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In this work, two desalination systems combined with a solar energy cycle, MED-PF and MED-PF-TVC are analyzed and evaluated thermo-economically. Solar energy is directly transferred from the solar collector field via the evaporator heat exchanger to MED-PF. In the second technique, the thermal energy produced is transmitted to the steam ejector of the MED-PF-TVC. The comparisons are handled according to 5000 m^3/day of distilled product as a case study. A reduction in consumption and specific energy costs is possible due to the reduction in the value of the compression ratio and the increase in the number of evaporators.

1. Introduction

Water and energy are two inseparable resources which govern the life of humanity and participate in the development of civilization. In fact, all the great civilizations appeared near the main sources of water. History shows the importance of water to maintain life. Perhaps the Nile in Egypt is the best example of this influence. The ancient Egyptian engineers were able to control the water in the river, which has made the country the largest exporter of wheat of all the Mediterranean countries [1].

At present, changing populations and climatic conditions affect many countries around the world. The shortage of fresh water continues to increase. In the Mediterranean region most countries have abundant seawater resources and an excellent level of solar radiation, which could be used as an inexhaustible source to desalinate seawater and meet their water needs. Experts recognize the great potential of seawater desalination by solar thermal energy, but existing technology and due to the specific cost of production cannot currently compete with conventional thermal distillation or reverse osmosis products, and therefore the process is not yet fully developed at commercial level [2].

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Several options to connect a seawater desalination system to a solar power plant are available, a MED thermal desalination system (multi-effect distillation) connected to a concentrated solar power (CSP) is one of the best choices [3]. Adding a thermal vapor compression system can improve the performance of a MED desalination process. The combination of a steam ejector with the MED process for thermal operation is known as MED-TVC (compression of thermal vapor by multi-effect distillation). The reuse of compressed steam is one of the main advantages of the TVC system, the heating steam significantly reduces the steam required as well as the size of the boiler and the condenser.

However, the large-scale application of this type of solar desalination technology remains far from their true potential, generally, hybrid systems are used in order to increase stability as well as production capacity by grading a competitive cost. Currently the race for the new generation of seawater desalination systems has already started with reverse osmosis (RO) and low temperature MED. Their low cost of energy consumption gives them more advantages compared to other systems like Multi Stage Flash (MSF) [4].

In this work, two configurations of the desalination process MED-PF and MED-PF-TVC, supplied by thermal energy of solar origin are studied and analyzed thermo-economically. The analyzes are made for a daily capacity of 5000 m^3/day. The techniques studied in this work are: The same feeding technique is carried out

Nomenclatures

A	Area, m^2
A_{col}	Solar collector area, m^2
$A_{effects}$	Effects heat transfer area, m^2
Af	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
Ex_{in}	Exergy in, kW
Ex_{ph}	Physical exergy rate, kW
Ex_q	Exergy transfer, kW
Ex_{out}	Exergy out, kW
E_{xw}	Exergy of work, kW
ΔEx_{stream}	The exergy stream of steam conditions based on inlet and outlet cases, kW
GR	Gain ratio, Md/Ms
Gb	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-TVC	Multi effect distillation parallel cross feed thermal vapor compression
M	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
N_{eff}	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
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
ZIC&OM	Total investment and operating and maintenance cost,$/h

aiming to transfer the thermal solar energy produced by the PTC concentrator for towards MED-PF (Multi effect distillation parallel feed configuration) and MED-PF-TVC (Multi effect distillation thermal vapor compression). The analyzes are carried out on the basis of a thermo-economic approach. The comparison is made to assess the most reliable technique to use for the use of solar desalination processes and to determine the impact of the TVC technique on technical and economic performance. The Solar Desalination Systems (SDS) software package [5] is used to design and simulate the processing units.

The aim of this work may be concluded into these points:

- Examine and analyze the design limits of the use different solar energy techniques for the two MED process configurations (MED-PF and MED-PF-TVC).
- Compare the performance of the MED configuration based on energy, exergy, cost and thermo-economic data.
- Study the impact of increasing the number of evaporators on performance and the impact of varying other process parameters.

2. Solar thermal power cycles for MED-PF processes (description)

2.1. Solar SMED-PF

MED-PF () is known for its effective adaptation with types of vapor compression [6,7]. In the MED-PF parallel supply model and as illustrated in Fig. 1. The feed that leaving the condenser is distributed equally for each evaporator. More details on the modes of seawater supply relative to the MED process are given by Dessouky et al. [6] and Darwish et al. [7].

The arrangement of the input (feed) is very important because it directly affects the all of the performances of the MED system.

2.2. Solar SMED-PF-TVC

In the SMED-PF-TVC system, the vapor formed in the last effect is introduced into the down condenser. Fig. 2 shows a schematic diagram of the process units SMED-PF-TVC. In the steam jet ejector, the kinetic energy of the driving vapor crosses exponentially and its speed becomes supersonic near the contraction point. The pressure drop created allows more vapor to be drawn [6]. Consequently, the GR (Gain Ratio) is significantly increased by the coupling SMED-PF with TVC.

3. Specifications and design parameters

The operating conditions considered for the two systems are assumed for Morocco (El Jadida) one of the Mediterranean countries (EL Jadida: Latitude [°] = 33,210, Longitude [°] = −8,500, Altitude [m] = 0). Fig. 3 presents the data which is extracted via the "METENORM software" and the Table 1 show and summarize the design points of MED.

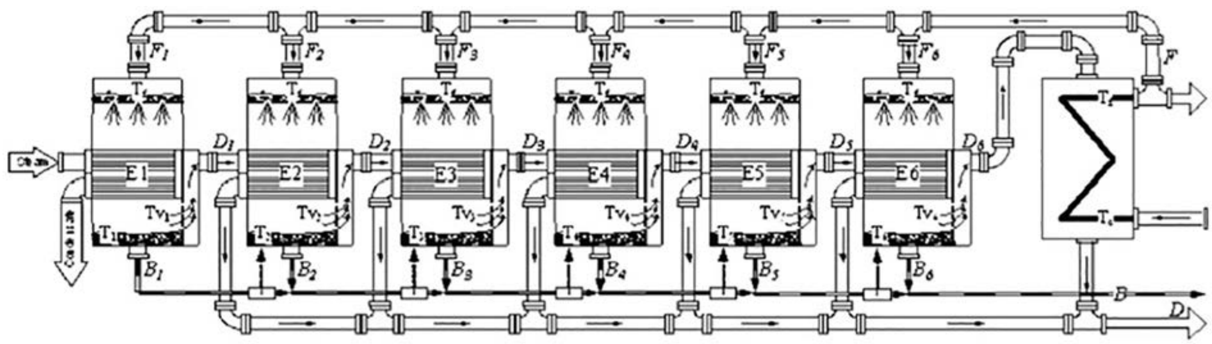

Fig. 1. A block diagram of MED-PF (MED parallel feed configuration).

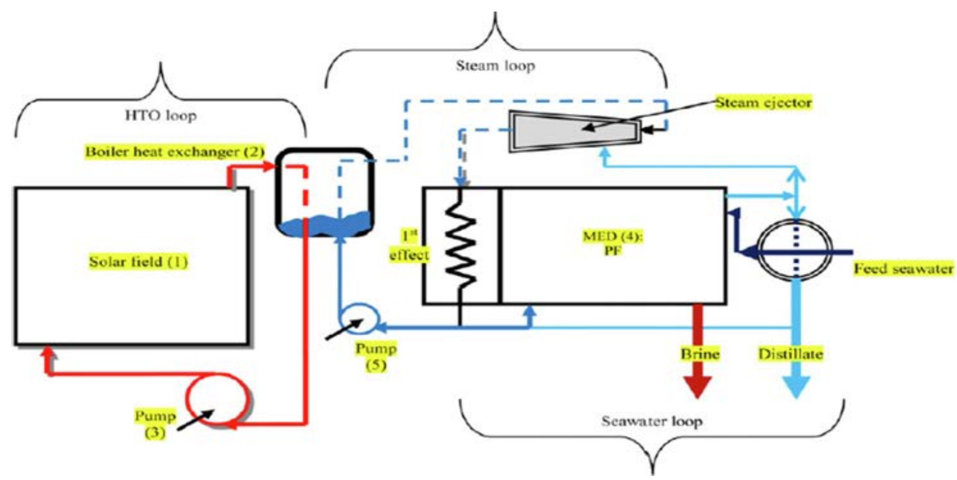

Fig. 2. A schematic diagram of solar MED-PF-TVC components: (1) Solar field, (2) Boiler heat exchanger, (3) HTO pump, (4) MED-PF-TVC [8].

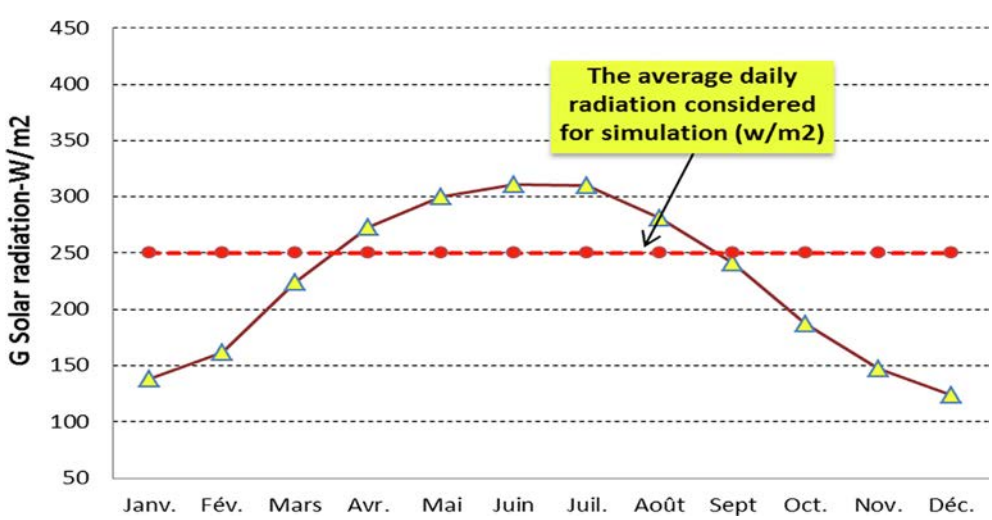

Fig. 3. Global solar radiation data of ELJADIDA (Morocco).

- The distilled product is set at 5000 m^3/day, the inlet seawater supply temperature is 22 °C with a salinity ratio of around 40,000 mg/kg. The output brine flow temperature is assigned to 45 °C where, the number of effects is fixed at 4 effects and the brine purge the salinity ratio is fixed at 70 g/kg.
- Solar radiation and ambient temperature would be fixed as the previous technique (250 W/m^2 and 20 °C).
- For MED-PF-TVC the SECR (Steam Ejector Compression Ratio) is maintained at value 2.
- The temperature of the outlet collector would be fixed at 350° C and the driving vapor pressure would be 2,600 kPa.
- The efficiency of all the condensers is fixed at 0.85 (85%).
- Isentropic pump yields are maintained at 75% [9].
- LTp is the plant lifetime and set as 20 years.

Table 1
Design points for SMED-PF and SMED-PF-TVC.

Design point MED-PF	Design point MED-PF	Design point MED-PF-TVC
Ambient temperature, °C	20	20
Gb, W/m^2	250	250
Seawater temperature, °C	22	22
ηp, %	75%	75%
Brine blow down temperature (Tbn), °C	40	40
Top steam temperature (TST), °C	350	350
Sea water salinity, ppm	40,000	40,000
Brine blow down salinity, ppm	70,000	70,000
Condenser effectiveness	0.85	0.85
Condenser inner tube diameter, m	0.04	0.04
Condenser outer tube diameter, m	0.04	0.04
Number of effects	10	10
Compression ratio (CR)	–	2
Effect inner tube diameter, m	0.03	0.03
Effect outer tube diameter,	0.03	0.03
Product mass flux rate, kg/s	57.87	57.87
Working fluids	HTO-Water-Seawater	
Electric power generation cost, $/kWh	–	0.06
Plant life time, year	20	20
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^2	Calculated	
Feed heaters area, m^2	Calculated	
Condenser area, m^2	Calculated	
Gain ratio	Calculated	

Table 2
Data results for MED-PF and MED-PF-TVC.

Parameter		MED-PF	MED-PF-TVC
Solar collector field	Total solar field area Acol, m^2	42,490	39589,68
	Solar field flow rate mcol, kg/s	6,017	13,94
	Solar field Re number	42,490	99,230
	No. of collectors (LS-3)/no of loops.	77/7	113/3
	Solar field width wcol, m	5,67	113,6
	Solar collector thermal efficiency ηcol, %	0,6965	0,6965
	Exergy destruction rate, kW	1,854*104	6106
	Exergy inlet rate, kW	9931	9253
	Cost stream to BHX, $/GJ	–	3,398
Boiler heat exchanger unit	Area, m^2	–	248
	Outlet HTO temperature, °C	130	118
	Ms, kg/s	3,62	2.6
	Exergy destruction rate, kW	320	523
	Motive steam pressure, kPa	–	2600
HTO pump unit	Power, kW	135,9	52,12
	Exergy destruction rate, kW	106,9	33
MED section (16 effects)	Md, kg/s	57,87	57,87
	Mf, kg/s	135	135
	Mcw, kg/s	5,695	5
	Ms, kg/s	3,62	2.72
	Tf, °C	36,65	35,78
	Td, °C	24,58	25,45
	TBT, °C	55,6	59,54
	TVT, °C	61	58,78
	TFT, °C	36,65	58,73
	Condenser area Acond, m^2	601,26	274,7
	Total effects' area Aeff, m^2	111409,96	48818,87
	Gain ratio (GR)	16,01	21,23
	Exergy destruction rate, kW	2,474*10^5	2,412*10^5
Performance and cost	STPC, kWh/m^3	1,49	0,8375
	ZIC&OM, $/h	147,1	109,4
	Total plant cost, $/y	1,3*10^6	9,58*10^5
	TWP, $/m^3	0,784	0,5826

The performance of MED-PF-TVC is better compared to MED-PF. As shown in Table 2, the thermal compression technique TVC has significantly reduced the heat exchange surfaces in the MED section, MED-PF consumes more energy, so it's more expansive, for example the total price per m^3 of water is higher by 34.5% to that produced by TVC. The gain ratio (GR) for MED-PF-TVC notice was higher than MED-PF (21.23 vs. 16.1) due to the minimum rate of steam needed (Ms = 2.72 vs. 3.62 kg/s). All the specific costs of MED-PF-TVC are better compared to those of MED-PF (Table 2).

4. Model of exergy analysis

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 [10].

$$Ex_2 - Ex_1 = Ex_q + Ex_w + Ex_{f0} - I \tag{1}$$

In general form in steady state condition become;

$$0 = Ex_q + Ex_w + Ex_{f0} - \dot{I} \tag{2}$$

The exergy destruction rate (kW) in solar collector is obtained by [11];

$$\dot{I}_{collector} = A_{col} \times G_b \times \quad 1 + \frac{1}{3}\left(\frac{T_{amb}}{T_{sum}}\right)^4 - \frac{4}{3}\left(\frac{T_{amb}}{T_{sum}}\right)\Bigg) + \dot{m_{col}}[h_i - h_0 - T_{amb}(s_i - s_0)] \tag{3}$$

In this study the recommendation of Bejan [12] is used (T_{sun} = 6000 K).

$$\dot{I}_{collector} = \dot{m}[\Delta h_{i-0} - T_{amb} \times \Delta s_{i-0}] - \dot{W}_{turbine} \tag{4}$$

$$\dot{I}_{rec,cond} = \dot{m_{hot}}[\Delta h_{i-0} - T_{amb} \times \Delta s_{i-0}]_{hot} + \dot{m_{cold}}[\Delta h_{i-0} - T_{amb} \times \Delta s_{i-0}]_{cold} \tag{5}$$

$$\dot{I}_{pump} = \dot{m}[\Delta h_{i-0} - T_{amb} \times \Delta s_{i-0}] - \dot{W}_{pump} \tag{6}$$

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

Feed seawater temperature for each stream [13] where;

$$h_{f,d,b} = h_0 + (A \times T + B/2 \times T^2 + C/3 \times T^3 + D/4 \times T^4) \tag{8}$$

where;

$$h_0 = 9.6296 \times s - 0.4312402 \times s^2$$

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

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

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

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

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

$$\dot{Ex}_{ph} = \dot{m}\left(C_P(T,S) \times (T - T_0) \times C_P(T,S)\log\frac{T}{T_0}\right) \quad (9)$$

T_0 is reference temperature.

The exergy stream (kg/s) should be calculated according to the following relation:

$$\dot{Ex}_{ch} = \dot{m}\left(N_{mol}(s, M_w, M_s) \times 10^{-3} \times 8.314 \times T_0\{-X_w \times \log X_w - X_s \times \log X_w\}\right) \quad (10)$$

A total stream exergy rate is calculated by:

$$\dot{Ex}_{total} = \dot{Ex}_{ph} + \dot{Ex}_{ch} \quad (11)$$

With;

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

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

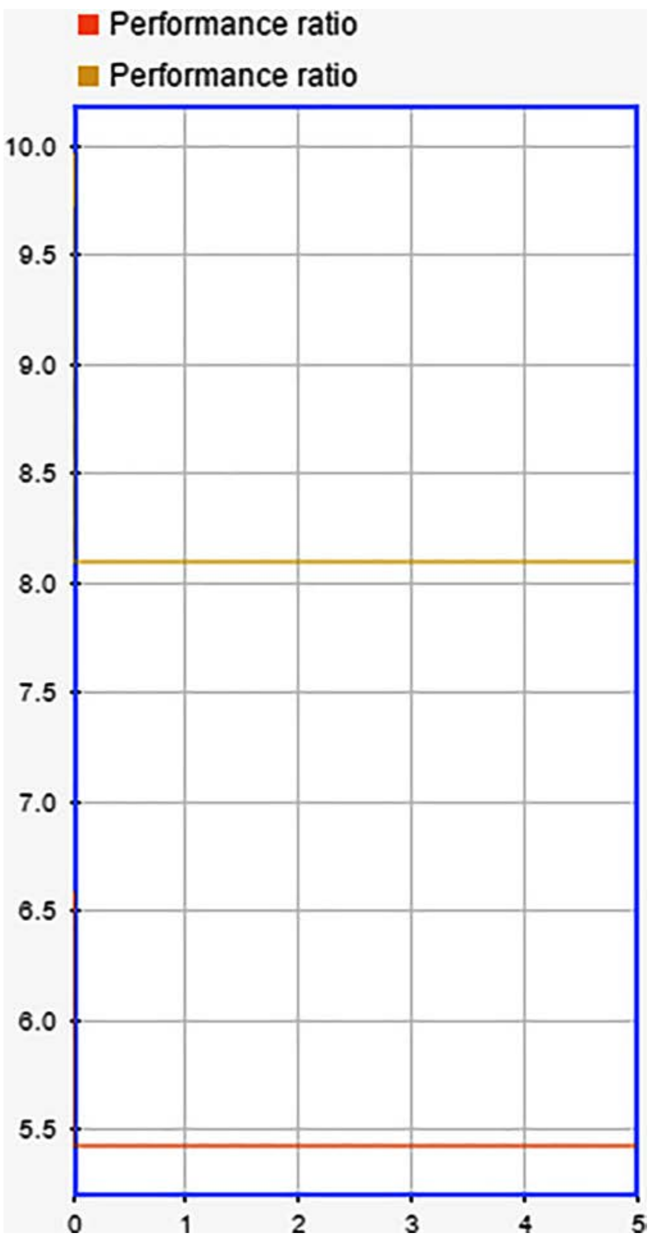

Fig. 4. Variation of Gain Ratio (GR) in MED-PF-TVC with the variations of effect numbres.

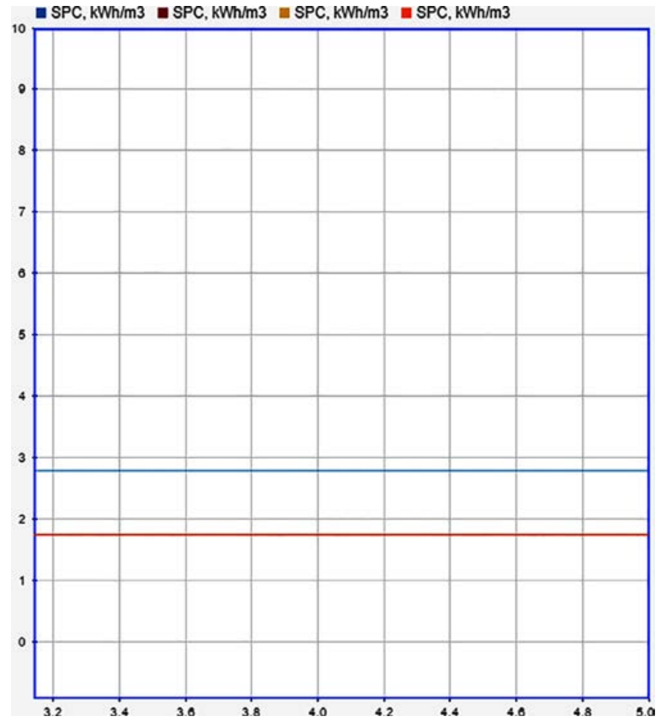

Fig. 5. Comparaison of SPC variation in MED-PF-TVC with variation on effect numbres.

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

$$N_{salt} = S/M_s$$

$$N_{mol} = N_{pure} + N_{salt}$$

The Exergy efficiency in this study is performed based on the following relation;

$$\rho_{ex} = 1 - \frac{\dot{I}_{total}}{\dot{Ex}_{in}} \quad (12)$$

5. The impact of numbers effect variation in MED-PF-TVC

Figs. 4 and 5, shows that the increase in the number of effects (without exceeding the limit zone), has a significant impact on the GR as well as the SPC [KWh/m^3].

6. Conclusion

MED has the advantage of using a low temperature, so the energy consumed is available and lower. The decrease in temperature differences considerably increases the heat transfer zones. The study has shown that the MED-PF-TVC is more efficient than MED-PF, which is normal due to the depression created by the ejector. We can conclude that the MED process coupled to the TVC can operate by solar energy and provide interesting results especially for countries that do not have petroleum resources (like Morocco); however the techniques studied in this area are still in the development stage. In this work, suggestions are highlighted to merge between concentrated solar power plants. The studied technique consists in transferring the useful energy of the sun collected by the solar collector (PTC) to the first MED-PF/MED-PF-TVC effect via the heat exchanger of the boiler. We have chosen Water is the working fluid and Therminol-VP1 heat transfer oil is chosen to operate the PTC collector.

Based on the analysis performed in this work, the following conclusions can be draw:

- To improve the performance of the MED Technique, the number of events up to 16 and important. At the reduction of TBT until reaching the surroundings of 60 °C. This method makes it possible to increase the gain ratio and to lower the specific production cost
- Maintaining the compression ratio at CR = 2 increase the performance of the cycle and to decrease the SPC kWh/m^3.
- SPC [kWh/m^3] and CR vary according to the maximum steam temperature. its growth improves SPC and CR
- SMED-PF-TVC gives best results compared to SMED-PF- MVC technique. It achieves lower SPC, steam flow rate, total water price and thermo-economic product cost compared with SMED-PF technique.
- The steam ejector unit may reduce the need of more evaporators to increase the GR.

CRediT authorship contribution statement

Y. Aroussy: Conceptualization, Formal analysis, Writing, Software. **D. Saifaoui:** Supervision, Validation. **A. Lilane:** Data curation, Investigation. **M. Tarfaoui:** Supervision, Validation.

Declaration of Competing Interest

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

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