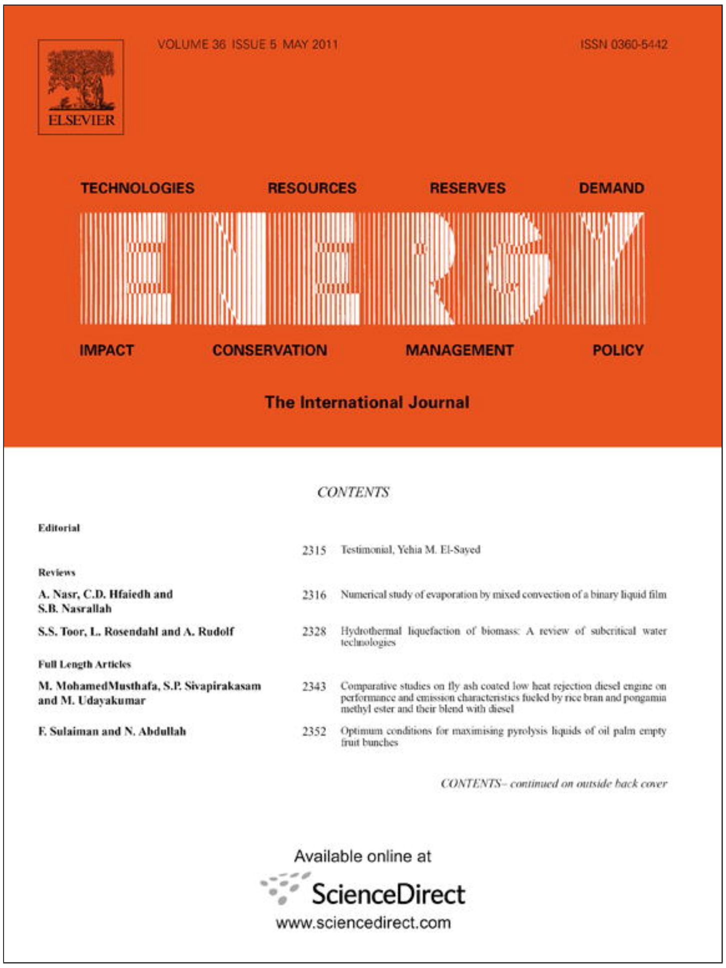

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Thermo-economic analysis of solar thermal power cycles assisted MED-VC (multi effect distillation-vapor compression) desalination processes

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ABSTRACT

Solar power assisted different techniques of MED-VC (multi effect distillation-vapor compression) processes is thermo-economically analyzed and evaluated. In this work, two techniques of solar power cycles are considered to power on MED-PF-TVC, MVC (multi effect distillation thermal and mechanical vapor compressions). In the first technique, the developed solar thermal power is directly transmitted from the solar collector field via boiler heat exchanger unit toward the steam ejector of the MED-PF-TVC process. In the second technique, the electrical power generated from the SORC (Solar Organic Rankine Cycle) is used to power on the vapor compressor of the MED-PF-MVC process. The comparison is implemented according to the operation of PTC (parabolic trough collector) with Toluene organic oil and Water working fluids (2nd technique). Therminol-VP1 HTO (Heat Transfer Oil) is considered across the solar field and water is considered for boiler heat exchanger (1st technique). A case study is performed according to 4545 m^3/day of distillate product. As a result, reducing the value of compression ratio with increasing the evaporator's numbers would reduce the specific power consumption, solar field area, and thermo-economic costs. Also it is clear that the operation of steam ejector would increase the gain ratio instead of increasing the evaporator's numbers.

1. Introduction

Countries in south Mediterranean basin 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 commercial level [1]. 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 MED (Multi Effect Distillation) and a solar trough field as the heat source is one of the most promising [2]. MED desalination plants could be improved by adding thermal or mechanical vapor compression devices. Steam ejector could be added to MED to operate it thermally and the plant known as MED-TVC (multi effect distillation thermal vapor compression). Also, vapor compressor could be added to MED plant and mechanically be operated and this operation is known as MED-MVC (multi effect distillation mechanical vapor compression). The main advantages of the TVC system which have created more interest in the last decade are the reuse of the compressed vapor as heating steam drastically reduces the required steam (motive steam) and the boiler size as well as the heat sink (i.e., cooling water and condenser). Also, Low amount of energy is used to operate the system, and low capital and construction costs. Moreover, the simplicity of the steam ejector, with no moving parts, gives a forward step compared against the mechanical vapor compression system using a mechanical compressor [3]. However; MEE–MVC is compact and confined. Another advantage of the MED-MVC system is the absence of the down condenser and the cooling water requirements [4]. However; MVC systems can't be operate for capacities exceeding over 5000 m^3/d. Both operations can favorably be powered and driven by CSP (concentrated solar power plants). CSP's operated by PTC (parabolic troughs) can offer a massive thermal or mechanical power to MED-VC processes.

Sufficient thermal power can operate MED-TVC via BHX (boiler heat exchanger) unit, however; SORC (solar organic Rankine cycle) can produce electricity via turbine unit that would be sufficient enough for MED-MVC process. However, such kind of solar desalination technologies is still far away from application. There are

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a very limited number of papers published in this regard. Regarding to thermal vapor compression with steam ejector, Almeria, Spain, at the PSA (Plataforma Solar de Almeria): A parabolic trough solar field was connected to a 14 effect-MED-TVC plant with capacity of 72 m^3/d [5]. Suzuki et al. [6] analyzed the technical performance of solar heating systems that use vapor-compression cycles. The results by Suzuki et al. [6] indicated that the vapor-compression system can collect almost 50% more solar energy than a conventional system if the collector areas of the two systems are the same. Chinnappa et al. [7] described a hybrid air-conditioning system consisting of a conventional R-22 vapor compression refrigeration system cascaded with a solar-operated, ammonia-water, and vapor absorption system. It was found to yield considerable savings in electrical energy consumption by the compression system. Badawi et al. [8] demonstrated a scheme where steam, generated from solar collectors, is used to drive a multiple-effect still with novel high performance rotating-disk wiped-film evaporators, thus resulting in an order of magnitude reduction of collector area.

For solar assisted MVC, Helal et al. [9] presented a diesel-solar-assisted MVC desalination system to provide small communities at remote areas with fresh water. The system utilized solar-PV to produce water capacity of 120 m^3/d. The system was depending on diesel engine to overcome uncertainties of solar energy. For solar powered VC, the technology is still away from the study. Moreover; most of the literature work on solar assisted TVC is concerned about refrigeration and cooling cycles that utilizes steam ejector. Significantly, the possibility of utilizing solar thermal power with MED-VC is in the scope however, it is still not well developed. Moreover, the technique of such utilization, mathematical model representing the process, examining different types of solar collectors and different working fluids also needs more investigation.

In this work, two configurations of MED-VC desalination process powered by two different techniques of solar thermal power cycles are thermo-economically investigated and analyzed. The analyses are introduced for MED-VC according to a capacity of 4545 m^3/day. The techniques studied in this work are: The 1st technique is performed to utilize the solar thermal power by using the concentrator (PTC) to deliver thermal power via BHX to drive MED-TVC directly through the steam ejector. However; the 2nd technique is performed to utilize the electric power from solar organic Rankine cycle to power on the MED-MVC. Both techniques use Therminol-VP1 [10] HTO (heat transfer oil) for indirect vapor generation via boiler heat exchanger unit. A capacity of 4545 m^3/day is planned in this study. The analyses are introduced based on thermo-economic mathematical approach. The comparison is performed to assess the most reliable technique that should be implemented for the use of solar combined MED-VC desalination processes. Also, parallel feed arrangement is considered in for Multi effect distillation process. SDS (Solar Desalination Systems) software package [11] is used to design and simulate the process units for the proposed techniques. The aim of this work may be concluded into the following points:

- Investigating and analyzing the design limitations of utilizing solar power with different techniques of MED-VC desalination process.
- Electing the most reliable MED-VC technique based on energy, exergy, cost and thermo-economic analyses putting in mind the number of MED-PF effects.
- 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).
- Studying the possibility of increasing the evaporators numbers (up to 16 effects) while operating MED-MVC in order to inspect the possibility to achieve higher performance results against MED-TVC.
- Studying the effect of compression ratio and top steam temperature on the gain ratios of the proposed techniques.

2. Solar thermal power cycles for MED-VC processes

Solar energy positively can operate and power on the MED-VC desalination processes according to many reasons such as; low TBT (top brine temperature), low TST (top steam temperature), high gain ratio, and lower specific power consumption comparing against multi-stage flash and/or reverse osmosis desalination types. According to vapor compression type (mechanical or thermal), the combination technique with CSP would be determined from technique to another. The following sub-sections clarify the process techniques and the promise of coupling CSP plants with MED-VC desalination process.

2.1. Solar SMED-PF-TVC: 1st technique

First of all, MED-PF (multi effect distillation parallel feed configuration)-regardless the any other configurations- is confirmed by the literature [12,13] to operate with vapor compression types. In the parallel feed (MED-PF) arrangement, the feed that leaving the condenser is divided and distributed almost equally to each effect. Darwish et al. [12] and Dessouky et al. [13] both gave more details about the seawater feed arrangements related to the MED process. The efficiency of the MED process is extensively improved by compressing the vapor from the last effect. This compression is used in order to increase vapor temperature of the last effect to power on-thermally-the first effect. Therefore; the GR (Gain Ratio) is significantly increased by the coupling of steam ejector unit with the MED process. The steam ejector unit requires motive steam at a pressure of 3–20 bar. Therefore; vapor is removed from the last evaporator at about 0.1 bar and is compressed to about 0.25 bar [14]. Simultaneously, operating conditions (TBT) of MED-PF-TVC allow the use of PTC (parabolic trough collector) in solar power plants [15]. In solar PTC application with desalination, the heated oil is transferred to a BHX unit in order to generate the essential steam for the MED-TVC plant. In this sub-section, the proposed technique consists of pump unit to overcome the pressure losses, solar collector field (PTC-LS-3 type [16]) for thermal power, BHX to generate the essential vapor for the MED process and MED-PF-TVC type with 5 effects. The organic HTO across the PTC would transfer its thermal power to the working fluid (water) that passing across the BHX unit. The generated motive steam is used to compress part of the vapor that generated in the last effect by the operation of the steam ejector. The expanded motive steam and the recompressed vapor that are leaving the steam ejector are directed to and condensed in the first effect. Part of the condensate returns to the BHX unit, and the other part join the potable water product. The vapor formed in the first effect by boiling is directed to the second effect where it acts as a heat source. Fig. 1 shows a schematic diagram of the process units for the 1st technique. Also, Table 1 shows the design criteria related to the 1st technique. The specifications and design parameters for this technique are pin pointed as following:

- Direct normal irradiance under winter operating conditions is assumed for Egypt and Mediterranean countries. It is estimated by reference [17] that the daily average global radiation in a typical day in winter would be in the range of 21$\sim$22 MJ/m^2. To dominate long operation along the day light, the solar radiation would be estimated and fixed at 252 W/m^2 (21.4 MJ/m^2 $\approx$ 503.7 W/m^2 hourly average $\approx$252 W/m^2 daily average). However, under summer conditions it will be expected that

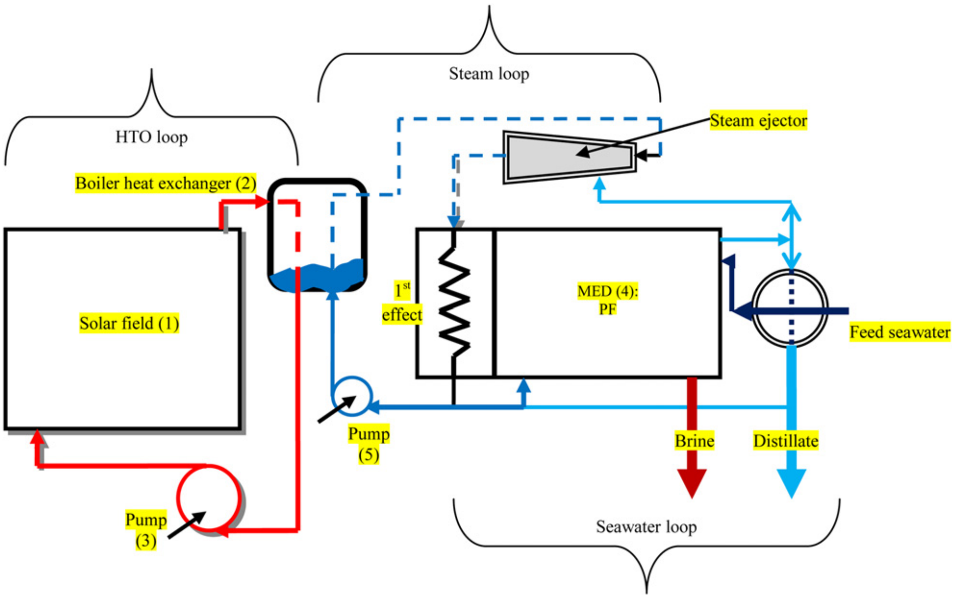

Fig. 1. A schematic diagram of solar MED-PF-TVC components: (1) Solar field, (2) Boiler heat exchanger, (3) HTO pump, (4) MED-PF-TVC.

there is an excessive energy due to large field area and it might be handled through bypassing some loops in the solar field for maintenance operation.

- The distillate product is assigned as 4545 m^3/day (52.6 kg/s), where the inlet seawater feed temperature stream is maintained at 25 °C with a salinity ratio about 46 g/kg. The outlet brine stream temperature is assigned as 48.6 °C where, the number of effects is fixed at 5 effects and the blow down brine salinity ratio is fixed at 69 g/kg.
- According to the design and operating temperature of the proposed HTO and the PTC, the outlet collector temperature would be fixed at 350 °C, and the motive steam pressure is assigned to be 2500 kPa.
- The steam ejector compression ratio is maintained at value 2.
- The isentropic efficiencies of the pumps are maintained at 75% [16].
- Effectiveness of all condensers (BHX and MED end condenser) is assigned at 0.8.
- The design specifications of the PTC are maintained according to LS-3 type [16].

2.2. Solar SMED-PF-MVC: 2nd technique

MED-MVC is one of the attractive techniques for remote and small population areas. The MED-MVC is compact and confined. The system is driven by electric power; therefore, it is suitable for remote population areas with access to power grid lines. It can also be driven mechanically by diesel engine. Another advantage of the MED-MVC system is the absence of the down condenser and the cooling water requirements. MED-MVC system is a viable alternative to the RO (reverse osmosis) systems. The barrier to achieving this potential is the absence of a specially designed steam compressor of a capacity comparable to that of the MSF (multi-stage flash) unit capacity [18]. MED-MVC system has specific power consumption similar to the RO system, which may vary between 6–8 kWh/m^3. However, the MVC system reliability and its plant factor are highly superior to the RO system with value close to 90%. Moreover, the system has much simpler pretreatment system and limited operational problems related to fouling and scaling [19].

During the last two decades, the compressor capacity is increased from values below 500 m^3/d to higher values of 1000 m^3/d. This allowed for the design of three effects MVC units capable of producing 3000 m^3/d. However, more recently, the compressor capacity is increased to a higher value of 5000 m^3/d, which gives a production capacity of 15,000 m^3/d for a three-effect units [13]. It should be noted that the multi effect units has the same power rating as the single unit and the increase in its capacity is approximately proportional to the number of effects. To reduce the specific power consumption (SPC kWh/m^3), the MVC unit is added to the MED-PF with 16 effects. Normally, MED-MVC is operated by 2–4 effects however; in this work, it is very important to increase the

Table 1
Design points for SMED-PF-VC according to the 1st and the 2nd techniques.

Design point:	1st technique (SMED-PF-TVC)	2nd technique (SMED-PF-MVC)
G_b, W/m^2	252	252
T_{amb}, °C	20	20
T_{co}, °C	350	350
η_t,%	–	85
η_g,%	–	95
η_p,%	75	75
Seawater end condenser effectiveness	0.8	–
S-ORC condensation temperature, °C	–	35
Recuperator effectiveness	–	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
Motive steam pressure, kPa	2500	–
Compression ratio (CR)	2	2
T_{bn}, °C	46.8	46.8
Feed salinity, ppm	46,000	46,000
Brine blow down salinity, ppm	69,000	69,000
No. of effects	5	16
Product mass flow rate, kg/s	52.6	52.6
Plant life time, year	20	20
Electric power generation cost, $/kWh	Fixed at 0.06	Calculated
Working fluids	HTO-Water-Seawater	HTO-Toluene-Seawater

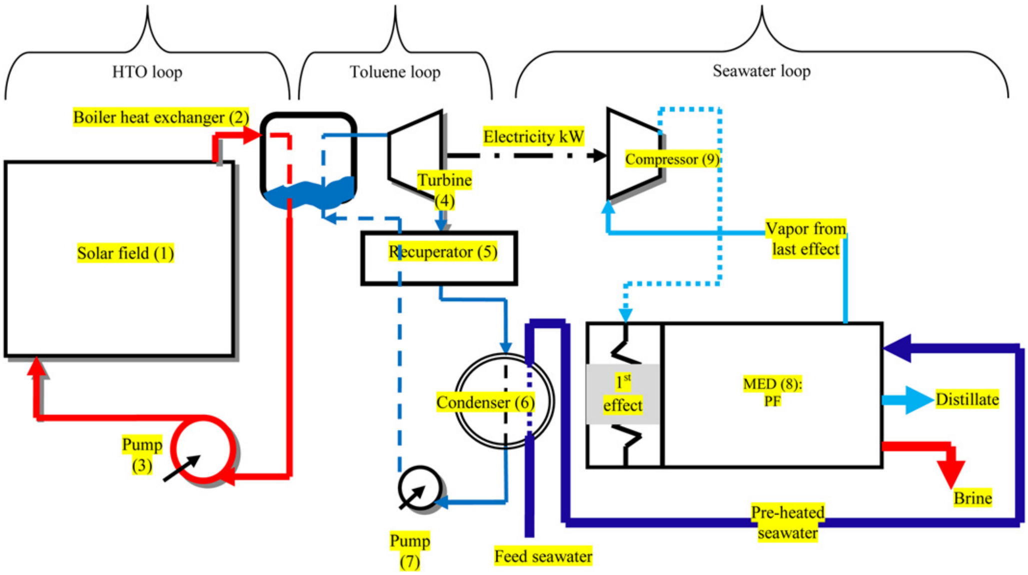

Fig. 2. A schematic diagram of solar MED-PF-MVC components: (1) Solar field, (2) Boiler heat exchanger, (3) HTO Pump, (4) Turbine, (5) Recuperator, (6) Condenser, (7) Pump (8) MED-PF, (9) MVC.

effects up to 16 in order to examine the competitive of the MED-MVC against the MED-TVC. To operate such technique, solar organic Rankine cycle (S-ORC) is dominated to develop the proper electric power for vapor compressor. The process cycle consists of pumps for circulation and pressure drops, solar collector field (PTC), boiler heat exchanger for thermal power exchanging, turbine expander unit, recuperator for regeneration, and MED-PF with 16 effects. The end condenser is removed and the feed seawater is preheated by the ORC condenser before entering the MED-PF plant. Fig. 2 shows a schematic diagram of the process units for the 2nd technique. Table 1 show and summarize the design points for this 2nd technique. The specifications and design parameters for this technique are pin pointed as following:

- Solar radiation and ambient temperature would be fixed at the same as the previous technique (252 W/m^2).
- The distillate product is fixed at 4545 m^3/day, and the inlet seawater feed temperature stream is fixed at 25 °C with a salinity about 46,000 ppm. The outlet brine stream temperature is adjusted as 46.8 °C and the number of effects is fixed as 16 effects. The brine blow down salinity is assumed as 69,000 ppm.
- Due to the operating conditions of the MED-PF and the BHX effectiveness, the collector outlet temperature is maintained at 350 °C (Therminol-VP1) to dominate sufficient saturated vapor (Toluene) that enters the turbine unit in the range of 300 °C. The outlet turbine conditions would be maintained at 35 °C (saturated temperature) putting in consideration the recuperator unit effectiveness and the top steam temperature (TST °C).
- TST °C temperature is controlled at 60 °C putting in consideration the compression ratio. The compressor adiabatic index is assigned as 1.32 with 75% efficiency.

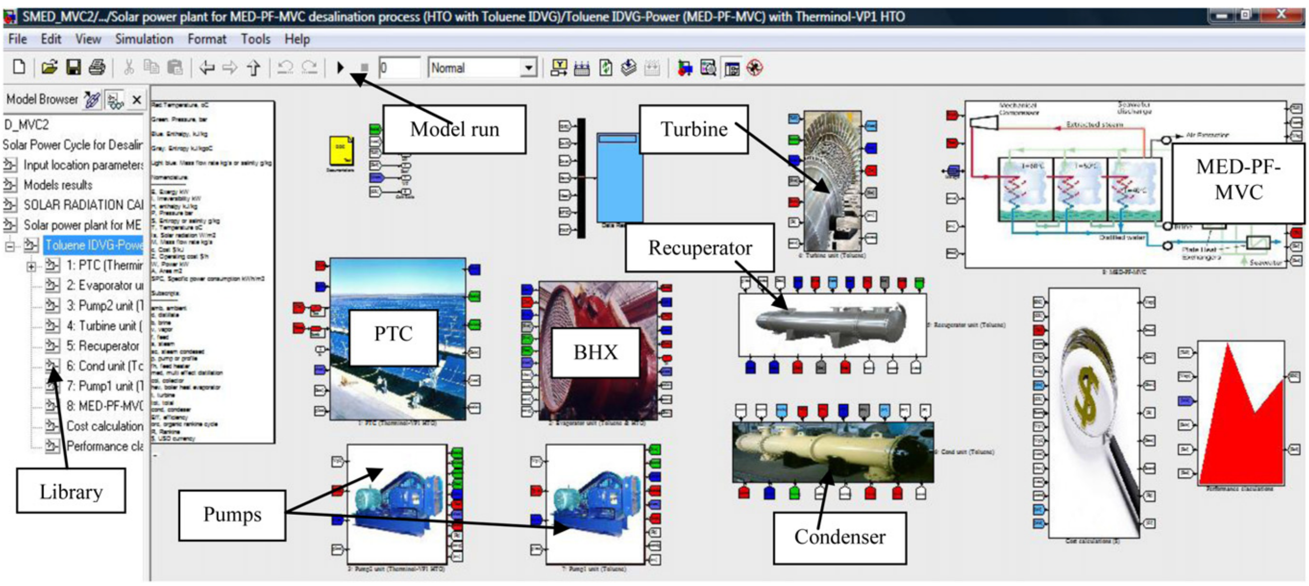

Fig. 3. SDS software panel example for solar organic Rankine cycle assisted MED-PF-MVC desalination process.

Table 2
Data validity results between SDS [11] and MED-PF-TVC process [3].

MED-PF-TVC, with 4 effects, and total productivity = 4545 m^3/d.													
Preheated feed temperature, °C		Brine profile for each effect, °C		Distillate profile, kg/s		Steam mass flow rate, kg/s		Entrained vapor mass flow rate, kg/s		Motive steam mass flow rate, kg/s		Steam pressure, kPa	
SDS [11]	Najem [3]	SDS [11]	Najem [3]	SDS [11]	Najem [3]	SDS [11]	Najem [3]	SDS [11]	Najem [3]	SDS [11]	Najem [3]	SDS [11]	Najem [3]
40.4	40	58.83	58	13.23	14	14.57	14.88	6	6.88	8.6	8	21.92	21.85
		54.8	54	13.177	13.2								
		50.8	50	13.12	12.86								
		46.8	46	13.07	12.56								
				52.597	**52.6**								

Bold value indicates the total productivity in kg/s.

Table 3
Data validity results between SDS [11] and MED-PF-MVC process [4].

MED-PF-MVC, with 2 effects, and total productivity = 1500 m^3/d.											
Brine mass flow rate, kg/s		Feed mass flow rate, kg/s		Vapor temperature, °C		Compression ratio		Compressor power, kW		Evaporators total area, m^2	
SDS [11]	Nafey [4]	SDS [11]	Nafey [4]	SDS [11]	Nafey [4]	SDS [11]	Nafey [4]	SDS [11]	Nafey [4]	SDS [11]	Nafey [4]
12.99	–	21.7	–	65.08	65	1.34	1.35	554.5	553	3650	3710
13.05	–	21.7	–	59.85	60						
26.04	**25.97**	**43.4**	**43.3**								

Bold value indicates the total productivity in kg/s.

- The isentropic and mechanical efficiencies of the turbine are maintained at 85% and 95% respectively. The isentropic efficiencies of the pumps are maintained at 75% [16]?
- The recuperator effectiveness is maintained at 80% [16]
- PTC configuration and design specifications are adjusted according to LS-3 type [16].

3. SDS software package: overview and validity

Using the developed SDS software package [11], different types and configurations of solar thermal desalination plants can be easily designed and simulated. The process units are modeled then the design and performance calculations are performed using the developed SDS program. Different types of calculations such as energy, exergy, and thermo-economics can be performed by the developed SDS package. Desalination plant components (units), such as heat exchangers, flash chambers, evaporators, pumps, pipes, etc. are stored as blocks in a visual library. Using this visual library, different configurations can be constructed by just clicking the mouse over the required units (blocks). To construct such a configuration, the designer needs to drag the required units from the visual library and drop it in the panel. Then these blocks (units) are visually arranged similar to the real plant (for more details, see reference [11]). Fig. 3 shows an SDS example of solar organic Rankine cycle assisted MED-PF-MVC desalination process. Tables 2 and 3 shows the validity of SDS for MED-TVC and MED-MVC processes. It is pointed from validity tables that SDS revels good accuracy with oriented comparison data. The validity results are performed for MED-TVC according to Najem [3] and for MED-MVC according to Nafey [4]. The specifications for Najem's [3] work are pointed as following:

- $M_d = 4545$ m^3/d, $T_{sea} = 30$ °C, $T_{bn} = 46.8$ °C.
- $S_f = 46$ g/kg, $S_b = 69$ g/kg.
- CR = 2.165, Motive steam pressure = 2500 kPa, MED section represented as 4 effects with TST = 60 °C.

The specifications for Nafey's [4] work (MED-MVC with 2 effects) are pointed as following:

- $M_d = 1500$ m^3/d, $M_b = 2244$ m^3/d, Seawater intake = 3744 m^3/d.
- CR = 1.35.
- $S_f = 42$ g/kg, $S_b = 70$ g/kg.

4. 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 [20];

$$Ex_2 - Ex_1 = Ex_q + Ex_w + Ex_{fi} - Ex_{fo} - \dot{I} \quad (1)$$

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 expressed as.$Ex_{fi,o} = \sum_{i,o} m_{i,o}^{\cdot} e_{fi,o}$ So the general form in steady state condition would become;

$$0 = Ex_q + Ex_w + Ex_{fi} - Ex_{fo} - \dot{I} \quad (2)$$

Table 4
ICC and *O&M* costs for solar organic Rankine cycle components.

Parameter	ICC, $	O&M, $	TCC, $/y	$Z^{IC\&OM}$, $/h	Ref
Solar field	$150 \times (A_{col})^{0.95}$	$15\% \times ICC_{col}$	$A_f \times (ICC + O\&M)_{col}$	$TCC_{col}/8760$	[22]
Steam turbine	$4750 \times (W_t)^{0.75}$	$25\% \times ICC_t$	$A_f \times (ICC + O\&M)_t$	$TCC_t/8760$	[22]
Condensers	$150 \times (A_{cond})^{0.8}$	$25\% \times ICC_{cond}$	$A_f \times (ICC + O\&M)_{cond}$	$TCC_{cond}/8760$	[22]
Pump	$3500 \times (W_p)^{0.47}$	$25\% \times ICC_p$	$A_f \times (ICC + O\&M)_p$	$TCC_p/8760$	[22]

Table 5
Cost parameters for MED desalination plant.

Parameter:	Correlation:	Ref:
Amortization factor, 1/y	$A_f = \frac{i\cdot(1+i)^{LTP}}{(1+i)^{LTP}-1}$	[23]
Direct capital costs, $	$DCC = A_f \times 10^5$	[13]
Annual fixed charges, $/y	$AFC = A_f \times DCC$	[13]
Annual heating steam costs, $/y	$AHSC = \frac{SHC\times L_s\times LF\times M_d\times 365}{1000\times PR}, SHC = \frac{1.466\$}{MkJ}$	[13]
Annual electric power cost, $/y	$AEPC = SEC\times SPC\times LF\times M_d\times 365, SEC = 0.06\$/kWh$	[13]
Annual chemical cost, $/y	$ACC = SCC\times LF\times M_d\times 365, SCC = 0.025\$/m^3$	[13]
Annual labor cost, $/y	$ALC = SLC\times LF\times M_d\times 365, SLC = 0.025\$/m^3$	[13]
Total annual cost, $/y	$TAC_{MED-VC} = AFC + AHSC + AEPC + ACC + ALC$	[13]
Operating and maintenance costs, $	$OMC_{MED-VC} = 0.02\times DCC$	[13]
Hourly operating & maintenance cost in $/h	$Z^{ICOM}_{MEX-VC} = \frac{OMC_{MED}\times A_f + AFC}{8760}$	[13]
The total plant costs, $/y	$TPC = TCC_{col} + TCC_{bhx} + TCC_{rec} + TCC_p + TCC_t$	[22]
Total water price $/m^3	$TWP = TPC/(D_p \times 365 \times LF)$	[22]

The exergy destruction rate (kW) in solar collector is obtained by [25] as;

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

Bejan [21] has recommended $T_{sun} = 6000$ K and this value is used in this study.

$$\dot{I}_{turbine} = \dot{m}[\Delta h_{i-o} - T_{amb}\times\Delta S_{i-o}] - \dot{W}_{turbine} \quad (4)$$

$$\dot{I}_{rec,cond} = \dot{m}_{hot}[\Delta h_{i-o} - T_{amb}\times\Delta S_{i-o}]_{hot} + \dot{m}_{cold}[\Delta h_{i-o} - T_{amb}\times\Delta S_{i-o}]_{cold} \quad (5)$$

$$\dot{I}_{pump} = \dot{m}[\Delta h_{i-o} - T_{amb}\times\Delta S_{i-o}] + \dot{W}_{pump} \quad (6)$$

$$\dot{I}_{MED} = \Delta\dot{Ex}_{steam} = +\dot{W}_{pumps} - \dot{W}_{turbine} + \dot{Ex}_f + \dot{Ex}_b - \dot{Ex}_d \quad (7)$$

Where $\dot{Ex}_f$ represents the chemical and physical exergy of seawater feed stream to the MED effects, $\dot{Ex}_b$ is the exergy stream associated with brine and neglected as loss stream, while $\dot{Ex}_d$ 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. The term "$\dot{W}_{turbine}$" is vanished in case of SMED-PF-MVC technique. Exergy of saline streams is obtained based on physical and chemical components. For 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 [26] where;

$$h_{f,d,b} = h_o + \left(A\times T + B/2\times T^2 + C/3\times T^3 + D/4\times T^4\right) \quad (8)$$

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

And;

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

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

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

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

Table 6
Data results for SMED-PF-TVC operated by Water and HTO fluids.

Parameter:	SMED-PF-TVC
Solar collector field:	
High pressure, bar	5.5
Total solar field area, m^2	9.476×10^4
Solar field flow rate, kg/s	33.76
Solar field R_e number	1×10^5
No. of collectors (LS-3)/No. of loops	170/8
Solar field width, m	113
Solar collector thermal efficiency,%	69.7
Solar collector thermal power, kW	1.664×10^4
Exergy destruction rate, kW	1.51×10^4
Exergy inlet rate, kW	2.27×10^4
Cost stream to BHX, $/GJ	3.345
Boiler heat exchanger unit:	
Motive steam pressure, kPa	2500
Area, m^2	57
Outlet HTO temperature, °C	118.3
Motive steam temperature, °C	225.7
Motive steam mass flow rate, kg/s	6.545
Exergy destruction rate, kW	1320
Cost stream to MED, $/GJ	0.00153
Cost stream to pump, $/GJ	3.345
HTO pump unit:	
Power, kW	122
Mass flow rate, kg/s	33.76
Exergy destruction rate, kW	80
Cost stream to PTC, $/GJ	4.744
MED-PF-TVC section (5 effects):	
Productivity, M_d, kg/s	52.6
Total feed seawater M_f, kg/s	168
Cooling flow rate M_{cw}, kg/s	10.16
Feed water to evaporators from end condenser, M_{fl}, kg/s	157.8
Motive steam M_{ms}, kg/s	6.545
Entrained vapor, M_{ev}, kg/s	4.988
Total steam mass flow rate M_{st}, kg/s	11.53
Entrained vapor ratio	1.312
Compressed vapor pressure, kPa	20.25
Steam temperature T_s, °C	60.33
Pre-heated feed temperature T_f, °C	41.81
Distillate temperature from end condenser T_d, °C	29.2
1^{st} effect brine temperature TBT, °C	58.47
1^{st} effect vapor temperature TVT, °C	57.47
1^{st} effect distillate temperature TDT, °C	57.42
$1^{st}/n^{th}$ effect pressure, kPa	17.68/10.12
End condenser area, m^2	532.8
Total effects area, m^2	11,024.61
GR	8.037
Exergy destruction rate, kW	2.693×10^5
Cost stream to BHX, $/GJ	0.00153
Product cost stream, $/GJ	0.2522
Performance & cost:	
Specific power consumption SPC, kWh/m^3	1.58–2
Total Water Price TWP, $/$m^3$	1.323

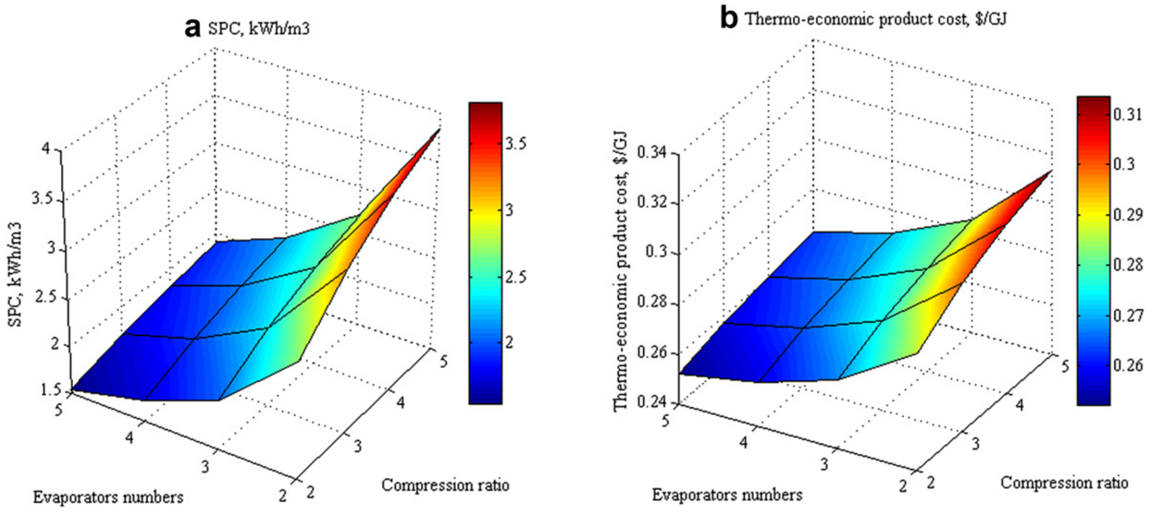

Fig. 4. Effect of CR and number of evaporators on both.

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

$$Ex_{ph}^{\cdot} = m\cdot\left(C_p(T,S)\times(T-T_o)\times C_p(T,S)\log\frac{T}{T_o}\right),$$
$$(T_o = \text{reference temperature}) \quad (9)$$

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

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

And total stream exergy rate is then calculated,

$$Ex_{total}^{\cdot} = Ex_{ph}^{\cdot} + Ex_{ch}^{\cdot} \quad (11)$$

Where;

$$X_w = N_{pure}(S,M_w)/N_{mol}(S,M_w,M_s) \quad (12)$$

$$X_s = N_{salt}(S,M_w)/N_{mol}(S,M_w,M_s) \quad (13)$$

$$N_{pure} = (1000-S)/M_w \quad (14)$$

$$Nsalt = S/M_s \quad (15)$$

$N_{mol} = N_{pure} + N_{salt}$ 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 considered in this study is performed based on the following relation;

$$\eta_{ex} = 1 - \frac{I_{total}^{\cdot}}{E_{xin}^{\cdot}} \quad (16)$$

5. Cost and thermo-economic analysis

In this part, investment and operating & maintenance costs analyses are performed for each unit (solar field, steam turbine, condensers, and pump units). The interest rate set as 5%, LT_p is the plant lifetime and set as 20 years. Tables 4 and 5 illustrate the *ICC* and *O&M* costs for the cycle components.

Thermo-economic is the branch of engineering that combines exergy analysis and economic principles to provide the system

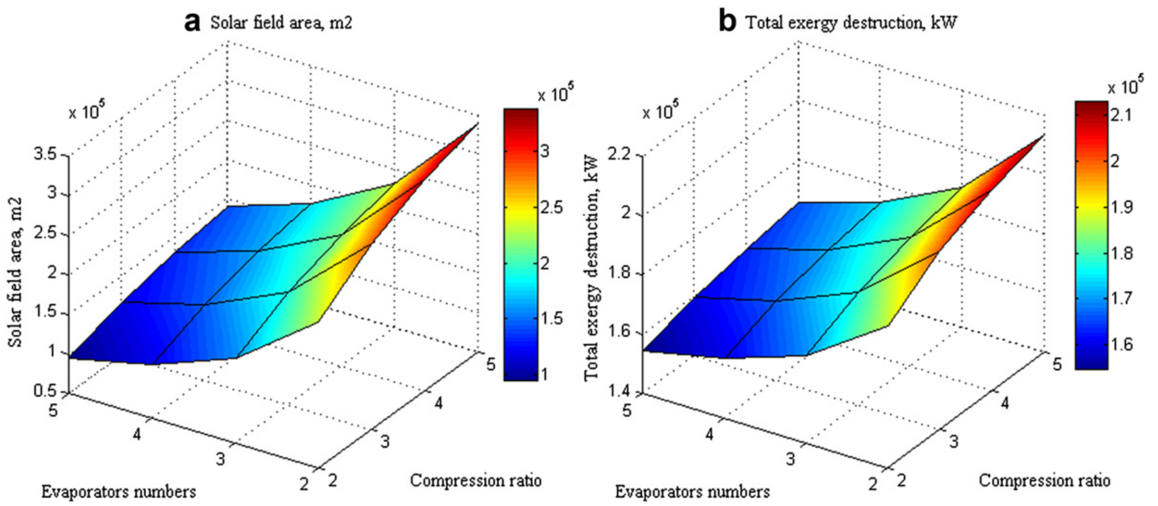

Fig. 5. Effect of CR and number of evaporators on both.

Table 7
Data results for SMED-PF-MVC operated by Toluene and HTO fluids.

Parameter	SMED-PF-MVC
Solar collector field:	
High pressure, bar	5.5
Total solar field area, m^2	1.437×10^4
Solar field flow rate, kg/s	5.815
Solar field R_e number	9.835×10^4
No. of collectors (LS-3)/No. of loops	25/1
Solar field width, m	75
Solar collector thermal efficiency,%	69.7
Solar collector thermal power, kW	2.5204×10^3
Exergy destruction rate, kW	2243
Exergy inlet rate, kW	3442
Cost stream to BHX, $/GJ	3.319
Boiler heat exchanger (BHX) unit:	
Vapor pressure, bar	32.75
Area, m^2	14
Outlet HTO temperature, °C	151.2
Outlet steam temperature to the Turbine, °C	300
Steam mass flow rate, kg/s	4.103
Exergy destruction rate, kW	167
Cost stream to turbine, $/GJ	4.018
Cost stream to pump, $/GJ	3.319
Turbine unit:	
Total power developed, kW	764.53
Exhaust temperature, °C	138.8
Exergy destruction rate, kW	147
Cost of power, $/GJ	6.39
Cost stream to recuperator, $/GJ	4.018
Recuperator unit:	
Power rejected, kW	485
Area, m^2	5
Outlet stream temperature to the condenser, °C	58.1
Outlet stream temperature to the BHX, °C	101.5
Cost stream to BHX, $/GJ	9.663
Cost stream to condenser, $/GJ	4.018
Condenser unit:	
Power rejected, kW	1784
Area, m^2	56
Cost stream to MED-MVC, $/GJ	0.0267
Cost stream to pump, $/GJ	4.018
Rankine pump unit:	
Power, kW	21
Mass flow rate, kg/s	4.103
Exergy destruction rate, kW	19.5
Cost stream to recuperator, $/GJ	5.498
Outlet temperature stream to recuperator, °C	38
HTO pump unit:	
Power, kW	6
Mass flow rate, kg/s	5.815
Exergy destruction rate, kW	3.665
Cost stream to PTC, $/GJ	3.523
MED-PF-MVC section (16 effects):	
Productivity M_d, kg/s	52.6
Total feed mass flow rate M_f, kg/s	157.8
Steam mass flow rate M_s, kg/s	3.525
Pre-heated feed temperature T_f, °C	28
Steam temperature TST, °C	60
1^{st} effect brine temperature TBT, °C	59.91
1^{st} effect vapor temperature TVT, °C	59.13
1^{st} effect distillate temperature TDT, °C	58.88
Vapor compressor power, kW	471.2
Compression ratio	1.939
Total effects area, m^2	9.261×10^5
GR	15
Exergy destruction rate, kW	1.322×10^5
Product cost stream, $/GJ	0.3183
Performance & cost:	
Specific power consumption SPC, kWh/m^3	4.18
Total water price, $/$m^3$	0.94

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 [24]. In a conventional economic analysis, a cost balance is usually formulated for the overall system operating at steady state as following [24];

$$\sum_{out} C\cdot = \sum_{in} C\cdot + Z^{ICOM} \quad (17)$$

Where the cost rate according to inlet and outlet streams, and Z^{ICCOM} is the capital investment and operating & 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 following;

$$\dot{C_{i,o}} = c_{i,o}\dot{E_{i,o}} \quad (18)$$

$$\dot{C_w} = c_w W\cdot \quad (19)$$

$$\dot{C_q} = c_q \dot{E_q} \quad (20)$$

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 balance for the SMED-PF-TVC technique units is developed as following. For turbo machinery units, the cost of electric power is assigned based on the price of the electricity 0.06 $/kWh [13]. Therefore the specific thermal power cost would be converted to become 0.06/3600 $/kJ. The cost equation for the pump unit stream toward the solar collector should become as;

$$C_{pump-col} = C_W + C_{bhx-pump} + Z^{ICOM}_{pump} \quad (21)$$

For solar collector; the relation should become;

$$C_{col-bhx} = C_q + C_{pump-col} + Z^{ICCOM}_{col} \quad (22)$$

Thermo-economic balance for BHX unit is performed as;

$$C_{bhx-med} + C_{bhx-pump} = C_{col-bhx} + C_{med-bhx} + Z^{ICOM}_{bhx} \quad (23)$$

For recuperator unit;

$$C_{rec-bhx} + C_{rec-cond} = C_{turbinr-rec} + C_{pump-bhx} + Z^{ICOM}_{rec} \quad (24)$$

For MED-VC process streams;

$$C_d + C_{brine} + C_{steam-pump} = C_{steam-med} + C_{fi} + Z^{ICOM}_{med} \quad (25)$$

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 feed stream cost.

6. Results and Discussions

6.1. Results of SMED-PF-TVC technique

The in use results about this technicality SMED-PF-TVC to produce what equates 4545 m^3/d exhibition through the next

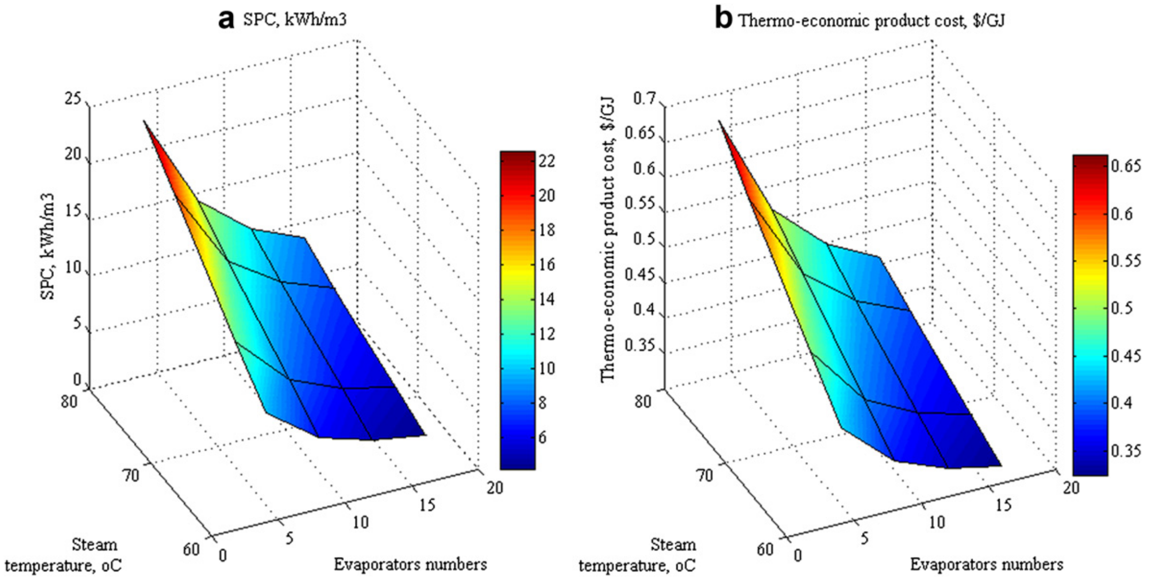

Fig. 6. Effect of Neff and steam temperature on both.

Table 6 is completed here. The results indicated that the complete area for the solar field is around 9.476×10^4 m^2 with total mass flow rate across the solar field reached at 33.76 kg/s. Such consumption harvests what about 170 solar PTC heaters distributed on 8 rows. According for the solar area requested, the total thermal power collected is about 1.664×10^4 kW with total rate of exergy inlet 2.27×10^4 kW and exergy rate of destruction with 1.51×10^4 kW. The cost stream goes from the solar field to the BHX unit reached at 3.345 $/GJ. Based on the quantitative motive steam designating and which informs 2500 kPa, the informed square area of the thermal BHX unit is around 57 m^2, and the degree heat of the steam according for the pressing is around 225 °C. The mass flow rate of the motive steam is about 6.545 kg/s. Based on the demanded thermal load, and the meant solar field area, the informed power of the recirculation organic pump is around 122 kW. For MED-PF-TVC part (five effects), the assigned productivity (52.6 kg/s) exhibits about 168 kg/s as a total feed seawater. The cooling water feed loss from the end condenser is about 10.16 kg/s, however, the required feed seawater for the effects is about 157.8 kg/s. The loss feed seawater (10.16 kg/s) is noticed very low according to many aspects such as increasing the number of evaporators, decreasing the compression ratio, and increasing the end condenser effectiveness. For parallel feed configuration, the feed mass flow rate per each effect considered equivalent about 31.56 kg/s per effect. The motive steam mass flow rate is 6.545 kg/s and the entrained vapor is about 4.988 kg/s with an entrained ratio with a value of 1.312. The steam temperature reaches 60.33 °C with TBT about 58.47 °C and the first effect top vapor TVT (temperature) about 57.47 °C. This temperature loss between TBT and TVT is resulted due to the effect of BPE (boiling point elevation). The end condenser area is 532 m^2 with total heat transfer area for the evaporators about 11024.61 m^2. The Specific Power Consumption (SPC kWh/m^3) for such technique is obtained less than 2 kWh/m^3 with total water price in the range of 1.3$/$m^3$. Also the gain ratio is obtained in the range of 7.8–8 based on only 5 effects. The effect of steam ejector is significantly high on the gain ratio according to the CR (compression ratio) and the

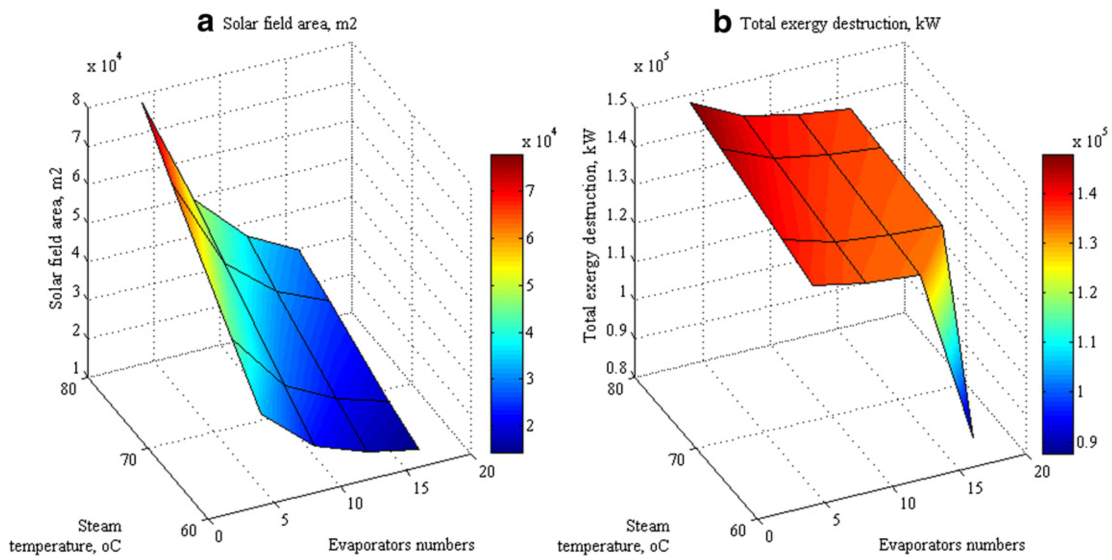

Fig. 7. Effect of Neff and steam temperature on both.

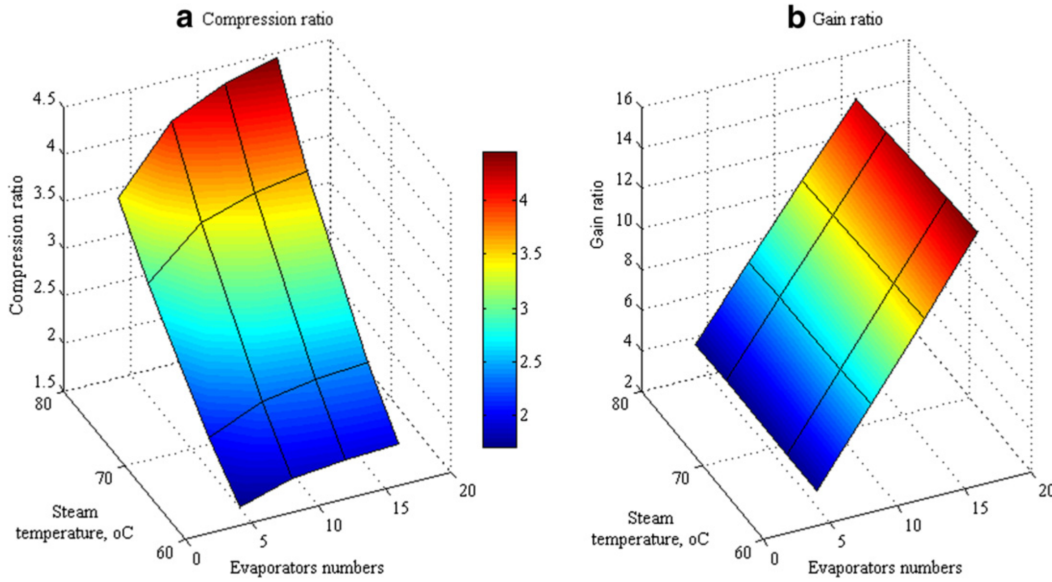

Fig. 8. Effect of Neff and steam temperature on both: (a) CR, and (b) GR.

motive steam pressure. It is evident that without steam ejector at the same number of effects (Neff = 5) the gain ratio would become in the range of 3.5–4. However, adding the steam ejector unit increased the gain ratio up to 8. Figs. 4 and 5 show the effect of CR and number of evaporators (Neff) on SPC, thermo-economic product cost, solar field area, and total exergy destruction rate. Fig. 4a shows that by increasing the CR the SPC would increase, however, the evaporators number increasing would decrease the SPC. Therefore, it is recommended to keep the CR to minimum values related to the desalination plant specifications. In this work, the CR is fixed at value equal to 2 with Neff = 5. Also Fig. 4b shows the same behavior for thermo-economic product cost. The minimum value of thermo-economic product cost (0.25$/GJ) is obtained at CR = 2 and Neff = 5. Also, Fig. 5(a and b) shows that minimum solar field area, and total exergy destruction rate that could be obtained at minimum CR and Neff.

6.2. *Results of SMED-PF-MVC technique*

Results obtained related to this technique are illustrated in Table 7. It is clear that the demanded productivity (4545 m^3/d) would harvest about 1.437 × 10^4 m^2 of solar field with about 5.8 kg/s mass flow rate across the solar collector's loops. Therefore, the solar field contains 25 collectors divided by one loop. Then, the field width should figure as 75 m length. Less in total solar field area means less in total exergy destruction rate. In this technique the rate of exergy destruction is about 2243 kW through the solar field. The power demanded from the desalination plant via vapor compressor is developed by the ORC turbine. Based on the specified design operating conditions for this technique, the obtained area for BHX is about 14 m^2, with mass flow rate across the ORC about 4.1 kg/s. The developed power by the turbine unit is about 765 kW and that considered very low related to the total plant productivity (4545 m^3/d). Recuperator and ORC condenser exhibits areas such 5 and 56 m^2 respectively. The ORC pump consumes about 21 kWe however, the solar field recirculation pump consumes about 6kWe. For MED-PF-MVC section, the total productivity 52.6 kg/s need about 157.8 kg/s of feed seawater where the end condenser unit is eliminated. Therefore, the feed water per each effect become 9.86 kg/s based on Neff = 16 effect. The steam mass flow rate is maintained at 3.52 kg/s and the TBT is maintained at 59 °C. The CR reached at 1.94–2 with total evaporators area about 9.261 × 10^5 m^2. The total evaporator's area considered too large because of the large number of evaporators (Neff = 16). Increasing the Neff would increase the gain ratio (GR = 15). But it is significantly for this technique that the SPC is about 4 kWh/m^3 with thermo-economic product cost with a value of 0.3 $/GJ. In case of comparing with the previous technique, it is found that MED-PF-MVC is remarkable and

Table 8
Data results for both techniques based on 4545 m^3/d.

	1st technique: SMED-PF-TVC				2nd technique: SMED-PF-MVC			
A_{col}, m^2	117,908.9				33,181.5			
SPC, kWh/m^3	2.44				9.68			
GR	6.44				3.82			
TWP, $/$m^3$	1.57				2.1			
c_d, $/GJ	0.2578				0.4265			
M_b, kg/s Profile	26.23	26.27	26.32	26.37	26.23	26.27	26.32	26.37
M_s, kg/s Profile	8.15				13.74			
M_f, kg/s Profile	39.45 (for each effect)				39.45 (for each effect)			
T_b, °C Profile	57.53	53.95	50.37	46.8	57.28	53.79	50.29	46.8
T_v, °C Profile	56.74	53.17	49.59	46.01	56.5	53	49.51	46.01
T_d, °C Profile	56.7	53.12	49.56	46	56.17	52.56	48.93	45.31
P, kPa Profile	17.09	14.41	12.1	10.12	16.68	14.02	11.73	9.76
S_b, kg/kg Profile	0.06918	0.06906	0.068936	0.06881	0.06918	0.06906	0.06893	0.0688
$A_{effects}$, m^2 Profile	4995.76	2206.41	1423.95	1056.05	5008.45	5015.65	5025.3	5037.7

Note: shaded cells gives nearly the same results.

attractive in case of increasing the Neff. The effect of TST and Neff on SPC and thermo-economic product cost is explained in Fig. 6(a and b). It is clear that by reducing the top steam temperature (80 down to 60 °C); at the same time increasing the Neff (up to 16 effects) the SPC and thermo-economic product cost are decreasing gradually. The same behavior is obtained for Fig. 7(a and b) related to solar field area and total exergy destruction rate. Minimum solar field area and total exergy destruction rate are obtained at minimum values of steam temperature (60 °C) and maximum values of Neff (16 effects). However, increasing the Neff would increase the CR. But that effect is significantly low compared with the effect of steam temperature. Steam temperature has a great influence on the CR against Neff. However, Neff has a great influence on the GR compared against the steam temperature (see Fig. 8-a,b).

6.3. General comparison: case study

To distinguish between these two techniques, it is important to united and uniform most of the operating conditions to give clear and real aspects about the best technique. Therefore, the design operating conditions for both techniques are considered as following:

- Seawater temperature = 25 °C.
- Neff = 4 effects.
- CR = 2.
- Steam temperature = 60 °C.
- Blow down brine temperature = 46.8 °C.
- Productivity = 52.6 kg/s.
- Seawater salinity = 46,000 ppm.
- Blow down salinity = 69,000 ppm.
- Motive steam in case of MED-PF-TVC = 25 bar.
- Outlet collector temperature = 350 °C.

Table 8 shows the obtained results for both techniques based on the uniform design operating conditions. It is obvious from the table that the first technique gives remarkable results against the second. Except the solar field area, all performance parameters revels that SMED-PF-TVC considered attractive based on GR, SPC, thermo-economic product cost (C_d), TWP (total water price), and even the area of each effect. Although the 1st technique consumes larger area than the second but the cost of pumping units, turbine and the vapor compressor has a great influence on the total water price and the thermo-economic product cost, hence the SPC. Also the steam mass flow rate for the first technique is less by 40% than the second technique casing an increase in GR for the first technique. Obviously, adding steam ejector unit improves the cycle performances even with less numbers of evaporators.

7. Conclusion

In conclusion, MED-PF-VC has the advantage of using a low-temperature heat source (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. In this work, suggestions are pin pointed to combine between solar filed (PTC solar collectors) and different techniques of MED-PF-VC (TVC and MVC) desalination plant (capacity of 4545 m^3/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 steam ejector of the MED-PF via boiler heat exchanger unit, and the second is to operate the mechanical vapor compression by ORC with toluene working fluid. Water is chosen for the first technique (without turbine). Therminol-VP1 heat transfer oil is chosen to operate through PTC collector (LS-3 type). The cycles are compared with the proposed techniques according to the terms of energy, exergy, cost and thermo-economic analysis. Based on the analysis performed in this work, the following conclusions can be draw:

1. Technical limitations for MED concluded in increasing number of effects up to 16 ~ 20 stages and lowering the TBT in the range of 60–65 °C. This may increase the gain ratio moreover; its effect on total water price is still not noticed. Also, increasing the effects number would reduce the SPC kWh/m^3, the thermo-economic product cost $/GJ, condenser area m^2, and seawater feed flow rate.
2. Decreasing the compression ratio down to a specified limit (CR = 2) may increase the cycle performance and would decrease the SPC kWh/m^3.
3. Increasing the top steam temperature will increase the SPC kWh/m^3 and the CR.
4. SMED-PF-TVC gives attractive results compared against SMED-PF-MVC technique. It achieves lower SPC, steam flow rate, total water price and thermo-economic product cost compared with SMED-PF-MVC technique.
5. Normally, MED-PF-MVC is operated within 2–4 effects however; it could be in competitive standing only by increasing the Neff's more than 12 effects.
6. The existence of steam ejector unit may reduce the need of more evaporators to increase the GR.

Nomenclature

A	Area, m^2
A_{col}	Solar collector area, m^2
$A_{effects}$	Effects heat transfer area, m^2
A_f	Amortization factor, y^{-1}
ACC	Annualized capital cost, $/year
BHX	Boiler heat exchanger
C	Cost, $
CC	Capital costs, $
CR	Compression ratio
c_d	Thermo-economic product cost, $/GJ
C_p	Specific heat capacity at constant pressure, kJ/kgK
DCC	Direct capital cost, $
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
E_{xin}	Exergy in, kW
Ex_{ph}	Physical exergy rate, kW
Ex_q	Exergy transfer, kW
E_{xout}	Exergy out, kW
Ex_w	Exergy of work, kW
GR	Gain ratio, M_d/M_s
G_b	Global solar radiation, W/m^2
h	Enthalpy, kJ/kg
I	Exergy destruction rate, kW
ICC	Investment capital costs, $
$IDCC$	Indirect capital cost, $
i	Interest, %
LF	Load factor
LT	Life time, year
MED-PF	Multi effect distillation parallel cross feed arrangement
MED-PF-MVC	Multi effect distillation parallel cross feed mechanical vapor compression
MED-PF-TVC	Multi effect distillation parallel cross feed thermal vapor compression

$M\cdot$	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
Neff	Number of effects
N_{pure}	Number of moles of pure water, gmol
N_{salt}	Number of moles of salt, gmol
OC	Operating cost, $
P	Pressure, kPa
S	Salinity ratio, g/kg (ppm)
S_b	Brine blow down salinity ratio, g/kg
S_f	Feed seawater salinity ratio, g/kg
S-ORC	Solar organic Rankine cycle
SCC	Specific chemical cost, $/m^3
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
T_d	Distillate temperature, °C
T_{bn}	Last effect brine temperature, °C
T_{sea}	Seawater temperature, °C
TBT	Top brine temperature, °C
TDT	Top distillate temperature, °C
TST	Top steam temperature, °C
TVT	Top vapor temperature, °C
T_{sun}	Sun temperature, 6000 K
TCC	Total capital cost, $
TWP	Total water price, $/m^3
$W_{turbine}$	Turbine power, kW
W_{pump}	Pump power, kW
$X_{w,s}$	Fraction of water and salt contents
V	Volume, m^3
$Z^{IC\&OM}$	Total 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
MED	Multi effect distillation
o	Out
p,pump	Pump
rec	Recuperator
s	Salt, steam
steam	Steam phase
t, turbine	Turbine
v	Vapor
w	Water

Greek

η	Thermal efficiency, %
η_g	Generator efficiency, %
η_p	pump efficiency, %
η_t	Turbine efficiency, %

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