MULTI STAGE DESALINATION ASSISTED BY SOLAR ENERGY

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ABSTRACT

A parallel cross feed flow multi-effect desalination plant using thermal vapor compression was simulated and optimized. MATLAB language programming has been utilized to create a simulation code. An analysis of the performance of the plant was conducted. Using a new design, a solar desalination plant consisting of solar parabolic collectors, steam generator, and MED unit has been used to substitute the above mentioned plant. An investigation was conducted in relation to indirect steam production via multiple thermal oils including THERMINOL VP1, THERMINOL 66, THERMINOL 59, THERMINOL SP, THERMINOL 55 and DOWTHERM A. Through the simulation, it was clear that THERMINOL VP1 had at least 1.025 % more desalinated water than others. Also, the operation cost of distillate production using mazoutor natural gas is much more than using solar energy by 99.992 %.

1 INTRODUCTION

Man has been urged to find alternative sources to manage the problem of the limited sources of clean portable water using Industrial desalination plants. Nowadays, the main concern of many research groups is to develop software tools for the purpose of simulating and optimizing desalination plants. For example, Sayyaadi et al. [1] introduced an economic model of a multi effect distillation (MED) desalination system with thermo-vapor compressor (TVC) on the basis of the energy and exergy analysis. Druetta et al. [2] offered a fairly detailed simplified model to precisely foretell the performance of a multiple effect evaporators (MEE) system. Sagharichiha et al. [3] used mathematical modeling of the (MEE) system for brackish water desalination. Dahdah et al. [4] carried out a multi-objective structural optimization of integrated thermal desalination and thermal compression systems. Chun-hua et al. [5] built A 30 ton/day low-temperature multi-effect evaporation seawater desalination system. Gabriel et al. [6] introduced a new mathematical formulation for modeling-based optimization of the MED plant.

Khalid et al. [7] optimizedthe location of the TVC or ejector which joined to the MEE system. Rezaei et al. [8] economically studiedthe operation of the Qeshm island desalination plant with multiple sources of energy.Cipollina et al. [9] simulated a model of the MED-TVC plant that lies in Trapani, Sicily (Italy) through the powerful equation-based process simulator gPROMS®.Mata-Torresa et al. [10]explored a polygeneration system incorporating concentrating solar power (CSP) integrated with a desalination plant. Astolfi et al. [11] investigated the probable synergies between desalination technologies and solar energy.Stuber et al. [12] displayed an optimized design of a solar-powered desalination process system based on a large parabolic trough solar thermal concentrator.

The present study investigated a 5000 m^3/dayMED-TVC system. A water tube boiler used to generate steam which is supplied to MED-TVC plant. The supplied steam is condensed at the first effect of the MED unit and results in the evaporation of the sea water. Then, the vapor is condensed into desalinated water (product water) at the next effect by another sea water stream. A new design for the MED-TVC plant which replaced the source of the steam generated from the traditional boiler by a solar steam generation technique using parabolic trough collectors which is presented in Fig.1. In a closed system of parabolic collectors, a heat transfer fluid (HTF) is heated and circulatedand then the absorbed solar energy is transferred to be used for heating water in the steam generator. The plant is located in the city of Alexandria, in the north part of Egypt.

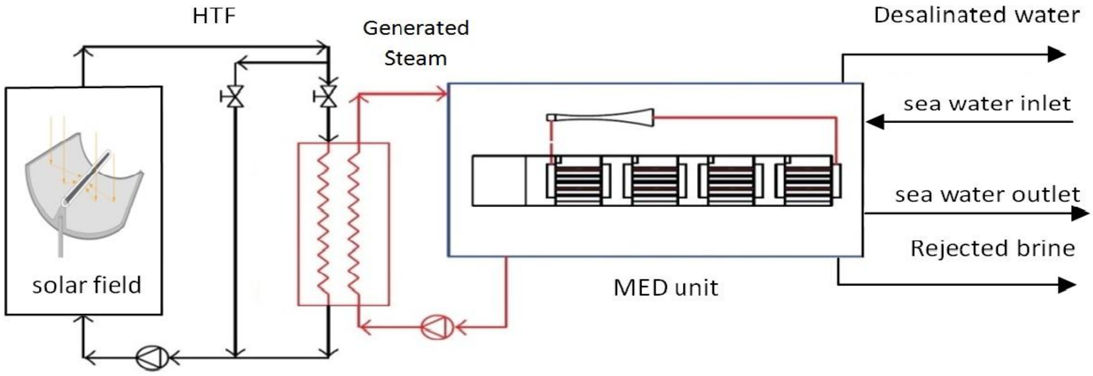

Figure2. Schematic of the solar MED desalination

2 EQUATIONS

2.1. Med Equations

An MED unit includes various impacts in relation to energy and mass balance. The pure mass balance and salt mass balanceequations in each (i) effect and in the total MED unit have been estimated.

Water Mass Balance

$$B_{i-1} + F_i = B_i + D_i \quad (1)$$

WhereB stands for the brine flow rate, F stands for the feed water flow rate, Dstands for the desalinated water flow rate and i is the effect number.

Salt Mass Balance

$$F_i X_{F_i} + B_{i-1} X_{B_{i-1}} = B_i X_{B_i} \quad (2)$$

Where X_B is the outlet brine concentration (in ppm) with the maximum of 70000 ppm [13].

$$PR = M_d / M_s \quad (3)$$

$$sA = \frac{\sum_{i=1}^{n} A_{co} + A_i}{M_d} \quad (4)$$

Where PR is the performance ratio, M_d is the total distillate flow, M_s is the supply steam flow, sA is the specific heat transfer area, A_i is the total area in each effect andA_{co} is the condenser area.

2.2. Solar collector equations

Equations of solar parabolic collectors performed by Kalogirou[14] was adapted in this study.

Energy balance

$$A_c(H_{r_{c-a}} + H_w)(T_c - T_a) = H_{r_{r-c}} A_r (T_r - T_c) \quad (5)$$

Where $H_{r_{c-a}}$ stands for linearized radiation coefficient from cover to ambient, $H_{r_{r-c}}$ stands for linearized radiation coefficient from receiver to cover, A_c stands for external area of glass cover, A_r stands for receiver area, T_r stands for receiver temperature, T_c stands for glass cover temperature of receiver and T_a stands for ambient temperature.

The collector efficiency can be obtained from the following equation:

$$\eta = Q_u / (A_a G_B) \quad (6)$$

where η is the collector efficiency, Q_u is the useful energy gain from the collector, A_a is aperture area of the collector and G_B is beam radiation (w/m^2).

3 VALIDATION

3.1 Med Design Validation

To validate the code, the simulation results for an MED unit including 6 effects were compared with the operational data of New Abu Qir power plant MED unit in Alexandria, Egypt. Table 1 shows a good agrement between the simulated results and the reported data.

Table 2. Data validation for MED simulation code

Parameter	Simulation code	Operational data	Difference (%)
Cooling water flow, (tons/hour)	263	260	1.011
Sea water feed flow, (tons/hour)	624.88	625	-0.99
Steam supply flow, (tons/hour)	40.94	40.91	1
Total distillate flow, (tons/hour)	208.33	208.33	Assumption
Total brine flow, (tons/hour)	416.55	416.5	1
Temperature of first effect, (°C)	64.640	65	-0.99
Temperature of second effect, (°C)	61.105	61	1
Temperature of third effect, (°C)	57.383	57	1
Temperature of fourth effect, (°C)	53.465	54	-0.99
Temperature of fifth effect, (°C)	49.341	50	-0.98
Temperature of sixth effect, (°C)	45.000	45	0

Also the solar collector code was validated by comparing it's results with the reported data of Kalogirou [14], As shown in Fig.3. The maximum deviation was found to be 4 %.

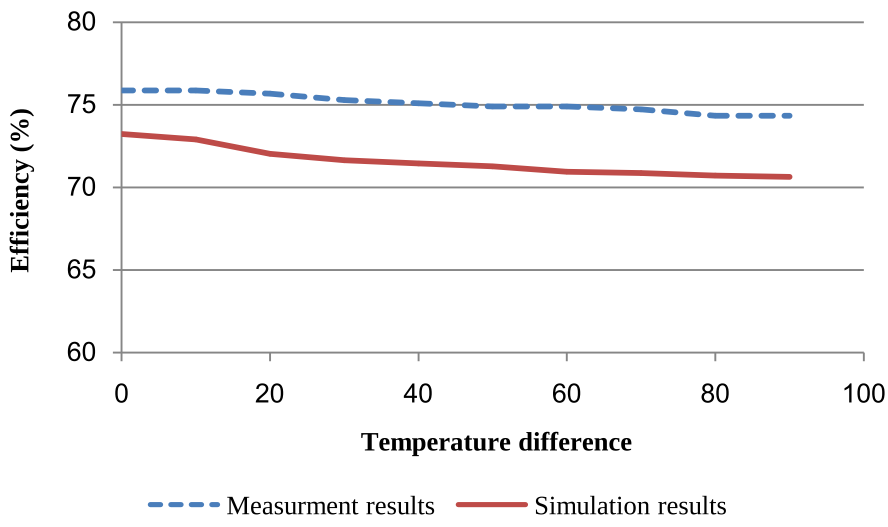

Figure4. Effect of temperature difference [Ti-Ta] on the collector efficiency and compared with measured data of Kalogirou[14]

4 RESULTS AND DISCUSSIONS

4.1. Med Performance Results

It can be observed that system performance ratio decreases with increasing steam temperature, as shown in Fig.5.This happen as; the reduction in compressed vapor latent heat, the raise in the amount of feed sensible heating and the increase in the amount of motive steam needed for vapor compression at higher temperatures. Also the rapid decrease in the specific heat transfer area due to increasing the heating steam temperature, shown in Fig.6, can be explained as a result of; rising the overall heat transfer coefficient and the temperature driving force per effect.

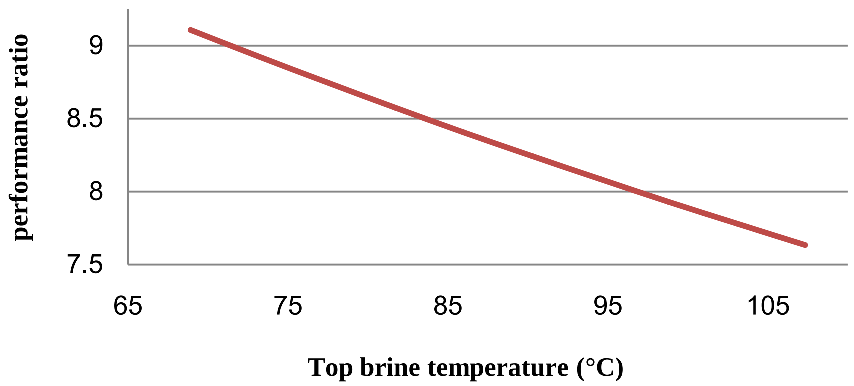

Figure 7. Variation in the performance ratio as a function of the top brine temperature

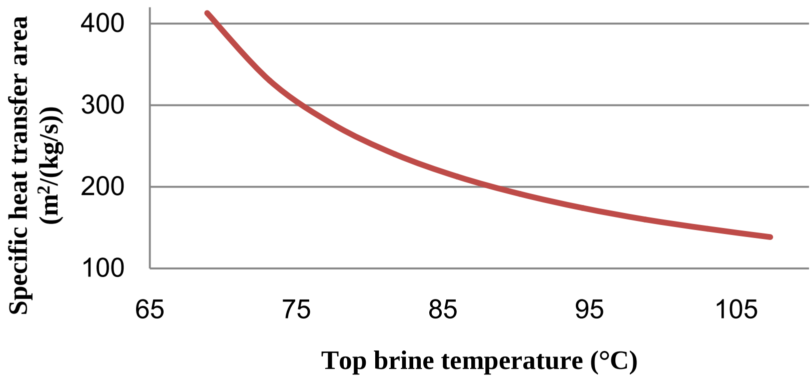

Figure 8. Variation in the specific heat transfer area as a function of the top brine temperature

4.2. Design of Solar Field

The previous section discussed the performance of New Abu qir MED using steam generation boiler by natural gas and mazout oil fuels for steam generation required for supplying steam to MED. In this paper, the traditional boiler will be replaced by solar steam generation system using parabolic trough collector solar array to save the operation cost of distillate production. A detailed design and performance simulation results for solar collector field is presented. Table 3 shows the collector design standard parameters used in this simulation.

Table4. Standard parameters for collector design

Parameter	Value	parameter	Value
Collector unit length, (m)	20	Aperture width, (m)	3.5
Tube inside diameter, (mm)	40	Receiver emissivity	0.92
Tube outside diameter, (mm)	50	Glass cover emissivity	0.87
Tube cover glass diameter, (mm)	90	Tubethermal conductivity, (w/m.k)	15
Number of solar collector units connected in series in the solar array	10	Number of solar collectorunits connected in parallel in the solar array	38

A comparison between six different thermal oils was developed during June. These oils are THERMINOL VP1, THERMINOL 66, THERMINOL 59, THERMINOL SP, THERMINOL 55 and DOWTHERM A. The first comparison criterion is collector pipe length which has been divided into six segments according to maximum allowable temperature to prevent oil oxidation. The total heat losses during pipe segments are shown in Fig.9 for different oils. THERMINOL VP1 represents the maximum heat loss in comparison to the others. Fig.10 indicates that; by increasing collector tube length, the heat losses increased, which in turn resulted into a decline in the collector thermal efficiency.

HTF outlet temperature, which represents the second comparison criterion, was considered 310 °C for all oils in relation to the maximum acceptable temperature of THERMINOL 59. Fig.11 shows that circulating fluid pump with THERMINOL SP has the minimum power consumption while it has the maximum power consumption with THERMINOL VP1.In spite of that THERMINOL VP1 has the maximum outlet temperature and maximum power consumption, it has the capacity to generate more live steam which leads to produce more desalinated water and as shown Fig.12. Therefore, this oil was selected as the optimum design for the rest of the calculations.

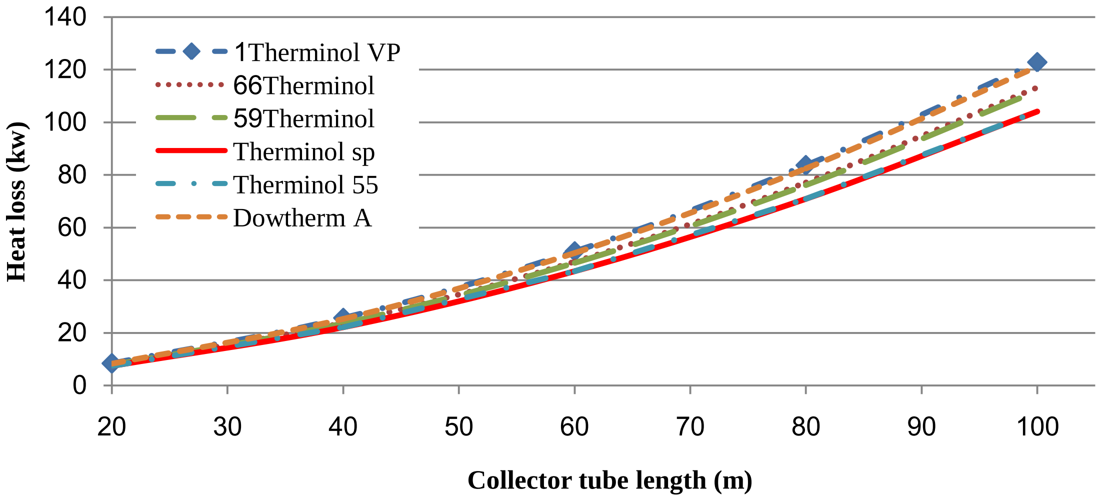

Figure 13. Heat loss versus collector tube length segments for different thermal oils

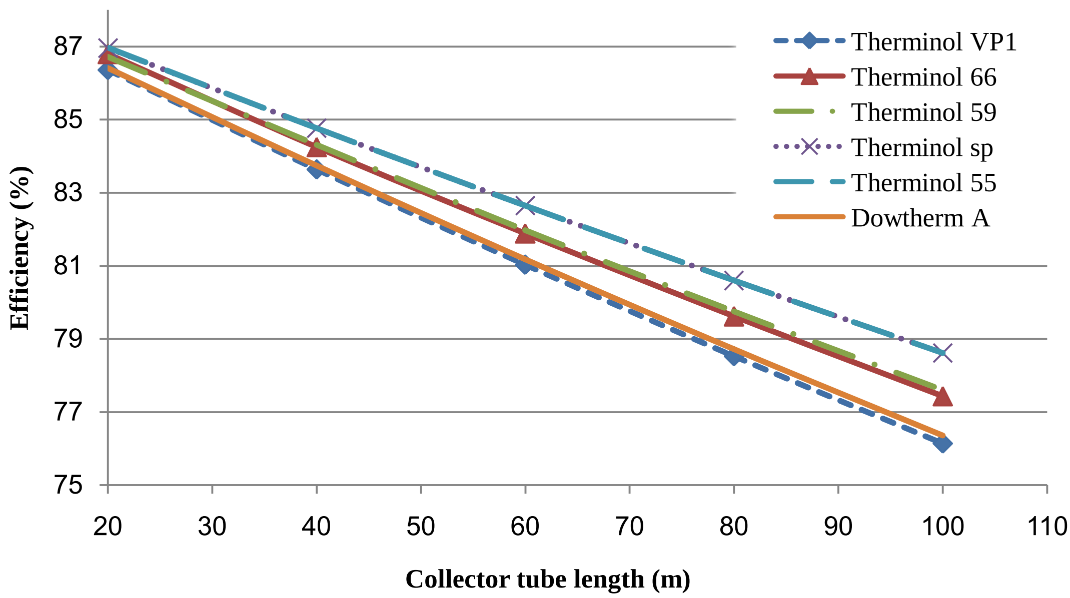

Figure14. Effect of collector tube length on collector efficiency at different HTF

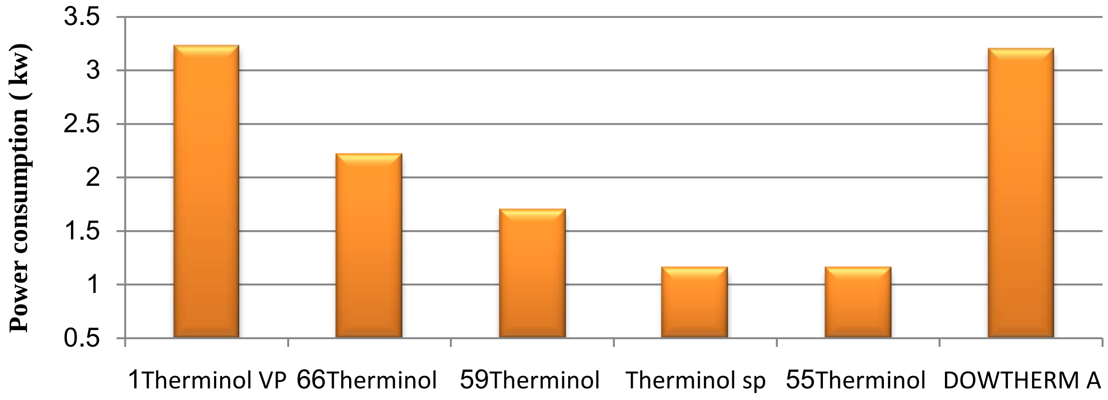

Figure 15. Variation of the total power consumption for different thermal oils

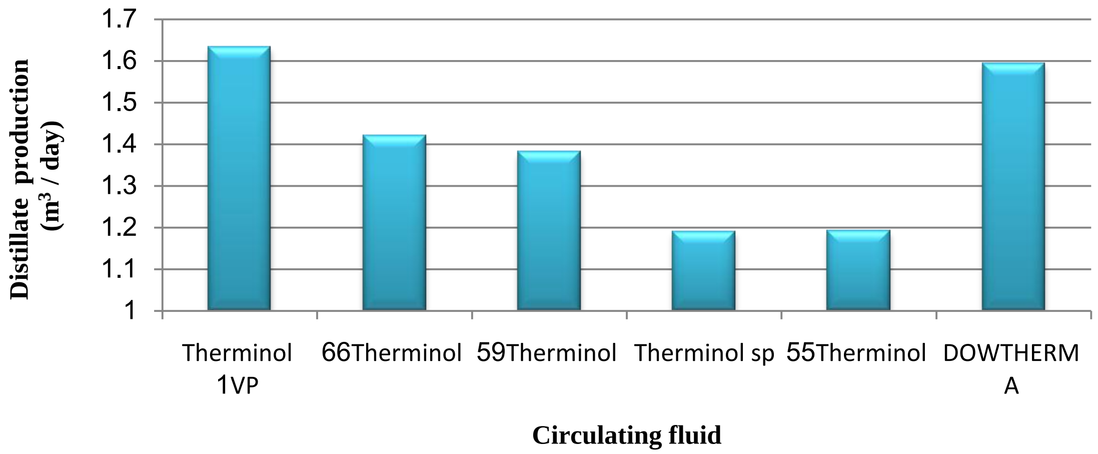

Figure16. Variation of fresh desalinated water flow rate for different thermal oils

4.3. Performance of Solar Field System

Variation of the distillate production rate during the year is shown in Fig.17. June, July and August have the same distillate production everyday (2500 m^3/day). December and January have the minimum required distillate (1458 m^3/day).

Variation of the collector heat loss during the year is shown in Fig. 18. December has the lowest heat loss because it has the lowest HTF exit temperature. May has the highest heat loss. As shown in Fig. 19, June has the highest efficiencybecause the highest HTF exit temperature in June leads to the highest useful energy gain through the collector pipe.

Fig. 20illustrates the economical comparison between using solar energy for steam generation producing distillate flow and using conventional system used natural gas or mazout for the same operating hours. they show that operation cost using mazout is the highest cost and using solar energy is the lowest cost during the year.

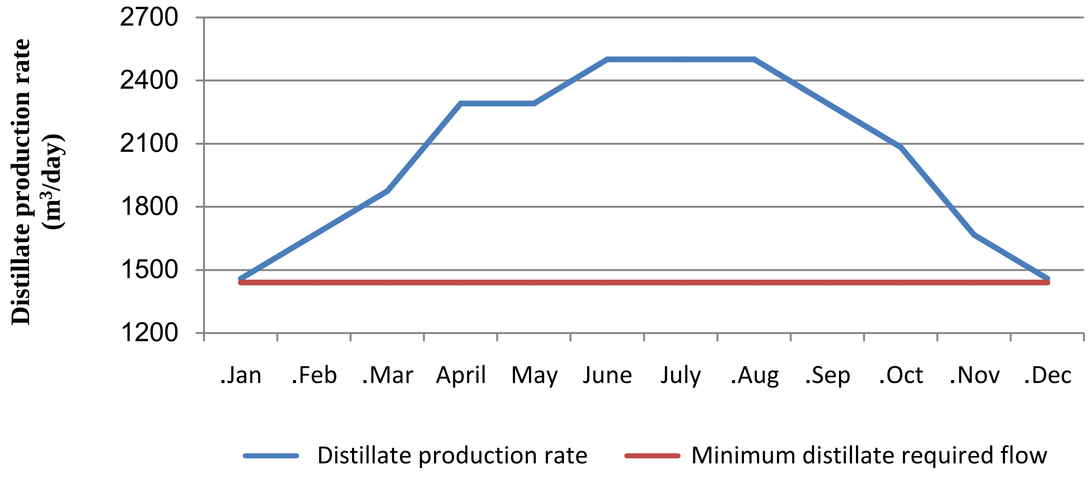

Figure21. Variation of the distillate production rate during the year

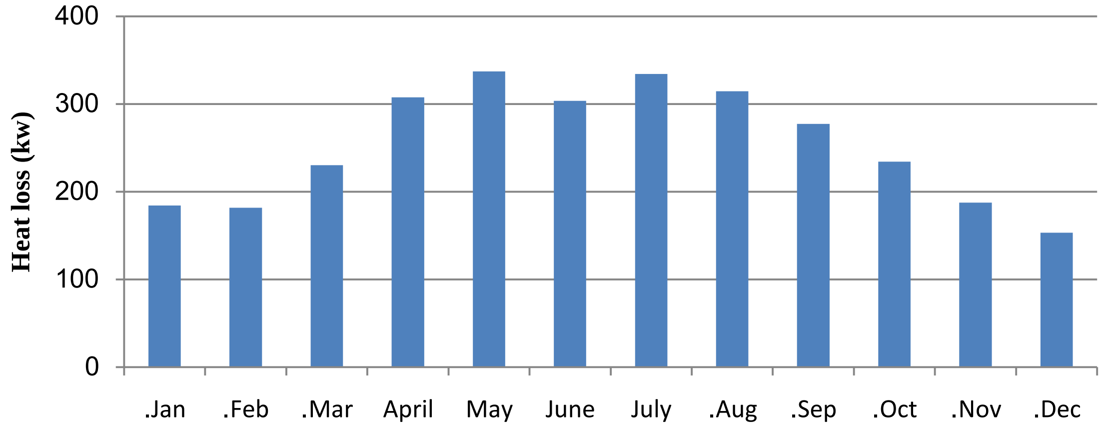

Figure22. Variation of the collector heat loss during the year

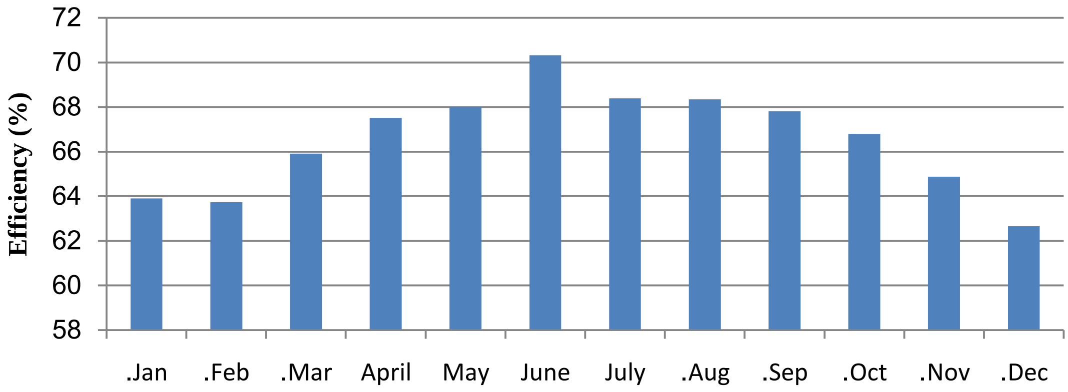

Figure 23. Effect of solar radiation change around the year on the collector efficiency

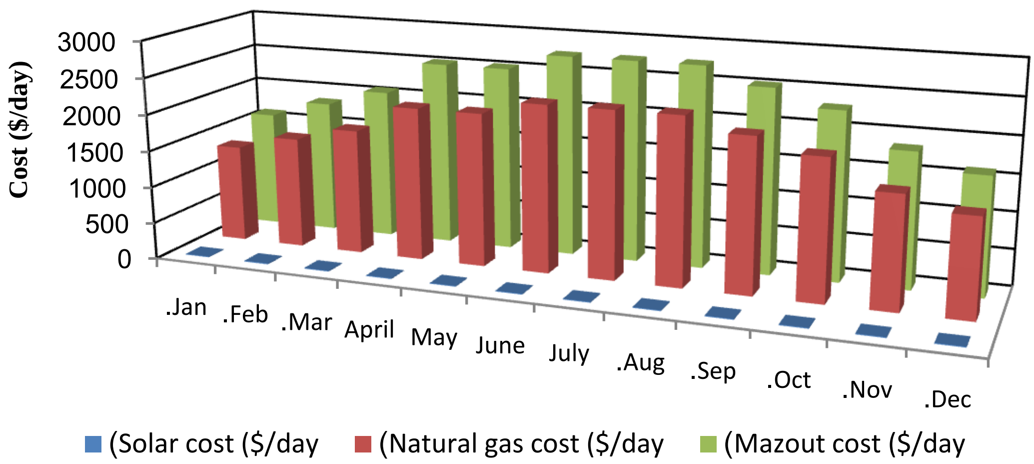

Figure 24. Comparison between solar operation cost versus natural gas and mazout operation cost during the year

5 CONCLUSION

The simulation results for New Abu qirmulti effect desalination plant producing 5000 m^3/day and located in the north part of Egypt to analyze the performance of the plant showed a reduction in the system performance ratio at higher top brine temperature. Moreover, it indicated that the specific heat transfer area of the MED system faces a rapid decrease with the increase of the top brine temperature. In addition, the simulation outcome for the new design for solar desalination plant indicated that, among six different thermal oils, THERMINOL VP1 required at least 1.01 % more power consumption than others taking into account the same outlet HTF temperature and generated at least 1.025 % more desalinated water. Finally, the simulation results showed that distillate production using solar energy save about 99.992 % of the operation cost than using traditional fuels like mazout and natural gas fuels.

NOMENCLATURE

B:Brine flow rate (kg/s)
F: Feed water flow rate (kg/s)
D:Desalinated water flow rate (kg/s)
X_b: Outlet brine concentration (ppm)
X_f:Feed water concentration (ppm)
M_d: Total distillate flow (kg/s)
M_s: Supply steam flow (kg/s)
sA: Specific heat transfer area (m^2/(kg/s))
A_i: Total area in each effect (m^2)
A_{co}:Condenser area (m^2)
A_c : External area of glass cover (m^2)
$H_{r_{c-a}}$:Linearized radiation coefficient from cover to ambient (W/m^2-k)
$H_{r_{r-c}}$:Linearized radiation coefficient from receiver to cover(W/m^2-k)
A_r: Reciever area (m^2)
T_r: Reciever temperature (°C)
H_W: Wind loss coefficient (W/m^2-k)
T_c : Glass cover temperature (°C)
T_a: Ambient temperature (°C)

Q_u: Useful energy gain from the collector (W)
A_a: Aperture area (m^2)
G_B: Beam radiation (W/m^2)

ABBREVIATIONS

TVCThermo-vapor compressor
MEDMulti effect distillation
MEEMultiple effect evaporators
CSP Concentrating solar power
HTF Heat transfer fluid

REFERENCES

A.Rezaei, A.Naserbeagi, Gh.Alahyarizadeh andM.Aghaie(2017).Economic evaluation of Qeshm island MED-desalination plant coupling with different energy sources including fossils and nuclear power plants.Desalination, 422,101-112.

A.Cipollina, M.Agnello, A.Piacentino, A.Tamburini, B.Ortega, P.Palenzuela, andG.Micale(2017).A dynamic model for MED-TVC transient operation.Desalination, 413,234-257.

C. Mata-Torres, R.A.Escobar,J.M.Cardemil,Y. Simsek and José A.Matute(2017).Solar polygeneration for electricity production and desalination: Case studies in Venezuela and northern Chile.Renewable Energy, 101,387-398

H.T. El-Dessouky, H.M. Ettouney and F. Mandani(2000). Performance of parallel feed multiple effect evaporation system for seawater desalination.Appl. Therm.Eng,(2017),1679–1706.

Hoseyn Sayyaadi and Arash Saffari(2009).Thermoeconomic optimization of multi effect distillation desalination systems.Appl. Energy, 87(4), 1122–1131.

KerronJ.Gabriela, PatrickLinke andMahmoud M.El-Halwagi(2015). Optimization of multi-effect distillation process using a linear enthalpy model.Desalination, 365,261-276.

K.A.Khalid, M.A.Antar, A.Khalifa andO.A.Hamed(2017).Allocation of thermal vapor compressor in multi effect desalination systems with different feed configurations.Desalination, 426,164-173.

M. Astolfi, S. Mazzola, P. Silva andE. Macchi(2017).A synergic integration of desalination and solar energy systems in stand-alone microgrids.Desalination, 419,169-180.

M.D.Stuber,C. Sullivan,S.A.Kirk,J.A.Farrand,P.V.Schillaci,B.D.Fojtasek andA.H.Mandell(2014).Pilot demonstration of concentrated solar-powered desalination of subsurface agricultural drainage water and other brackish groundwater sources.Desalination, 355,186-196.

M. Sagharichiha, A. Jafarian, M. Asgari and R.Kouhikamali(2013). Simulation of a forward feed multiple effect desalination plant with vertical tube evaporators.Chem. Eng. Process,75,110–118.

PaulaDruetta, PioAguirre andSergio Mussati(2012).Optimization of Multi-Effect Evaporation desalination plants. Desalination, 311,1–15.

Qi Chun-hua, FengHou-jun, Lv Qing-chun, Xing Yu-lei andLi Nan(2014). Performance study of a pilot-scale low-temperature multi-effect desalination plant.Appl. Energy,135,415–422.

SoterisKalogirou (2009). Solar Energy Engineering: Processes and Systems,Elsevier, NewYork, USA, 1st edition.

Tawfiq H.Dahdaha and Alexander Mitsos(2014). Structural optimization of seawater desalination: II novel MED–MSF–TVC configurations. Desalination,344(1–3),219–227.