1.88 \times 10^5$	$1.79 \times 10^5$
TWP, \$/m <sup>3</sup>	7.139	12.87	5.75	5.47

**Table 5**

Data results for the 2nd technique operated by toluene and HTO fluids.

Parameter	MED-BF	MED-FF	MED-FFH	MED-PF
<i>Solar collector field</i>				
Total solar field area $A_{col}$ , m <sup>2</sup>	2855	5762	1393	1353
Solar field flow rate $m_{col}$ , kg/s	1.157	2.334	0.564	0.548
Solar field $R_e$ number	$3.28 \times 10^4$	$6.56 \times 10^4$	$1.608 \times 10^4$	$1.608 \times 10^4$
No. of collectors (LS-3)/no. of loops	5/1	10/1	2/1	2/1
Solar field width $w_{col}$ , m	25	50	12	12
Solar collector thermal efficiency $\eta_{col}$ , %	69.7	69.7	69.7	69.7
Solar collector thermal power, kW	501.4	1012	244	237
Exergy destruction rate, kW	445.7	900	217	211
Exergy inlet rate, kW	684	1380	333.6	324
Cost stream to BHX, \$/GJ	3.593	3.454	3.75	3.75
<i>Boiler heat exchanger unit</i>				
Area, m <sup>2</sup>	1524	3.07	0.74	0.722
Outlet HTO temperature, °C	151.5	151.5	151.5	151.5
$M_s$ , kg/s	0.9972	2.012	0.4864	0.472
Exergy destruction rate, kW	62	125	30.26	29
Cost stream to turbine, \$/GJ	0.1026	0.076	0.1417	0.1435
Cost stream to pump, \$/GJ	3.593	3.454	3.75	3.75
<i>Turbine unit</i>				
Power developed, kW	120	241	58.2	56.76
Outlet temperature, °C	111.2	111.2	111.2	111.2
Exergy destruction rate, kW	40.24	82	20	19.07
Cost of power, \$/GJ	3.794	3.17	4.565	4.59
Cost stream to recuperator, \$/GJ	0.1026	0.076	0.1417	0.1435
<i>Recuperator unit</i>				
Power rejected, kW	32	64.2	15.5	15
Area, m <sup>2</sup>	1	2	0.46	0.45
TST, °C	90.67	90.67	90.67	90.67
Preheated stream temperature, °C	101.9	101.9	101.9	101.9
Cost stream to BHX, \$/GJ	2.517	1.845	3.493	3.54
Cost stream to MED, \$/GJ	0.1026	0.076	0.1417	0.1435
<i>Rankine pump unit</i>				
Power, kW	1.162	2.346	0.566	0.55
Mass flow rate, kg/s	0.9972	2.012	0.4864	0.4727
Exergy destruction rate, kW	0.844	1.7	0.411	0.4
Cost stream to recuperator, \$/GJ	38.57	28.3	53.73	54.46
<i>HTO pump unit</i>				
Power, kW	0.428	1.898	0.43	0.417
Mass flow rate, kg/s	0.572	2.334	0.564	0.548
Exergy destruction rate, kW	0.212	1.148	0.258	0.251
Cost stream to PTC, \$/GJ	4.289	3.601	4.046	4.056
<i>MED section (16 effects)</i>				
$M_d$ , kg/s	1.157	1.157	1.157	1.157
$M_f$ , kg/s	2.894	2.894	2.894	2.894
$M_{cw}$ , kg/s	0.6733	0.6733	0.6733	0.6733
$M_s$ , kg/s	0.9972	2.012	0.4864	0.4727
$T_f$ , °C	36.38	36.38	36.38	36.38
$T_d$ , °C	27.85	27.85	27.85	27.85
TBT, °C	88.23	88.23	88.23	88.23
TVT, °C	87.46	87.46	87.46	87.46
TFT, °C	36.38	36.38	84.61	36.38
Condenser area $A_{cond}$ , m <sup>2</sup>	12.93	12.93	12.93	12.93
Total effects area $A_{eff}$ , m <sup>2</sup>	987	1983	480	505
Total feed heaters area $A_{fh}$ , m <sup>2</sup>	–	–	68.7	–
GR	1.16	0.58	2.38	2.45
Exergy destruction rate, kW	5076	5089	5072	5072
Cost stream to BHX, \$/GJ	0.1026	0.0759	0.1417	0.1435
Product cost stream $c_d$ , \$/GJ	1.749	1.799	1.72	1.72
<i>Performance and cost</i>				
STPC, kWh/m <sup>3</sup>	71.13	143.5	43.7	33.7
$Z^{ICOM}$ , \$/h	13.4	17.64	11.1	11
Total plant cost, \$/y	$2.638 \times 10^5$	$4.517 \times 10^5$	$1.686 \times 10^5$	$1.66 \times 10^5$
TWP, \$/m <sup>3</sup>	8.031	13.75	5.132	5.057

configuration. MED-FF configuration did not give the desired performance results as compared to other forms and therefore has been ruled out. Also results revealed that MED-BF cannot compete against MED-PF and/or MED-FFH due to the salinity gradients in the first effect under high steam and brine temperatures. MED-FF and MED-BF configurations are not selected due to the following reasons: (1) The salinity gradients in the first effect (MED-BF) considered in a very high (almost in the range of 60–70 g/kg) concentration and corrosively affect on the tubes status. (2) MED-FF configuration consumes large power while increasing the temperature of the first effect inlet feed stream that comes from the end condenser unit (increasing the TBT normally from 36 °C up to 73 °C). That explained the larger area needed per effect and lower gain ratio compared with the remaining configurations. (3) Both techniques (MED-BF and MED-FF) give lower gain ratio, larger solar collector area, larger effects area, and high total water price compared against the remaining configurations. Unlike other configurations, MED-PF better takes it,

even as compared to MED-FFH configuration gaining less area is required for the solar collector field (1096 vs. 1005 m<sup>2</sup>), which means less cost and less control issues. For both configurations (MED-PF, FFH), the plant under the specified operating conditions (100m<sup>3</sup>/day) would harvest about one module of solar PTC (LS-3 type) with one loop. Due to lower mass flow rate across the solar field (about 0.372 kg/s), and lower solar field area, MED-PF gives lower exergy destruction rate per solar collector against MED-FF (159 vs. 173.5 kW). Although the total heat transfer area ( $A_{eff}$ ) of MED-PF considered was a little bit higher vs. MED-FFH but by adding the heat transfer area of the feed heaters (about  $A_{fh}=53$  m<sup>2</sup>) the total heat transfer area becomes 835 m<sup>2</sup> vs. 853 m<sup>2</sup> giving an advantage to MED-PF configuration. The gain ratio (GR) for MED-PF noticed was higher than MED-FFH (15.2 vs. 13.93) due to the minimum rate of steam needed ( $M_s=0.076$  vs. 0.083 kg/s). The total water price (TWP \$/m<sup>3</sup>) is around 5.7 and 5.4\$/m<sup>3</sup> with a little bit advantage to the MED-PF configuration against MED-FFH. Moreover, thermo-economic unit product cost (\$/GJ) resulted lower ( $c_d=1.72$ \$/GJ) by MED-PF configuration against MED-FFH. Related to this technique, MED-PF configuration was considered the most reliable among the other configurations based on many terms such as total water price, areas, mass flow rates, exergy destruction rates, and gain ratio. However, reducing the number of effects gives an advantage to MED-FFH configuration against the MED-PF. Therefore, it depends on the designers' decision about the reliable operating conditions, areas, and cost. However, increasing the number of effects ( $N_{eff}$ ) gives an advantage to the desalination plant by reducing the TWP and increasing the GR. Fig. 4 shows the increase of the GR by increasing the  $N_{eff}$ . It is obvious from Fig. 4 that MED-PF and MED-FFH exhibit larger GR against MED-BF and MED-FF respectively. Moreover, when dealing with effects' number less than 8–10 effects, MED-FFH is dominated; however, when going further than 10 effects MED-PF reveals to be more reliable and dependable.

#### 4.2. Results of PSDMED technique

In this technique; electricity power is generated via turbine unit beside freshwater production. Therefore, the system mainly contains solar collector field (PTC LS-3), boiler heat exchanger (BHX), turbine, recuperator for regeneration, pump, and MED desalination plant. Therminol-VP1 (hot saturated liquid) is maintained through the PTC collector; however, Toluene organic fluid (dry saturated steam) is maintained between the organic Rankine cycle (ORC) and the first effect of MED process. Toluene has a high molecular weight (92.138 kg/mol) to reduce the turbine nozzle velocity. Also, it has

reasonable pressure corresponding to boiling temperature. Moreover, it has dry expansion, i.e., positive slope of the vapor saturation curve on T-S diagram, to assure that all expansion states in the turbine exist on the super heat region [19]. Generally, it is so clear from Table 5 that MED-PF shows potential results against the remaining configurations. MED-FFH comes next and followed by MED-BF. MED-FF was considered not applicable due the low performance results obtained based on energy, exergy, and thermo-economic terms. Also MED-BF cannot compete against MED-PF and MED-FFH due to many reasons such as presented in the previous subsection. Therefore, MED-BF and MED-FF are eliminated from the comparison related to this technique. MED-PF was noticed to be a little bit reliable against MED-FFH by achieving lower solar collector area  $A_{col}$  (about 2.8% less area) meaning by this lowering control and maintenance issues. For both configurations (MED-PF and FFH), the plant would harvest about two modules of solar PTC (LS-3 type) with one loop for each module. Although the total effects' area  $A_{eff}$  for MED-PF was considered a little bit higher vs. MED-FFH but by adding the calculated area of the feed heaters (about 68 m<sup>2</sup>) it becomes 548 m<sup>2</sup> vs. 505 m<sup>2</sup> giving an advantage to MED-PF configuration. The gain ratio (GR) for MED-PF is higher than MED-FFH (2.45 vs. 2.38) due to the minimum rate of steam needed ( $M_s=0.472$  vs. 0.486 kg/s). Total water price (TWP \$/m<sup>3</sup>) is around 5\$/m<sup>3</sup> for both configurations with a little bit advantage to the MED-PF configuration against MED-FFH. Moreover, the thermo-economic unit product cost (\$/GJ) is nearly the same for both configurations. Associated to this technique, MED-PF configuration is the most reliable one among other configurations based on many criteria such as TWP \$/m<sup>3</sup>,  $A_{eff}$  m<sup>2</sup>,  $A_{cond}$  m<sup>2</sup>,  $A_{col}$  m<sup>2</sup>, mass flow rates, exergy destruction rates kW, and gain ratio (GR). The main advantage of this technique is the electricity power produced that could serve up the facilities and auxiliaries in the plant.

#### 4.3. General comparisons: case study

It is clear from the previous analysis that MED-PF configuration is reliable and most elected among the remaining configurations. However, MED-FFH is dominated when less number of effects is operated (normally 8–12 effects). It is very important now to decide which technique is thermo-economically attractive. Consider an example of concentrated solar power plant (CSP) to operate eight effects of MED-PF desalination plant with a capacity of 5000 m<sup>3</sup>/day, and the top steam temperature (TST) is maintained at 73 °C (see reference [10]). The example specification is pointed as follows:

- Sea water temperature  $T_{sea}$ , 27 °C.
- Salt concentration in feed  $S_f$ , 45 g/kg.
- Brine temperature at the last effect  $T_b$ , 40 °C.
- Salt concentration at the reject stream  $S_b$ , 70 g/kg.

SDMED technique consumes about  $1.009 \times 10^5$  m<sup>2</sup> solar collectors with 37 kg/s mass flow rate through the solar field, where the circulation pump consumes about 30 kWe. The gain ratio is about 7.56 with evaporators' total heat transfer area of about 17,425 m<sup>2</sup> of MED-PF effects. The product TWP is about 1.645\$/m<sup>3</sup> with specific power consumption about 2.179 kWh/m<sup>3</sup>. For PSDMED technique, the plant harvest about  $1.32 \times 10^5$  m<sup>2</sup> solar collectors with 50.83 kg/s mass flow rate through the field, and the circulation pump consumes about 164.3 kWe. The turbine unit would supply about 5.381 MWe to serve the plant facilities and the rest might supply to the community grid. There is an amount of 4.831 MW of net power ( $P_{net}=P_{tur}-P_{cons}=5.381-0.55$ ) which could be provided to the main electricity grid. The gain ratio is about 3 with evaporators' total heat transfer area about 15,061 m<sup>2</sup> of MED-PF effects. The product TWP is about 1.845\$/m<sup>3</sup> with specific power consumption (SPC) about 2.676 kWh/m<sup>3</sup>. The GR was considered very low (3) in this technique. That is because of the effect of latent heat of vaporization of the toluene which is considered

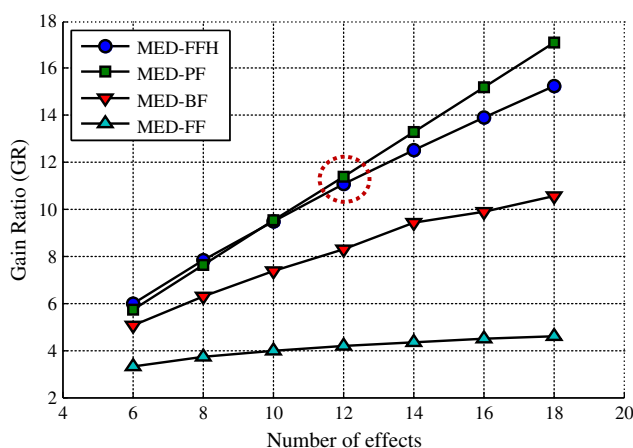


Fig. 4. The GR variations for different MED configurations due to the variations of effect numbers at 100 m<sup>3</sup>/day based on the SDMED technique.



**Table 6**  
Data results for both techniques based on 5000 m<sup>3</sup>/day.

	1st technique: SDMED-PF	2nd technique: PSDMED-PF
$A_{col}$ , m <sup>2</sup>	$1.009 \times 10^5$	$1.32 \times 10^5$
SPC, kWh/m <sup>3</sup>	2.17	2.67
GR	7.56	3
TWP, \$/m <sup>3</sup>	1.645	1.845
$C_d$ , \$/GJ	0.4878	0.4117
$Z^{IC&OM}$ , \$/h		
Total exergy destruction, MW	155.7	157.8
Overall exergy efficiency $\eta_{ex}$ , %	31.82	33.1
Turbine power $P_{tur}$ , MW	–	5.381
$M_s$ , kg/s	7.65	46.05
$A_{eff}$ , m <sup>2</sup>	17,425	15,061

very low compared against the water. Table 6 shows the data comparison between the proposed techniques based on 5000 m<sup>3</sup>/day parallel feed configuration.

It is clear that PSDMED gives a little bit higher values against the SDMED technique comparing based on TWP (\$/m<sup>3</sup>), solar field area  $A_{col}$ , and total exergy destruction rate. However, it is considered attractive based on the results of effects' area  $A_{eff}$ , exergy efficiency  $\eta_{ex}$ , and the developed power by the organic turbine. This is referring to the cost of power developed by the turbine unit to serve the auxiliaries (pumps, fans, and other facilities) through the plant.

Solar collector area might drop by 48% under summer operating conditions. An amount of 64,230 m<sup>2</sup> might be out of service for maintenance and cleaning operations during the summer time.

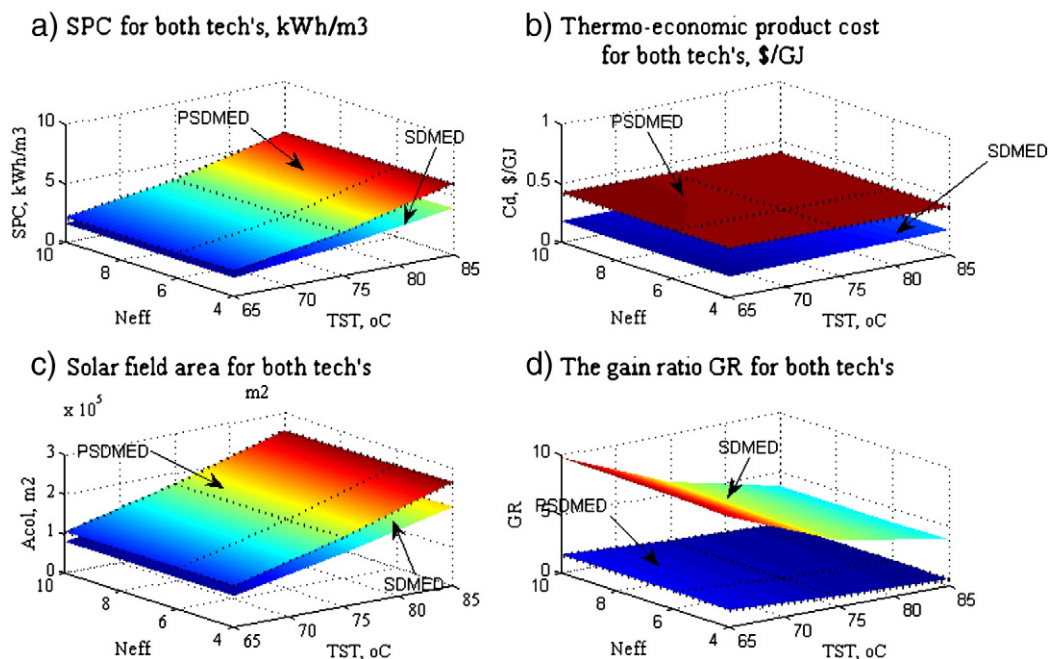
The effect of evaporators' numbers ( $N_{eff}$ ) was considered an essential parameter to moderate the plant performance. Increasing the  $N_{eff}$  would increase the gain ratio thence decreasing the TWP. Fig. 5 shows the effect of evaporators' numbers on SDMED and PSDMED techniques. The results are obtained based on the above case study (5000 m<sup>3</sup>/day). It is pin pointed from Fig. 5-a that increasing  $N_{eff}$  would decrease the SPC kWh/m<sup>3</sup>. That is referring to the effect of total feed flow rate and cooling water flow rate according to the increase of  $N_{eff}$ .

Reducing the mass flow rates would decrease the required pumping power thence the SPC kWh/m<sup>3</sup>. Steam temperature has a rarely significant effect on the SPC; however, increasing the steam temperature would decrease the SPC a little bit. Thermo-economic product cost (\$/GJ) is also decreased by the increasing of the  $N_{eff}$  (Fig. 5-b).

Also the gain ratio (GR) is increased as a direct effect of  $N_{eff}$ . For  $N_{eff}$  around 10, the GR would become 9. However, the opposite behavior significantly happened for evaporators' area. Also, solar field area is gradually decreased by the increase of  $N_{eff}$ . Physically that happened due to the decrease of steam mass flow rate across the heat exchanger unit. As seen from Fig. 5, the steam temperature increases have a negative potential on all performance parameters.

## 5. Conclusion

In conclusion, MED has the advantage of using a low-temperature heat source (around 65–70 °C for either steam or hot water) when it operates at low TBT, and this can give much lower equivalent work or available consumed energy than MSF units. The decrease of  $\Delta T$  to less than 2–3 °C significantly increases the heat transfer areas. It is clear from the literature that MED distillation process can be provided by solar thermal power instead of fossil fuel; however the techniques studied in this field are still in the developing stage. In this work, suggestions are pinpointed to merge between concentrated solar power plants (PTC solar collectors) and different configurations of MED (BF, FF, FFH, and PF) desalination plants (capacity of 100 m<sup>3</sup>/day). The combination is introduced based on two techniques: the first is to transfer the useful energy from the sun collected by solar collector to the first MED effect via boiler heat exchanger unit, and the second is considered the same as the first however adding turbine unit for power generation as an advantage stage before the first effect of MED. Water is chosen as a working fluid for the first technique (without turbine). However, toluene is chosen for the second technique based on its high performance across the turbine unit. Therminol-VP1 heat transfer oil is the organic fluid that is chosen to operate PTC collector (LS-3



**Fig. 5.** Effect of evaporators' number and steam temperature based on both techniques: (a) SPC, kWh/m<sup>3</sup>, (b) thermo-economic product cost, \$/GJ, (c) solar field area, m<sup>2</sup>, and (d) gain ratio.

type). The cycle is compared with the proposed techniques according to the terms of energy, exergy, cost and thermo-economic analyses. Based on the analysis performed in this work, the following conclusions can be drawn:

1. Technical limitations for MED concluded in increasing number of effects up to 16–20 stages and lowering the TBT in the range of 70–75 °C. This may increase the gain ratio; moreover, its effect on total water price is noticed. Also, increasing the effects' number would reduce SPC kWh/m<sup>3</sup>, thermo-economic product cost \$/GJ, condenser area m<sup>2</sup>, and seawater feed mass flow rate.
2. MED-BF is not favorable due to the increase of salt gradient in the 1st effect which also has the highest TBT.
3. MED-FF exhibits lower results against the rest of the MED configurations due to the huge energy loss to increase the preheated feed stream to the desired TBT.
4. Both MED-FFH and MED-PF give attractive results. However, MED-PF was considered most efficient when the number of effects is increased up to 16–18 effects. The use of feed heaters enhances the GR, but adds more complexity, capital cost, and pumping energy.
5. Both technique operations (SDMED and PSDMED) give nearly the same results with a little bit advantage to the 1st technique based on total water price, total solar field area and exergy destruction rate. Also, lower solar field area means lower costs in maintenance and control issues.
6. The second technique has an advantage concluded in developing power but depending on the amount of distillate product and the outlet collector/boiler operating conditions.
7. Toluene gives attractive results however, to develop much power (example of 11MWe), it is recommended to increase outlet collector temperature to 300 °C at the same time increasing the demanded fresh water productivity up to 20,000 m<sup>3</sup>/day. Also, the designer should put into consideration the controlling issues of the large area of the solar field.
8. The electricity provided from power technique could serve for pumps in the same technique and the rest of the power can be implemented into the main grid.

#### Nomenclature

<i>A</i>	Area, m <sup>2</sup>
<i>A<sub>col</sub></i>	Solar field area, m <sup>2</sup>
<i>A<sub>BHX</sub></i>	Boiler Heat Exchanger area, m <sup>2</sup>
<i>A<sub>cond</sub></i>	Condenser area, m <sup>2</sup>
<i>A<sub>eff</sub></i>	Effect heat transfer area, m <sup>2</sup>
<i>A<sub>f</sub></i>	Amortization factor, y <sup>-1</sup>
<i>ACC</i>	Annualized capital cost, \$/year
<i>B</i>	Brine
<i>BHX</i>	Boiler heat exchanger
<i>C</i>	Cost, \$
<i>CC</i>	Capital costs, \$
<i>C<sub>p</sub></i>	Specific heat capacity at constant pressure, kJ/kg K
<i>c<sub>d</sub></i>	Thermo-economic product cost, \$/GJ
<i>D</i>	Distillate
<i>DCC</i>	Direct capital cost, \$
<i>E<sub>x</sub></i>	Exergy rate, kW
<i>E<sub>xin</sub></i>	Exergy in, kW
<i>E<sub>xout</sub></i>	Exergy out, kW
<i>F</i>	Feed
<i>G<sub>b</sub></i>	Daily average direct irradiance, W/m <sup>2</sup>
<i>GR</i>	Gain ratio = Distillate mass flow rate/Steam mass flow rate
<i>h</i>	Specific enthalpy, kJ/kg
<i>I</i>	Exergy destruction rate, kW
<i>I<sub>total</sub></i>	Total exergy destruction rate, kW
<i>ICC</i>	Investment capital costs, \$
<i>IDCC</i>	Indirect capital cost, \$

<i>i</i>	Interest, %
<i>LF</i>	Load factor
<i>LT</i>	Life time, year
<i>M<sub>d</sub></i>	Distillate mass flow rate, kg/s
<i>M<sub>s</sub></i>	Steam mass flow rate, kg/s
<i>MED-BF</i>	Multi effect distillation backward feed arrangement
<i>MED-FF</i>	Multi effect distillation forward feed arrangement
<i>MED-FFH</i>	Multi effect distillation forward feed with feed heaters arrangement
<i>MED-PF</i>	Multi effect distillation parallel cross feed arrangement
<i>m'</i>	Mass flow rate, kg/s
<i>N<sub>pure</sub></i>	Number of moles of pure water, gmol
<i>N<sub>salt</sub></i>	Number of moles of salt, gmol
<i>N<sub>eff</sub></i>	Number of effects
<i>OC</i>	Operating cost, \$
<i>ORC</i>	Organic Rankine cycle
<i>P<sub>net</sub></i>	Net power, MW
<i>P<sub>cons</sub></i>	Consumed power, MW
<i>P<sub>tur</sub></i>	Turbine power, MW
<i>S</i>	Salinity ratio, kg/kg
<i>s</i>	Specific entropy, kJ/kg °C
<i>SHC</i>	Specific heating steam cost, \$/Mkj
<i>SCC</i>	Specific chemical cost, \$/m <sup>3</sup>
<i>SLC</i>	Specific labor cost, \$/m <sup>3</sup>
<i>SPC</i>	Specific power consumption, kWh/m <sup>3</sup>
<i>STPC</i>	Specific thermal power consumption, kWh/m <sup>3</sup>
<i>SEC</i>	Specific electrical cost, \$/kWh
<i>T</i>	Temperature, °C
<i>TBT</i>	Top brine temperature, °C
<i>TFT</i>	Top feed temperature, °C
<i>TST</i>	Top steam temperature, °C
<i>T<sub>sun</sub></i>	Sun temperature, 6000 K
<i>TCC</i>	Total capital cost, \$
<i>TWP</i>	Total water price, \$/m <sup>3</sup>
<i>V</i>	Volume, m <sup>3</sup>
<i>w<sub>col</sub></i>	Solar field width, m
<i>W<sub>t</sub></i>	Turbine work, kW
<i>W<sub>p</sub></i>	Pump work, kW
<i>X<sub>w,s</sub></i>	Fraction of water and salt contents
<i>Z<sup>IC&amp;OM</sup></i>	Total investment and operating and maintenance cost, \$/h

#### Subscripts

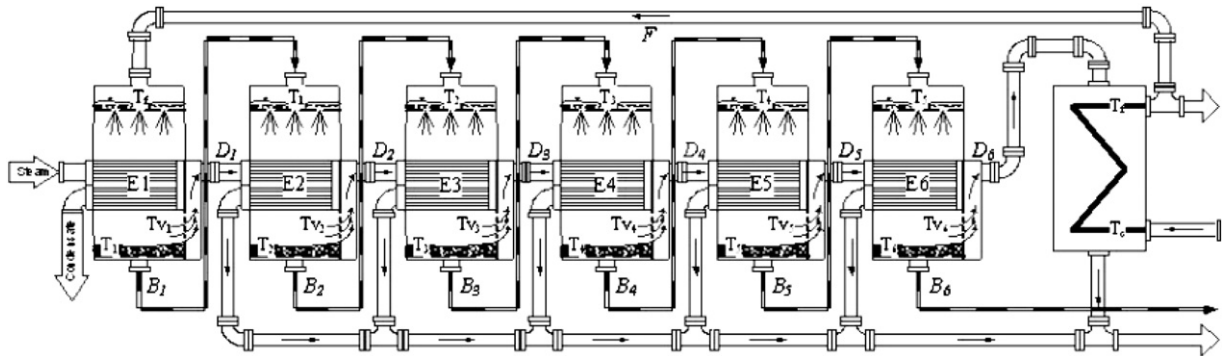
<i>amb</i>	Ambient
<i>av</i>	Average
<i>b</i>	Brine
<i>chim</i>	Chemical
<i>col</i>	Collector
<i>cond</i>	Condenser
<i>cw</i>	Cooling water
<i>d</i>	Distillate product
<i>f</i>	Feed
<i>i</i>	In
<i>MED</i>	Multi effect distillation
<i>o</i>	Out of reference
<i>p</i>	Pump
<i>rec</i>	Recuperator
<i>s</i>	Salt
<i>t</i>	Turbine
<i>w</i>	Water

#### Greek

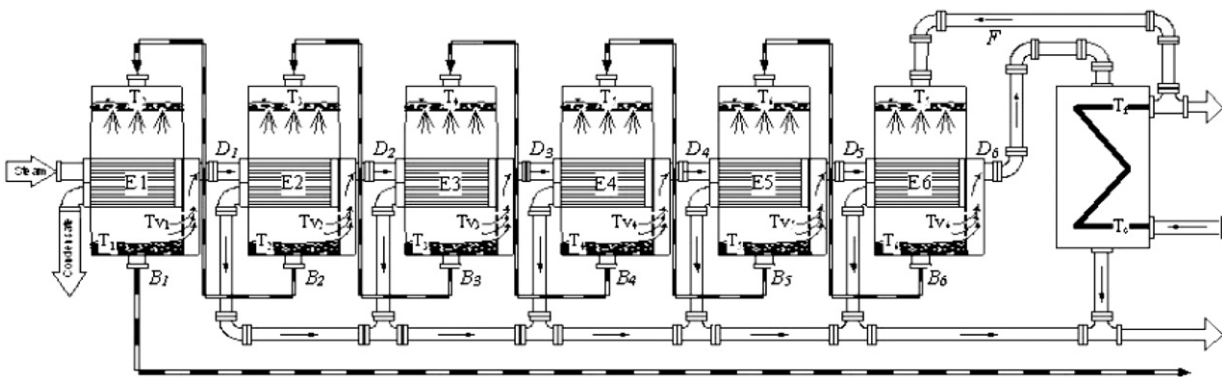
<i>η</i>	Efficiency, %
<i>η<sub>ex</sub></i>	Exergy efficiency, %
<i>η<sub>o</sub></i>	Optical efficiency, %

## Appendix-A

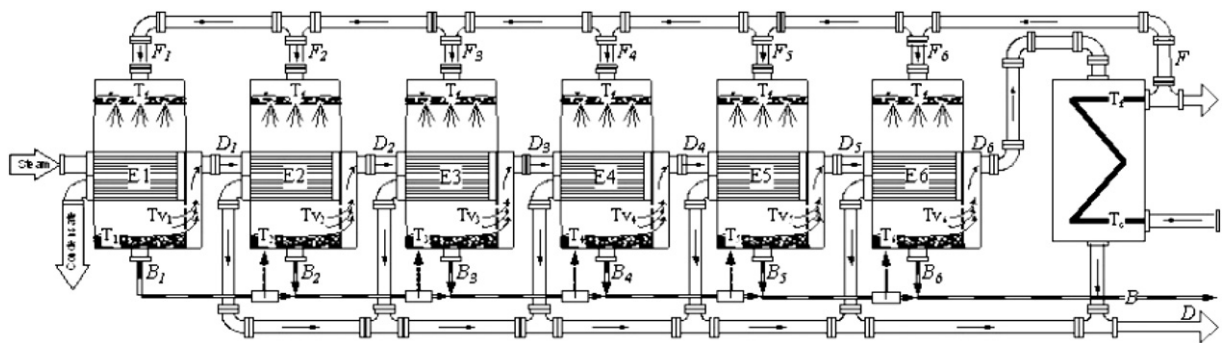
### A-1. MED forward feed configuration



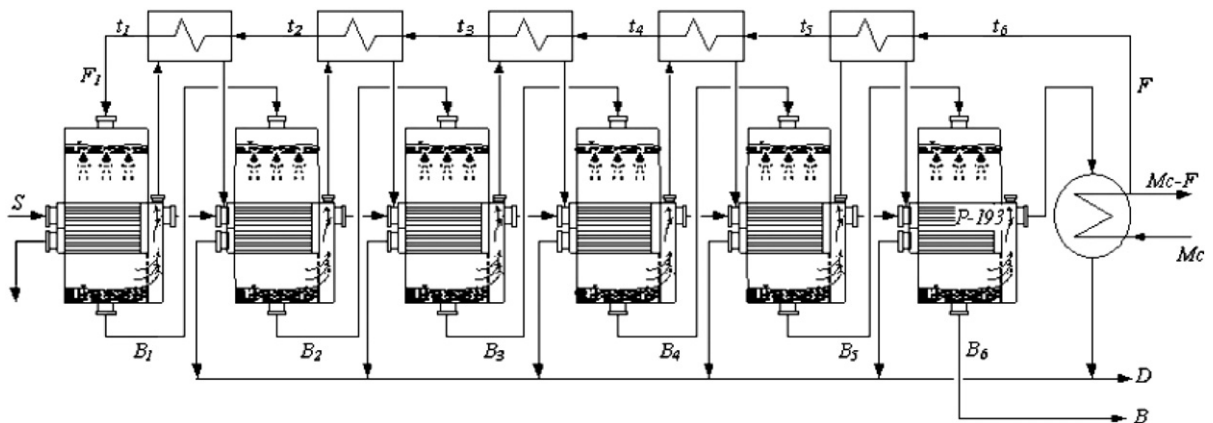
### A-2. MED backward feed configuration



### A-3. MED parallel feed configuration



### A-4. MED forward feed configuration with feed water heaters



## Appendix-B

### B-1. Solar PTC collector

The solar collector instantaneous efficiency can be determined from its characteristic curve using the solar irradiance, mean collector and ambient temperatures. The corresponding efficiency equation for the medium-high temperatures Parabolic Trough Collector (PTC) is given by Eq. (B-1) [22].

$$\eta_{col} = \eta_0 - a_1(T_{co} - T_{amb}) - a_2\left(\frac{T_{co} - T_{amb}}{G_b}\right) - a_3\left(\frac{T_{co} - T_{amb}}{G_b}\right)^2 \quad (B.1)$$

**Table B-1**

Efficiency parameters for PTC collector.

Solar collector	$a_1$ W/m <sup>2</sup>	$a_2$ W/m <sup>2</sup>	$a_3$ W/m <sup>2</sup>	Optical efficiency $\eta_0$	Operating temp, °C
<b>PTC</b>	$4.5 \times 10^{-6}$	0.039	$3 \times 10^{-4}$	0.75	>170–450

The collector total area is estimated based on the collector energy balance equation as a function of collector efficiency as:

$$A_{col} = Q_u / \eta_{col} G_b \quad (B.2)$$

where  $Q_u$  is the collector useful thermal power, ( $G_b$ ) is the normal beam solar radiation (W/m<sup>2</sup>) hits of the collector surface area, and  $A_{col}$  is the collector area. The collector useful energy equation may exist according to the following relation:

$$Q_u = m_{col}^* \times \Delta h \quad (B.3)$$

### B-2. Exergy analysis

Unlike energy, which is conserved in any process according to the first law of thermodynamics, exergy is destroyed due to irreversibility taking place in any process, which manifests itself in entropy creation or entropy increase. The general form of the exergy is defined by the following equation:

$$Ex_2 - Ex_1 = Ex_q + Ex_w + Ex_{ft} - Ex_{fo} - \dot{I} \quad (B.4)$$

where  $Ex_2 - Ex_1 = 0$  is the non-flow exergy change in steady state condition,  $Ex_q = \sum_j (1 - T_{amb}/T_j) Q_j$  is the exergy transfer due to the heat transfer between the control volume and its surroundings,  $Ex_w = -W_{cv} + P_o(V_2 - V_1)$  is equal to the negative value of the work produced by the control volume but in most cases the control volume has a constant volume, therefore  $Ex_w$  can be further simplified, and  $I = T_{amb} \times S_{gen}$  is the exergy destruction in the process. The flow availability is expressed as  $Ex_{ft,o} = \sum_{i,o} m_{i,o}^* e_{ft,o}$ . So the general form in steady state condition would become;

$$0 = Ex_q + Ex_w + Ex_{ft} - Ex_{fo} - \dot{I} \quad (B.5)$$

The exergy destruction rate (kW) in solar collector is obtained by [28] as follows:

$$\dot{I}_{collector} = A_{col} \times G_b \times \left(1 + \frac{1}{3} \left(\frac{T_{amb}}{T_{sun}}\right)^4 - \frac{4}{3} \left(\frac{T_{amb}}{T_{sun}}\right)\right) + m_{col}^* [h_i - h_o - T_{amb}(S_i - S_o)] \quad (B.6)$$

Bejan [25] has recommended  $T_{sun} = 6000$  K and this value is used in this study.

$$\dot{I}_{turbine} = \dot{m}[\Delta h_{i-o} - T_{amb} \times \Delta S_{i-o}] - W_{turbine}^* \quad (B.7)$$

$$\dot{I}_{rec,cond} = m_{hot}^* [\Delta h_{i-o} - T_{amb} \times \Delta S_{i-o}]_{hot} + m_{cold}^* [\Delta h_{i-o} - T_{amb} \times \Delta S_{i-o}]_{cold} \quad (B.8)$$

$$\dot{I}_{pump} = \dot{m}[\Delta h_{i-o} - T_{amb} \times \Delta S_{i-o}] W_{pump}^* \quad (B.9)$$

$$\dot{I}_{MED} = \Delta Ex_{stream}^* + W_{pumps}^* - W_{turbine} + Ex_f^* - Ex_b - Ex_d \quad (B.10)$$

where  $Ex_f^*$  represents the chemical and physical exergy of seawater feed stream to the MED effects,  $Ex_b$  is the exergy stream associated with brine and neglected as loss stream, while  $Ex_d$  is the chemical and physical exergy stream of distillate product, and  $\Delta Ex_{stream}^*$  is the exergy stream of steam conditions based on inlet and outlet cases. The term " $W_{turbine}^*$ " is vanished in the case of the PSDMED technique. Exergy of saline streams is obtained based on physical and chemical components. For the physical part, the exergy streams for 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 [31] where:

$$h_{f,d,b} = h_o + \left(A \times T + \frac{B}{2} \times T^2 + \frac{C}{3} \times T^3 + \frac{D}{4} \times T^4\right) \quad (B.11)$$

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:

$$Ex_{ph}^* = m^* \left( C_p(T, S) \times (T - T_o) + C_p(T, S) \log \frac{T}{T_o} \right), \quad (B.12)$$

( $T_o$  = reference temperature)

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

$$Ex_{ch}^* = m \left( N_{mol}(S, M_w, M_s) \times 10^{-3} \times 8.314 \times T_o \{ -X_w \times \log X_w - X_s \times \log X_s \} \right) \quad (B.13)$$

and total stream exergy rate is then calculated,

$$Ex_{total}^* = Ex_{ph}^* + Ex_{ch}^* \quad (B.14)$$

where;

$$X_w = N_{pure}(S, M_w) / N_{mol}(S, M_w, M_s) \quad (B.15)$$

$$X_s = N_{salt}(S, M_w) / N_{mol}(S, M_w, M_s) \quad (B.16)$$

$$N_{pure} = (1000 - S) / M_w \quad (B.17)$$

$$N_{salt} = S / M_s \quad (B.18)$$

$N_{mol} = N_{pure} + N_{salt}$  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. The overall exergy efficiency that is considered in this study is performed based on the following relation:

$$\eta_{ex} = 1 - \frac{I_{total}^*}{E_{xin}^*}$$

### B-3. Cost and thermo-economic analyses

Investment and operating and maintenance cost analyses are performed for each component, solar field, steam turbine, recuperator, boiler heat exchanger (BHX), and pump unit. The interest rate is set as 5%,  $LT_p$  is the plant lifetime and set as 20 years. Tables B-2 and B-3 illustrate the ICC and O&M costs for the cycle components. For the MED part, cost analyses are estimated based on direct capital costs (DCC) and the total capital costs (TCC).

**Table B-2**

ICC and O&M costs for solar organic Rankine cycle components.

Parameter	ICC, \$	O&M, \$	TCC, \$/y	$Z^{IC\&OM}$ , \$/h	Ref
Solar field	$150 \times (A_{col})^{0.95}$	$15\% \times ICC_{col}$	$A_f \times (ICC + O\&M)_{col}$	$TCC_{col}/8760$	[29]
Steam turbine	$4750 \times (W_t)^{0.75}$	$25\% \times ICC_t$	$A_f \times (ICC + O\&M)_t$	$TCC_t/8760$	[29]
Condensers	$150 \times (A_{cond})^{0.8}$	$25\% \times ICC_{cond}$	$A_f \times (ICC + O\&M)_{cond}$	$TCC_{cond}/8760$	[29]
Pump	$3500 \times (W_p)^{0.47}$	$25\% \times ICC_p$	$A_f \times (ICC + O\&M)_p$	$TCC_p/8760$	[29]

**Table B-3**

Cost parameters for MED desalination plant.

Parameter	Correlation	Ref
Interest rate, %	5	
Plant life time, y	20	[21]
Amortization factor, 1/y	$A_f = \frac{i(1+i)^{LT_p}}{(1+i)^{LT_p}-1}$	[30]
Direct capital costs, \$	$DCC = 9 \times 10^5$	[26]
Annual fixed charges, \$/y	$AFC = A_f \times DCC$	[26]
Annual heating steam costs, \$/y	$AHSC = \frac{SHC \times L_s \times LF \times M_d \times 365}{1000 \times PR}, SHC = \frac{1.466}{MJ}$	[26]
Annual electric power cost, \$/y	$AEPC = SEC \times SPC \times LF \times M_d \times 365, SEC = 0.06\$/kWh$	[26]
Annual chemical cost, \$/y	$ACC = SCC \times LF \times M_d \times 365, SCC = 0.025\$/m^3$	[26]
Annual labor cost, \$/y	$ALC = SLC \times LF \times M_d \times 365, SLC = 0.1\$/m^3$	[26]
Total annual cost, \$/y	$TAC_{MED} = AFC + AHSC + AEPC + ACC + ALC$	[26]
Operating and maintenance costs, \$	$OMC_{MED} = 0.02 \times DCC$	[26]
Hourly operating and maintenance costs in \$/h	$Z_{MED}^{IC\&OM} = \frac{OMC_{MED} \times A_f + AFC}{8760}$	[26]
The total plant costs, \$/y	$TPC = TCC_{col} + TCC_{bhx} + TCC_{rec} + TCC_p + TCC_t + TAC_{MED}$	[26]
Total water price \$/m <sup>3</sup>	$TWP = TPC / (D_p \times 365 \times LF)$	[26]

The cost stream equation from pump unit to solar collector should become as follows:

$$C_{pump-col} = C_w + C_{bhx-pump} + Z_{pump}^{IC\&OM} \quad (B.19)$$

So, the unit product cost for the pump should become

$$C_{pump-col} = \frac{C_w Ex_w + C_{bhx-pump} Ex_{bhx-pump} + Z_{pump}^{IC\&OM}}{Ex_{pump-col}} \quad (B.20)$$

For solar collector, the relation should become

$$C_{col-bhx} = C_q + C_{pump-col} + Z_{col}^{IC\&OM} \quad (B.21)$$

The product cost rate from solar collector field to the boiler heat exchanger unit would be as follows:

$$C_{col-bhx} = \frac{C_{p-col} Ex_{p-col} + Z_{col}^{IN\&OM}}{Ex_{col-bhx}} \quad (B.22)$$

Thermo-economic balance for boiler heat exchanger unit is found to be as follows:

$$C_{bhx-med} + C_{bhx-pump} = C_{col-bhx} + C_{med-bhx} + Z_{bhx}^{IC\&OM} \quad (B.23)$$

The unit product cost stream from boiler heat exchanger to the condenser unit is performed as;

$$C_{bhx-med} = \frac{C_{med-bhx} Ex_{med-bhx} + Z_{bhx}^{IC\&OM}}{Ex_{bhx-pump}} \quad (B.24)$$

and  $C_{bhx-pump} = C_{col-bhx}$

For recuperator unit,

$$C_{rec-bhx} + C_{rec-med} = C_{st-rec} + C_{p-bhx} + Z_{rec}^{IC\&OM} \quad (B.25)$$

Assuming that  $C_{rec-bhx} = C_{p-bhx}$  so, for MED process streams,

$$C_d + C_{brine} + C_{steam-p} = C_{steam-med} + C_{fi} + Z_{med}^{IC\&OM} \quad (B.26)$$

where  $C_d$  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 inlet feed stream cost and is estimated to be 0.3284\$/h for both techniques. So the relation for thermo-economic distillate cost would become as follows:

$$C_d = \frac{C_{fi} E_{fi} + C_{steam-med} \Delta Ex_{steam} + Z_{med}^{IC\&OM}}{Ex_d} \quad (B.27)$$

## References

- [1] E. Zarza, J. Blanco, Advanced MED solar desalination plant: seven years of experience at the Plataforma Solar de Almería, Proceedings of the Mediterranean conference on renewable energy sources for water production. EURORED network, 1996, pp. 45–49.
- [2] M. Bernhard, E. Zarza, Advanced MED solar desalination plants: configurations, costs, future—seven years of experience at the Plataforma Solar de Almería (Spain), Desalination 108 (1996) 51–58.
- [3] M.A. Darwish, Technical aspects of reducing desalting water costs in distillation methods, Desalination 72 (1989) 381–393.
- [4] M.A. Darwish, Faisal Al-Juwayhel, H. Abdurrahman, Multi-effect boiling systems from an energy viewpoint, Desalination 194 (2006) 22–39.
- [5] El-Nashar, Abu Dhabi solar distillation plant, Desalination 52 (1985) 217–234.
- [6] Belessiotis, E.E. Delyannis, The history of renewable energies for water desalination, Desalination 128 (2) (2000) 147–159.
- [7] A.A. Madani, Economics of desalination systems, Desalination 78 (1990) 187–200.
- [8] E.E. Delyannis, Status of solar assisted desalination: a review, Desalination 67 (1987) 3–19.
- [9] K.S. Spiegler, Y.M. El-Sayed, The energetic of desalination processes, Desalination 134 (2001) 109–128.
- [10] A.S. Nafey, H.S. Fath, A.A. Mabrouk, Thermo-economic investigation of multi effect evaporation (MEE) and hybrid multi effect evaporation–multi stage flash (MEE-MSF) systems, Desalination 201 (2006) 241–254.
- [11] A. Piacentino, E. Cardona, Advanced energetics of a Multiple-Effects-Evaporation (MEE) desalination plant. Part II: potential of the cost formation process and prospects for energy saving by process integration, Desalination 259 (2010) 44–52.
- [12] Hoseyn Sayyaadi, Arash Saffari, Thermo-economic optimization of multi effect distillation desalination systems, Applied Energy 87 (2010) 1122–1133.
- [13] [www.therminol.com](http://www.therminol.com).
- [14] A.S. Nafey, M.A. Sharaf, Lourdes García-Rodríguez, A new visual library for design and simulation of solar desalination systems (SDS), Desalination Journal (2010).
- [15] A. Ophir, F. Lokiec, Advanced MED process for most economical sea water desalination, Desalination 182 (1–3) (2005) 187–198.
- [16] M.A. Darwish, H. Abdurrahman, Feed water arrangements in a multi-effect desalting system, Desalination 228 (2008) 30–54.

- [17] Lourdes Garcia-Rodriguez, Carlos Gomez-Camacho, Conditions for economical benefits of the use of solar energy in multi-stage flash distillation, *Desalination* 125 (1999) 133–138.
- [18] Agustín M. Delgado-Torres, Lourdes García-Rodríguez, Preliminary assessment of solar organic Rankine cycles for driving a desalination system, *Desalination* 216 (2007) 252–275.
- [19] A.S. Nafey, M.A. Sharaf, Combined solar organic Rankine cycle with reverse osmosis desalination process: energy, exergy, and cost evaluations, *Renewable Energy* 35 (2010) 2571–2580.
- [20] Moustafa M. Elsayed, Ibrahim S. Taha, Jaffar A. Sabbagh, *Design of Solar Thermal Systems*, Scientific Publishing Center, King Abdulaziz University, Jeddah, (1994) 57–61, (book).
- [21] Agustín Manuel Delgado-Torres, García-Rodríguez Lourdes, Comparison of solar technologies for driving a desalination system by means of an organic Rankine cycle, *Desalination* 216 (2007) 276–291.
- [22] J. Blanco, Technical comparison of different solar-assisted heat supply systems for a multi-effect seawater distillation unit, ISES Solar World Congress, 2003.
- [23] WLi Kam, *Applied Thermodynamics—Availability Method and Energy Conversion*, University of North Dakota State, 1995, (Chaps 1,2,3).
- [24] A.S. Nafey, M.A. Sharaf, Lourdes García-Rodríguez, Thermo-economic analysis of a combined solar organic Rankine cycle-reverse osmosis desalination process with different energy recovery configurations, *Desalination* 261 (2010) 138–147.
- [25] Adrian Bejan, George Tsatsaronis, Micheal Moran, *Handbook of Thermal Design and Optimization*, Wiley, New York, 1996, Chapter 8 (book).
- [26] Hisham T. El-Dessouky, Hisham M. Ettouney, *Fundamental of Salt Water Desalination*, Kuwait University, Elsevier Science, 2002, (book).
- [27] Vicente Romero-Ternero, Lourdes Garcia-Rodriguez, Carlos Gómez-Camacho, Exergy analysis of a seawater reverse osmosis plant, *Desalination* 175 (2005) 197–207.
- [28] Fawzi Banat, Nesreen Jwaied, Exergy analysis of desalination by solar-powered membrane distillation units, *Desalination* 230 (2008) 27–40.
- [29] N.G. Voros, C.T. Kiranoudis, Z.B. Maroulis, Solar energy exploitation for reverse osmosis desalination plants, *Desalination* 115 (1998) 83–101.
- [30] A. Malek, M.N. Hawlader, J.C. Ho, Design and economics of RO seawater desalination, *Desalination* 105 (1996) 245–261.
- [31] Nafey AS, Design and simulation of seawater—thermal desalination plants II, Leeds University, Ph.D. thesis, 1988.