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Optimisation of multi effect distillation based desalination system for minimum production cost for freshwater via repetitive simulation

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Abstract

The shortage of fresh water resources is a global problem which requires a prompt solution. Thus, the multi effect distillation (MED) was successfully used for the production of fresh water from seawater. Despite the use of MED desalination system extensively, the influence of the number of effects on the fresh water production cost has not been covered in the open literature. Thus, this paper tries to rectify this specific challenge via simulation at given operating conditions of seawater salinity and temperature. The study is performed using a detailed mathematical model contains the suitable cost correlations. gPROMS model builder suite has been used to carry out an extensive simulation. The results of the study show that the lowest fresh water production cost can be achieved at an optimal number of effects of 17 for a certain operating conditions.

Keywords: Seawater desalination, MED system, Simulation, gPROMS, Fresh water production cost.

1. Introduction

In the 19th century, the multi effect distillation (MED) was used for the first time to overcome the shortage of freshwater especially in the Middle East countries (Sadri et al., 2017). The desalination technologies are categorised into thermal type and membrane type. The thermal technologies use heat to vaporise and condense the seawater whereas the membrane technologies are pressure driven process. The MED technology is the oldest and most competent thermal distillation process, despite it stands in second place after multi stage flash (MSF) in thermal desalination market. It is denoted multi effect desalination when the high quality water is the main product of this process.

To increase the system's productivity and decrease the cost of the produced water, more research and technical efforts are required. As a matter of fact, the main task is to minimise the cost of energy by enhancing the steam economy or performance ratio PR (kg of fresh water per kg of steam employed) (Darwish and AL-Juwayhel, 2006). Interestingly, MED attained more devotion compared to other thermal technologies. This is because of the high capacity and quality of produces water. Specifically, MED has the ability to produce fresh water at very low level of salinity (Ettouney and El-Dessouky, 1999). Moreover, the low specific heat consumption provided by MED system was specifically denoted as one of its advantages, which made this process as a strong competitor to other desalination systems (Darwish and Abdulrahim, 2008). Also, MED can be operated with low top brine temperatures from 60-70 ^{o}C compared to higher top brine temperature for Multi Stage Flash (MSF) (Al-Sahali and Ettouney, 2007). This in turn has attracted the interest of researchers into improving the operation of the MED system in order to maximise its profitability. Recently, around 65% of the total fresh water production in the desalination industry is produced from the thermal processes.

A number of successful mathematical models were investigated for the MED process. The following presents a review of some successful models with a brief description.

Minnich et al. (1999) investigated the optimum values of the gained output ratio (GOR) and top brine temperature (TBT) of MED process as 14 and 60 °C, respectively, via a primitive modelling. In this respect, the variation of GOR against the top brine temperature and the number of effects of the MED system has been analysed by El-Allawy (2003). The instillation of TVC has also considered to carry out this study. The implementation of three to six effects would increase noticeably GOR by approximately two-folds.

The influence of design parameters of MED process on the performance indicators has been mathematically outlined by Ameri et al. (2009). This in turn deduced the maximum performance that associated with the optimum number of effects. The variation of seawater salinity, seawater temperature has also embedded.

A steady state mathematical model for MED process was elaborated by Delgado et al. (2017), which corroborated against experimental data. A simulation study is carried out to investigate the influence of top brine temperature on the key design parameters. Specific heat transfer area and GOR are included as well.

A comprehensive model has been developed by Filippini et al. (2018) to assess the variation of the total energy consumption of MED system. This is specifically suggested that increasing the number of effects would increase total energy consumption. Also, Al-Obaidi et al. (2019) studied the impact of several operating conditions of MED system and RO process of a hybrid system of MED+RO processes on the fresh water production cost. This is basically done using the model developed by Filippini et al. (2018) and economic model of MED system developed by Druetta et al. (2014) to find the total fresh water production cost. This in turn affirmed the feasibility of MED+RO hybrid system from the economic perspectives.

A more recent study of Tlili et al. (2019) is the only attempt that investigated the influence of several pertinent parameters including the number of effects on the MED process performance. However, no precise detail of the impact of number of effects on the fresh water production cost were yet elaborated.

Up to the authors' knowledge, no previous attempt that investigated the optimal number of effects of MED system (at variable seawater feed flow rate) to attain the lowest fresh water production cost can be found in the open literature. To achieve this, both Filippini et al. (2018) and Al-Obaidi et al. (2019) models are currently involved to explore the appropriate number of effects that would attain the lowest fresh water production cost of MED system.

2. Description of MED process

The capacity of the MED systems ranges from 600 to 30,000 m^3/day, and they are designed in two different arrangements: (a) vertical tubes where the seawater evaporates in a thin film within the tube while the vapour condensate on the heat transfer surface of the tubes and (b) horizontal tubes where the feed seawater is divided onto the outside surface area of the tubes while the vapour flows inside the tubes horizontally and condensed to produced distilled water.

Fig. 1 shows a schematic diagram of the feed forward MED process that entails of a number of effects with thermal compression system. Specifically, the effects constitutes an evaporator, spray nozzle, demister and feed pre-heater. The feed seawater is firstly directed to the last unit of MED process of condenser. This is specifically aiding to preheat feed water and condense the vapor of the final effect. Therefore, the latent heat of vaporization of the last effect is almost totally transferred into the feed water which in turn preserved the heat of steam and raised the feed water temperature. This is followed by directing a considerable part of feed water into preheater just to raise its temperature to its boiling point same as the first effect temperature. In this regard, the steam flows inside the tubes has a significant role to vaporise the sprayed feed water inside the effect. Moreover, the feed water is passed into a spray nozzle in each effect to be sprayed over a horizontal tube of high temperature-pressure steam. It is noteworthy to mention that the feed water is firstly passing through a valve in each effect to decrease its pressure and boiling point. This in turn would aid to vaporise the feed water of zero salt content due to heat transferred from steam into low pressure feed water. The same mechanism is repeated in the other effects in which the vapour generated in each effect provides an energy to the brine of the following effects. However, this would associated with a reduction of the formed vapor as a consequence of increasing the number of effects. The decrease of the evaporation temperature due to raising the latent heat of evaporation would interpret the reason and therefore the temperature is gradually decreased with increasing the number of effects.

The second associated part of MED system is the thermal vapour compression unit (TVC, which is responsible to provide steam as an external steam source. Specifically, TVC compresses a portion of the last effect vapor and therefore its temperature and pressure are significantly increased. This would specifically aid the steam of the first effect by upgrading its energy. The fresh water generated in the last effect (condensate) would be collected in a separate tank at the same time of disposing high salinity seawater back to the sea.

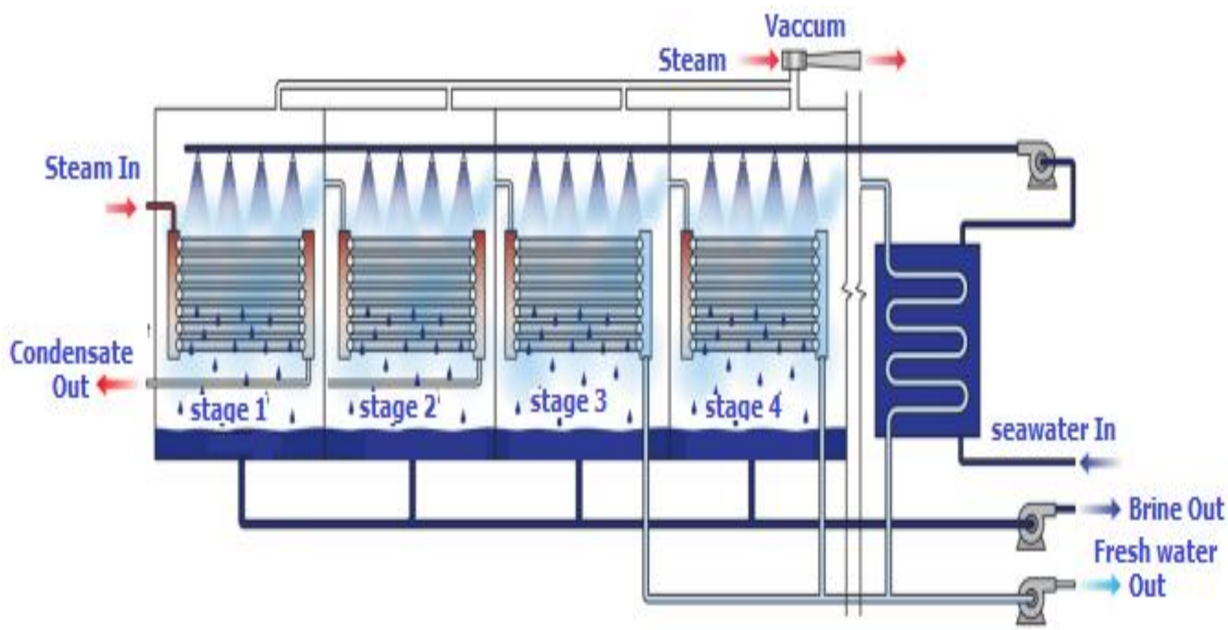

Fig. 1. Schematic diagram of MED system (Adapted from Zak et al., 2012)

3. Modelling of MED system

Modelling of MED system has an important role to recognise the transport phenomenon and filtration mechanism. A successive modelling would therefore aid to design the process in its optimum operation. Specifically, the modelling of MED process helps to achieve a comprehensive simulation to analyse the effect of operating conditions on the process performance indicators. Moreover, the process optimisation can be carried out based on modelling to allocate the best conditions to attain the maximum performance of high quality and quantity of fresh water.

The recent study applied the model developed by Filippini et al. (2018) besides the cost model of Al-Obaidi et al. (2019). Al-Obaidi et al. (2019) investigated that an inclusion of TVC section would raise the total annualised cost and therefore TVC section has been recently relaxed from the calculation of fresh water production cost.

Filippini et al. (2018) developed their model based on the assumptions as follows;

1. Steady-state process.
2. Vapour phase has no is salt.
3. Neglected energy loss to the environment.
4. Equal transfer area in all the stages of MED process.
5. Neglected pressure drop and non-equilibrium allowance (NEA).
6. Specific heat and boiling point advancement are related to salinity temperature.
7. Latent heat of evaporation and overall exchange coefficient are related to temperature.
8. Fouling propensity in the heat exchanger is allocated via an experimental relationships.
9. The external utility obtains saturated steam that leaves it as saturated liquid.

It is important to mention that the perfection of the model developed by Filippini et al. (2018) has been already confirmed in Filippini et al. (2018) as a result to a simple comparison between the model predictions and other preceding models' accuracy.

For the convenience of the reader, Tables A.1 and A.2 in Appendix A present full details of the mathematical models of Filippini et al. (2018) and Al-Obaidi et al. (2019), respectively. Moreover, the parameters of the economic model are provided in Table A.3 in Appendix A.

4. Simulation of MED system

The aim of this section is to carry out a comprehensive analysis based on simulation of MED system to recognise the lowest fresh water production cost. The MED system is systematically simulated in this section based on the model developed by Filippini et al. (2018) besides the cost model of Al-Obaidi et al. (2019). Specifically, the simulation is carried out at fixed operating parameters of seawater and MED system same as what have been taken by Filippini et al. (2018)

to analyse the impact of operating conditions on the performance of MED system via simulation. In this regard, seawater temperature and salinity of 25 ^{o}C and 39 kg/m^3, respectively, are considered. Also, the external steam flow rate and temperature and pressure are 8 kg/s, 70 ^{o}C, and 1300 kPa, respectively. However, the disposed brine temperature and salinity are 40 ^{o}C and 60 kg/m^3, respectively. The simulation results are discussed in the following;

Fig. 2 depicts the fresh water production cost (\$/m^3) (presented in Eq. 6 in Table A.2 in Appendix A) in contradiction of the increase in the number of effects of the MED process from 8 to 25 for different seawater salinities. The repetitive simulation exhibited an optimal number of effects in the MED process of 17 to obtain the minimum fresh water production cost of 0.6149 \$/m^3 at 39 kg/m^3 of seawater salinity as a base case. It is noteworthy to mention that, below 13 effects, the fresh water production cost decreases exponentially with the number of effects. Also, a slow progress in the fresh water production cost can be noticed after 17 effects of MED process. However, the increase of fresh water production cost after 17 effects is of around 1.3% if compared to the optimal value. Basically, Fig. 2 can be used to elucidate the impact of variable seawater salinity on the optimum number of effects of MED_TVC system and the corresponding minimum fresh water production cost. Fig. 2 depicts that increasing seawater salinity from 20 kg/m^3 to 45 kg/m^3 requires less number of optimal effects to obtain the minimum fresh water production cost. Statistically, 20, 18, 17, and 16 are optimal numbers of effects associated with 20 kg/m^3, 30 kg/m^3, 39 kg/m^3, and 45 kg/m^3, respectively. This phenomenon can be due to the requirements of increasing the transferring of thermal energy as the seawater salinity decreases. Interestingly, it is recommended to shut down a specific number of effects of MED_TVC system as the seawater temperature increases during summer season. This would offer an opportunity to maintain repetitive cleaning up and maintenance operations for the desalination system. It is important to mention that the repetitive simulation results of Fig. 2 have been generated based on the operating parameters of section 4 including fixed seawater temperature of 25 °C.

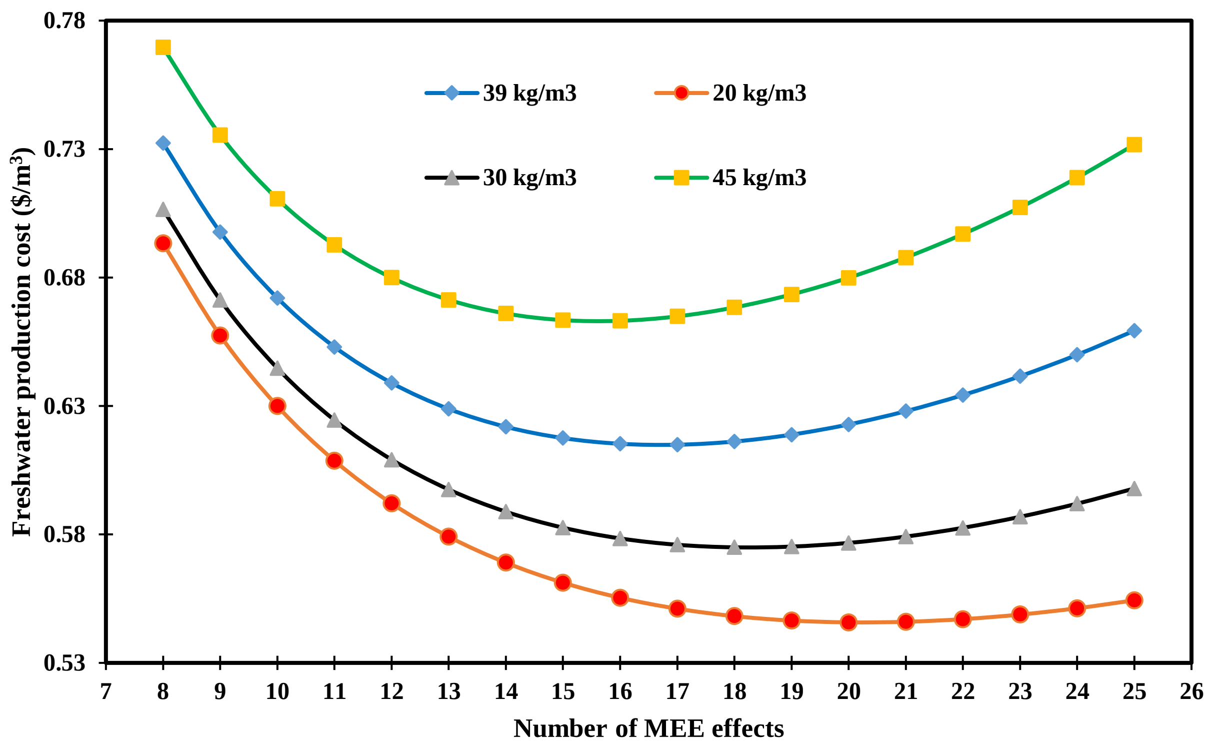

Fig. 2. Fresh water production cost vs number of effects of MED process at different seawater salinity

To systematically understand the behaviour of an optimum fresh water production cost against the number of effect, it is important to analyse the associated parameters. Basically, the fresh water production cost relates to the total annualised cost (comprises of total capital cost and operating cost) and fresh water flow rate as indicated in Eq. 5 in Table A.2 in Appendix A. It is important to mention that the total annual production cost over the total annual productivity is known as the fresh water cost of the of the MED system desalination process. Also, the total annual cost (TAC) of the MED system consists of the total capital cost (TCC) and the annual operational cost (AOC). Note, TCC contains of the indirect costs, equipment and installation costs. Whereas, the operational and maintenance cost consist of steam cost, chemicals cost, labor cost, and other costs associated to the MED system.

The variation of total annualised cost (TAC) (Eq. 13 in Table A.2 in Appendix A) against the number of effects of MED system at the base case of 39 kg/m^3 of seawater salinity can be shown in Fig. 3. It appears clearly that TAC roughly and linearly increases by around 112% as a result to increasing the number of effects. This is basically corresponding to increasing several cost parameters. For instance, increasing the number of effects would almost linearly increase the total capital cost (Eq. 1 in Table A.2 in Appendix A) (Fig. 4), increase the MED plant cost (Eq. 4 in Table A.2 in Appendix A) (Fig. 5), and increase the final condenser cost (Eq. 17 in Table A.2 in Appendix A) (Fig. 6). Therefore, it can be said that an increase of the number of stages of MED system has a negative impact on the total annualised cost as a result to lifting the requirements of several operational costs. In the same regard, the total production fresh water flow rate (Md) is another important parameter to specify the total fresh water production cost (Eq. 6 in Table A.2 in Appendix A). Fig. 7 presents an improvement by around 150% of Md in a quasi-linear relationship against the increase of the number of effects from 8 to 20 at the base case of 39 kg/m^3 of seawater salinity. Occasionally, increasing the number of effects requires an increase in the total inlet feed flow rate of seawater (Fig. 8). This is a critical point to be noticed as the model of has been built to predict the inlet seawater feed flow rate for a given brine salinity of 60 kg/m^3. This is quite different strategy than the one presented by Tlili et al. (2019) who assumed fixed feed flow rate of seawater that have not clearly demonstrated an optimum number of effects of maximum distillate or minimum fresh water production cost. Interestingly, the present study have not precisely given critical optimal values of TAC and Md, which might aid to interpret the optimal value of fresh water production cost depicted in Fig. 2. However, the massive increase of MD compared to TAC may reason the exponential relationship of an optimum value of fresh water production cost against the number of effects. Moreover, it is fair to expect a significant overlap in the operation of MED system after 17 effects which entails a rise in the fresh water production cost and produces 17 effects as the optimal one.

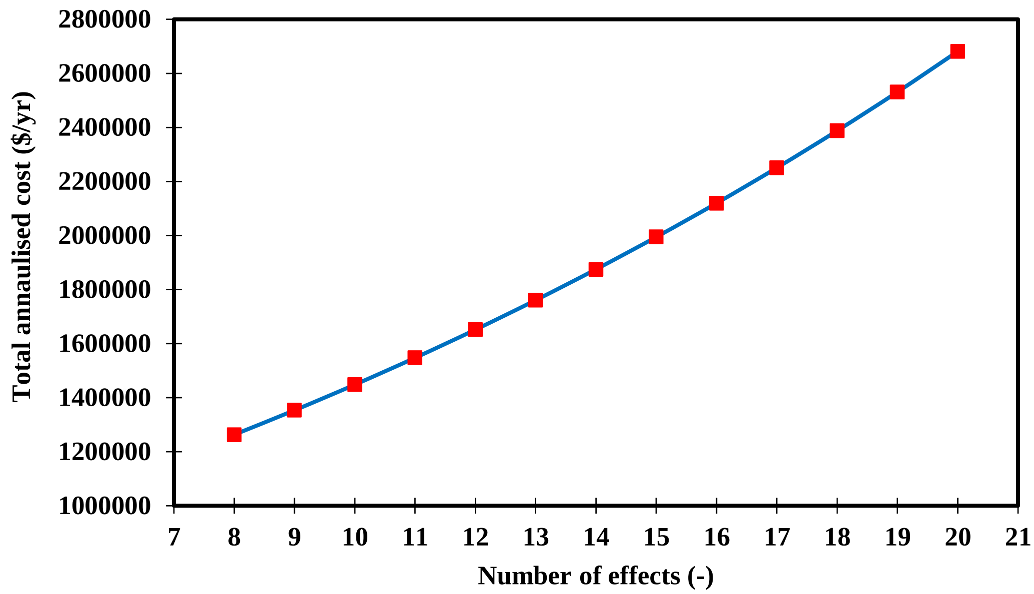

Fig. 3. Total annualised cost vs number of effects of MED process at the base case of 39 kg/m^3 of seawater salinity

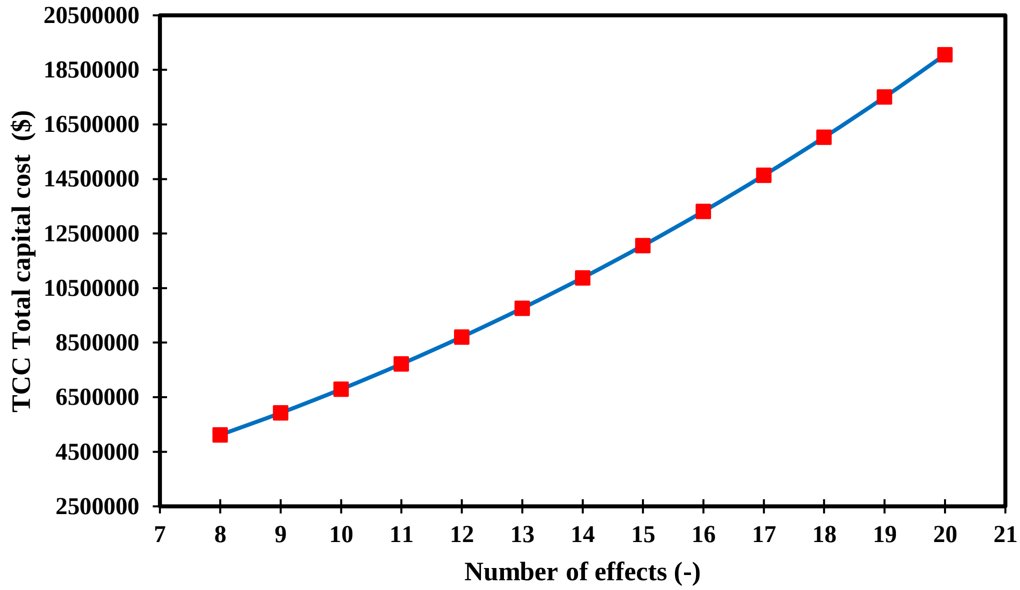

Fig. 4. Total capital cost vs number of effects of MED process at the base case of 39 kg/m^3 of seawater salinity

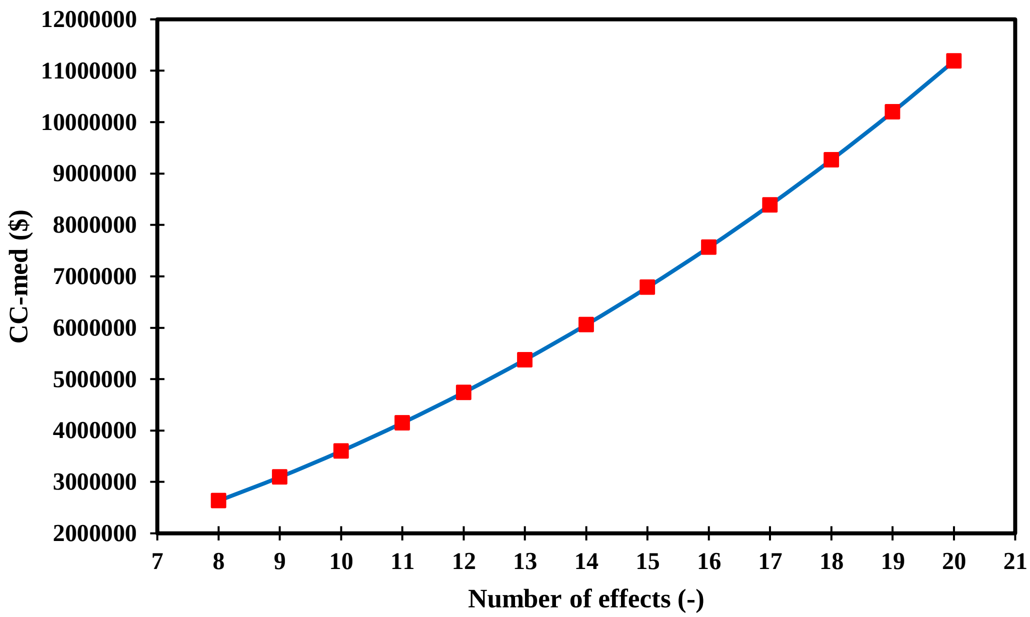

Fig. 5. Total MED plant cost vs number of effects of MED process at the base case of 39 kg/m^3 of seawater salinity

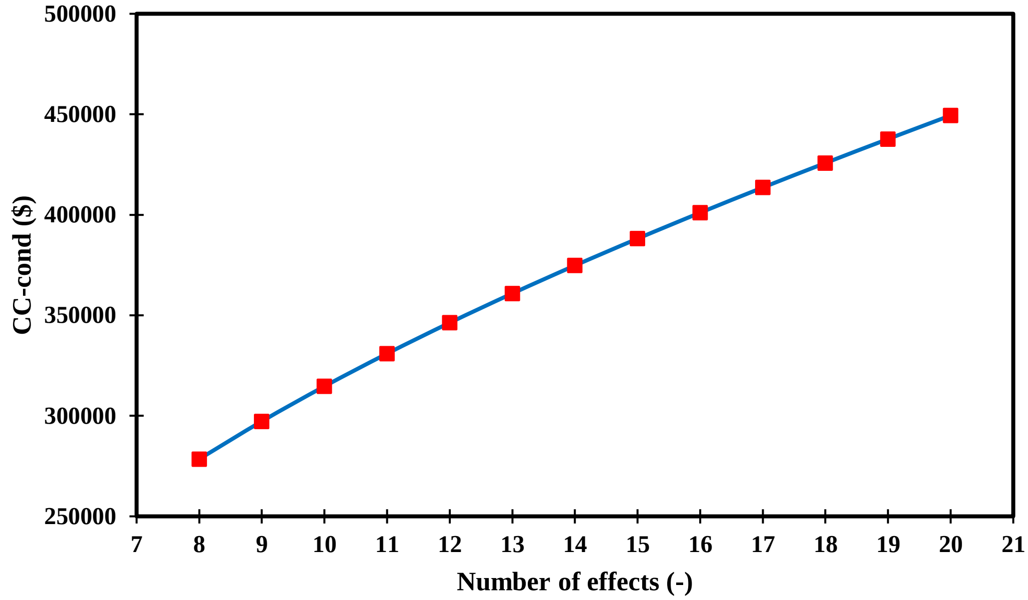

Fig. 6. Final condenser cost vs number of effects of MED process at the base case of 39 kg/m^3 of seawater salinity

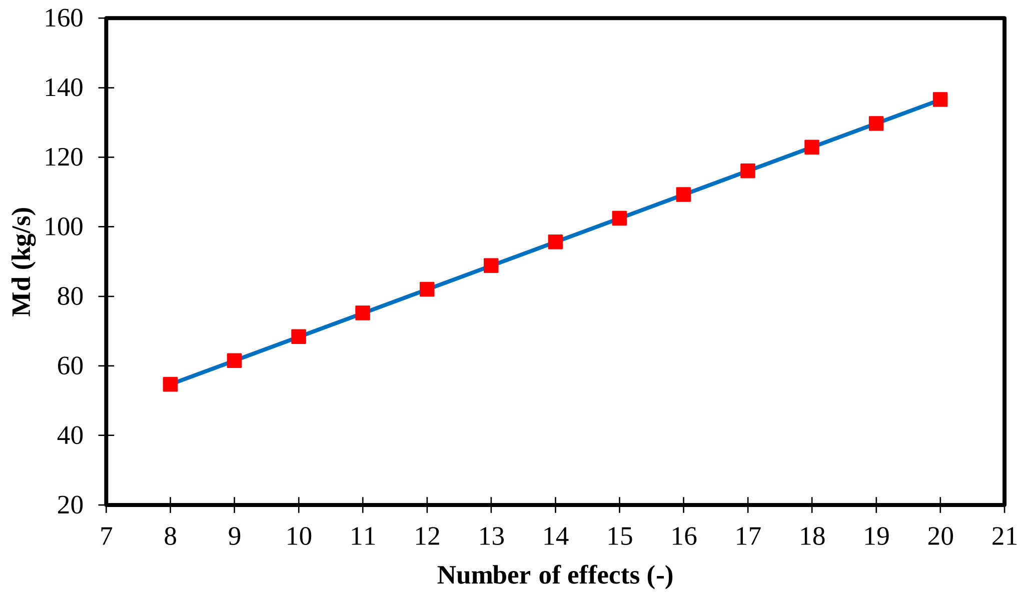

Fig. 7. Total fresh water production flow rate vs number of effects of MED process at the base case of 39 kg/m^3 of seawater salinity

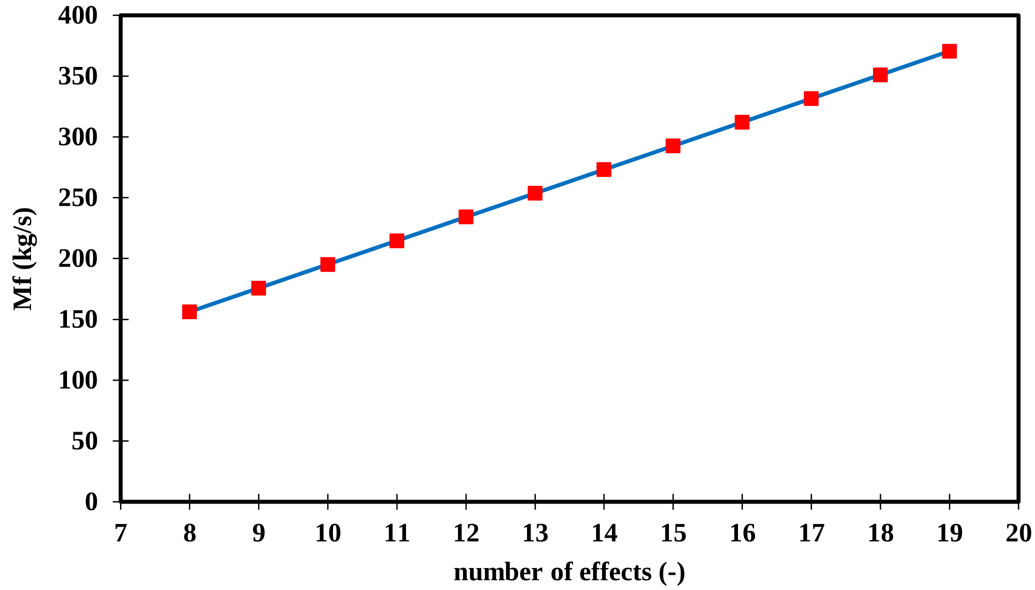

Fig. 8. Total seawater feed flow rate vs number of effects of MED process at the base case of 39 kg/m^3 of seawater salinity

The Gain Output Ratio (GOR) (mathematically described in Eq. 20 in Table A.1 in Appendix A) is one of the well-known performance indicators of the thermal desalination. Therefore, it is important to investigate if GOR would aid to assess the optimum fresh water production cost. The dimensionless GOR defined as an energy ratio of the total latent heat of evaporation of the product water to the input thermal energy. However, GOR can be alternatively defined as a ratio of mass of fresh water in kilograms to mass of steam utilised as external utility in kilograms. Basically, GOR related to economic perspectives as it entails with steam consumption and energy consumption. Also, it is fair to expect higher values of GOR at lower energy consumption. Due to the importance of GOR, the following section would investigate the effect of number of effects on GOR as illustrated below;

The variation of GOR against the number of effects is presented in Fig. 9. This in turn indicated a significant positive correlation between the improved GOR and the number of effects. An increase of the number of effects means an increase of distillate product which entirely improves GOR. It is important to mention that the current simulation is carried out at fixed steam flow rate of 8 kg/s. Fig. 9 also shows a maximum value of 17.06 of GOR that can be achieved at 20 effects of MED system. However, the minimum cost obtained at 17 effects (Fig. 2) associated with an optimum GOR of 14.5.

It is fair to mention that the repetitive simulation of number of effects of MED system has confirmed 17 effects as an optimum value to gain the lowest fresh water production cost at the base case of 39 kg/m^3 of seawater salinity. However, the influence of number of effects on other operating conditions such as total annualised cost, total capital cost, fresh water flow rate and seawater flow rate (Figs. 3 – 9) has not confirmed any optimum values at optimum number of effects. Therefore, it is fair to mention that the optimum number of effects (17) is uniquely corresponding to the lowest (optimum) fresh water production cost as depicted in Fig. 2.

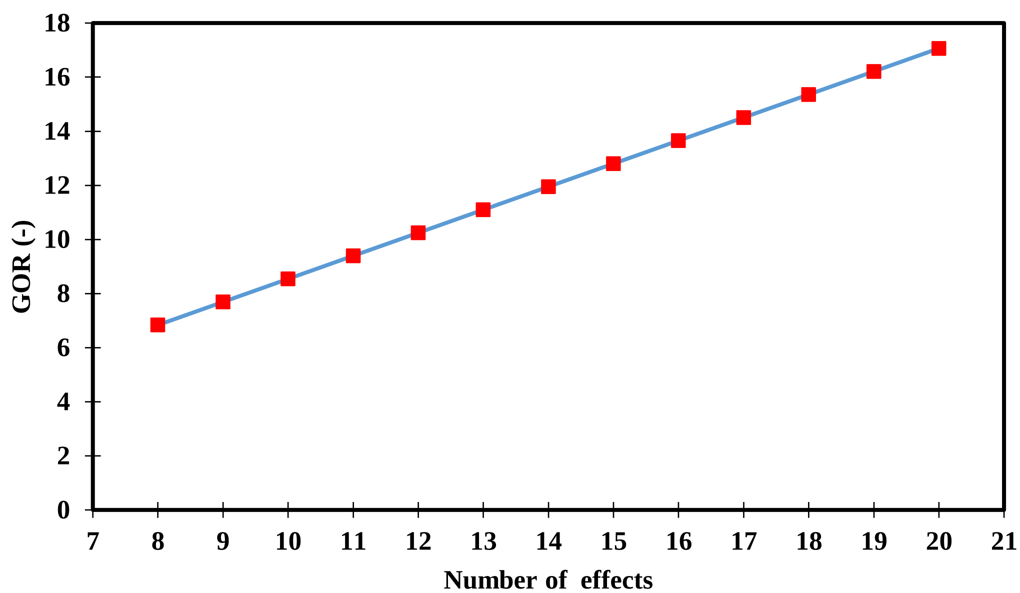

Fig. 9. Gained Output Ratio vs number of effects of MED process at the base case of 39 kg/m^3 of seawater salinity

In the same trend, an increase in the GOR as a result to increase in the number of effects would raise the total annualised cost (Fig. 10) as a result to increasing several cost parameters.

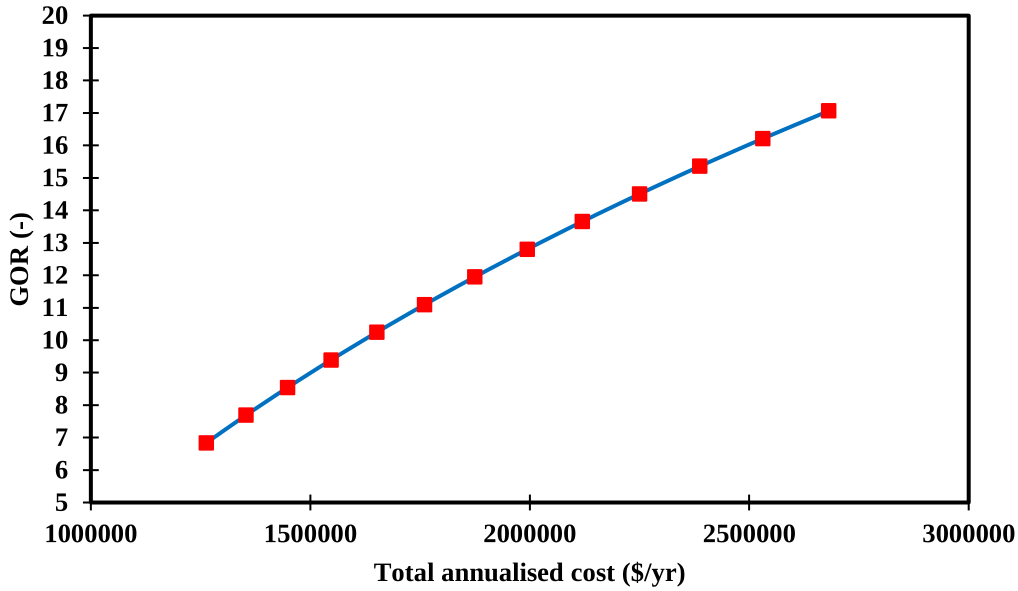

Fig 10. Gained Output Ratio vs total annualised cost at the base case of 39 kg/m^3 of seawater salinity

Up to this point, it is fair to comment that the GOR cannot be directly used to predict the optimum number of effects that can achieve the lowest fresh water production cost. However, GOR can aid to reflect the progress of product flow rate.

5. Conclusions

In this work, the model developed earlier by the authors for MED desalination system together with an economic model collected from the literature were used to appraise the fresh water production cost at changed number of effects. Repetitive simulation was carried out to find the optimum number of effects that gives the lowest fresh water production cost. The simulation results depict that it is more beneficial to apply 17 effects as an optimum number, which elaborates the key solution to reduce the fresh water production cost to 0.614 \$/m^3. Moreover, the results obtained confirmed a meaningful improvement of product capacity as a result to increasing the number of effects.

Though GOR is frequently used as a performance indicator, it cannot evaluate the optimum number of effects. However, increasing the number of effects would improve GOR with a penalty of increasing the total annualised cost due to increasing several operational costs.

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Nomenclature

$A_{ev\ mean}$: Average exchange area of evaporators [m^2]

A_{cond}: Exchange area of final condenser [m^2]

$A_{tot,s}$: Specific total area [m^2 s/kg]

A_{tot}: Total area [m^2]

B_i: Brine rejected in the i-th effect [kg/s]

BPE: Boiling Point Elevation [°C]

$D_{boil,i}$: Distillate produced by boiling in i-th evaporator [kg/s]

$D_{flash,i}$: Distillate produced by flashing in i-th flashing box [kg/s]

D_i: Total distillate produced in i-th effect [kg/s]

GOR: Gained Output Ratio

Mb: Rejected brine flowrate [kg/s]

Ms: Total steam flowrate [kg/s]

Md: Distillate from MED process (kg/s)

Mf: Water intake in the first effect (kg/s)

Mw: Intake water flowrate [kg/s]

Mws: Specific seawater intake [-]

n: Number of effects

PR: Performance Ratio

Q_i: Thermal load at i-th evaporator [kW]

Q_{latent}: Latent heat used in first effect [kJ/kg]

$Q_{sensible}$: Sensible heat used in first effect [kJ/kg]

T1: Top brine temperature (Ttop) [°C]

t_i: Feed temperature after i-th pre-heater [°C]

T_{mean}: Average temperature in the plant [°C]

tn: Feed temperature after final condenser [°C]

Ts: Steam temperature [°C]

Tvi: Temperature of the vapor phase in i-th effect [°C]

$U_{ev,i}$: Global heat exchange coefficient in i-th evaporator [kW/m^2 °C]

xb: Salinity in rejected brine [ppm or w/w%]

x*f*: Salinity in the feed [ppm or w/w%]

x_{mean}: Average salinity in the plant [ppm or w/w%]

X_i: Salinity in i-th evaporator [ppm or w/w%]

FWC_{ME}: Fresh water cost [\$/m^3]

TA: Total annualised cost [\$/yr]

TC: Total capital cost [\$]

$CAPEX_{di}$: Direct CAPEX [\$]

$CAPEX_{ind}$: Indirect CAPEX [\$]

$CAPEX_{equipmen}$: Equipment cost [\$]

$CAPEX_{civil\_wo}$: Civil work cost [\$]

C_{inta}: Seawater intake and pre-treatment cost [\$]

C_M: MED plant cost [\$]

C_{co}: Final condenser cost [\$]

AOC: Annual operating cost [\$/yr]

AOC_{che}: Cost of chemical treatment [\$/yr]

AOC_l: Cost of human labor [\$/yr]

AOC_p: Cost of power for pumps [\$/yr]

AOC_m: Cost of manutention [\$/yr]

AOC_{ste}: Cost of external steam [\$/yr]

CRF: Capital recovery factor [1/yr]

THY: Total hour per year [hr yr]

K_{intake} **:** Seawater intake [$ day m^3]

K_{MED} **:** Coefficient related to MED system [-]

K_{cond}**:** Coefficient related to condenser [-]

C_{chem}**:** Chemical treatment [$/m^3]

C_{lab} **:** Labour [$/m^3]

Cp: Power [$/kWh]

C_{steam}**:** External steam [$/kg]

C_{mat_MED}**:** Material of MED [$/m^2]

C_{mat_cond} **:** Material of condenser [$/m^2]

Ir**:** Interest rate [-]

Life**:** Life of the plant [year]

f(ΔP)**:** Pressure losses [-]

μ **:** Efficiency of power generation [-]

A_{co} **:** Exchange area of final condenser [m^2]

Greek

α : Fraction of rejected brine from previous effect flashed in the associated pre-heater [-]

β : Fraction of total distillate boiled in each evaporator [-]

λ : Latent heat of evaporation [kJ/kg]

ρ **:** Density (kg/m^3)

Δt_i : Temperature increase between two pre-heaters [°C]

$\Delta T_{ex,i}$: Driving force for heat exchange in i-th evaporator [°C]

$\Delta t_{log,i}$: Driving force for heat exchange in i-th pre-heater [°C]

ΔT_i **:** Temperature drop between two evaporators [^{o}C]

Appendix A

Table A.1. Model equations of MED_TVC system of Filippini et al. (2018)

No	Title	Unit	Equation
1	Temperature drop among effects first attempt	(ºC)	$\Delta T = \frac{T1-Tb}{n-1}$ or $\Delta T = \frac{Ts-Tb}{n}$
2	Temperature drop among pre-heaters first attempt	(ºC)	$\Delta T = \Delta t$
3	Average temperature in the plant	(ºC)	$T_{mean} = \frac{T1 + Tb}{2}$
4	Average salinity	(ppm)	$x_{mean} = \frac{xf + xb}{2}$
5	Fraction of flashed distillate	(-)	$\alpha = \frac{cp(T_{mean}, x_{mean})\Delta T}{\lambda(T_{mean})}$
6	Fraction of total distillate boiled in each evaporator	(-)	$\beta = \frac{\alpha[xb(1-\alpha)^n - xf]}{(xb - xf)[1-(1-\alpha)^n]}$
7	Heat load in i-th effect	(kJ/s)	$Qi = D_{boiled,i-1}\lambda(Tv_{i-1})$
8	Sensible heat used in first effect	(kJ/kg)	$Q_{sensible} = Mf\int_{t1}^{T1} cp(T1, x1)dT$
9	Feed flowrate	(kJ/s)	$Mf = \frac{Ms\,\lambda(Ts)}{Q_{sensible} + Q_{latent}}$
10	Latent heat in first effect	(kJ/s)	$Q_{latent} = D1\lambda(Tv1)$
11	Rejected brine flow rate	(kg/s)	$Mb = Mf - Md$
12	Feed flow rate	(kg/s)	$Mf = Md\frac{xb - xf}{xb}$
13	Distillate produced by boiling in i-th evaporator	(kg/s)	$D_{boiled,i} = \beta Md$
14	Total distillate produced in i-th effect	(kg/s)	$D_i = D_{boiled,i} + D_{flash,i}$
15	Brine rejected in the i-th effect	(kg/s)	$B_i = B_{i-1} - D_i$
16	Average salinity in the plant	(ppm or w/w%)	$x_i = \frac{x_{i-1}B_{i-1}}{B_i}$
17	Feed temperature in first effect	(ºC)	$t1 = tn + (n-1)\Delta t$
18	Temperature of the vapour phase in i-th effect	(ºC)	$Tv = T - BPE(T, x)$
19	Driving force for heat exchange in i-th pre-heater	(ºC)	$\Delta t_{log,i} = \frac{\Delta t}{\log\left(\frac{Tv_i - t_{i+1}}{Tv_i - t_i}\right)}$
20	Gained Output Ratio (GOR)	(-)	$GOR = \frac{Md}{Ms}$
21	Performance Ratio (PR)	(-)	$PR = GOR\frac{2330\ KJ/Kg}{\lambda(Ts)}$
22	Specific total area	(m^2 s/kg)	$Atot_s = \frac{Atot}{Md}$
23	Specific seawater intake	(-)	$Mw_s = \frac{Mw}{Md}$
24	Area of i-th effect	(m^2)	$A_{ev,mean} - \frac{Q_i}{U_{ev,i} \triangle T_{ex,i}}$

Table A.2. The economic model of Al-Obaidi et al. (2019)

No.	Title	Unit	Equation
1	Total Capital cost	(\$)	$TCC = CAPEX_{dir} + CAPEX_{indir}$
2	Indirect CAPEX	(\$)	$CAPEX_{indir} = 025\ CAPEX_{dir}$
3	Direct CAPEX	(\$)	$CAPEX_{dir} = CAPEX_{equipment} + CAPEX_{civil\_work}$
4	Civil work cost	(\$)	$CAPEX_{civil\_work} = 0.15\ CAPEX_{equipment}$
5	MED plant cost	(\$)	$C_{med} = K_{MED}\ C_{mat\_MED}\ A_{MED}{}^{0.64}$
6	Fresh water production cost	(\$/m^3)	$FWC_{MED} = \frac{TAC}{M_{fresh,MED} THY\ 3600}$
7	Annual operating cost	(\$/yr)	$AOC = AOC_{chem} + AOC_{lab}\ AOC_{pow} + AOC_{man} + AOC_{steam}$
8	Seawater intake and pre-treatment cost	(\$)	$C_{intake} = \frac{K_{intake} 243600 M_{seawater.MED}}{2a}$
9	Capital recovery factor	(1/yr)	$CAF = \frac{\mathrm{Ir}(1+\mathrm{Ir})^{lift}}{(1+\mathrm{Ir})^{lift}\_1}$
10	Cost of human labor	(\$/yr)	$AOC_{lab} = \frac{C_{lab} THY 3600 M_{fresh,MED}}{\rho}$
11	Cost of manutention	(\$/yr)	$AOC_{man} = 0.002 TCC$
12	Cost of external steam	(\$/yr)	$AOC_{steam} = \frac{C_{steam} THY (Ts - 40) M_{steam}}{80} + 0.005\ TCC$
13	Total Annual Cost	(\$/yr)	$TAC = AOC + CRF \times TCC$
14	Equipment cost	(\$)	$CAPEX_{equipment} = C_{intake} + C_{MED} + C_{cond}$
15	Direct CAPEX	(\$)	$CAPEX_{dir} = CAPEX_{equipment} + CAPEX_{civil\_work}$
16	Cost of power for pumps	(\$/yr)	$AOC_{Pow} = \frac{C_{pow} THY 100\ M_{fresh,MED}}{\rho\mu} f(\Delta P)$
17	Final condenser cost	(\$)	$C_{cond} = K_{cond}\ C_{cond}\ C_{mat\_cond} A_{cond}{}^{0.8}$
18	Cost of chemical treatment	(\$/yr)	$AOC_{chem} = \frac{C_{chem} THY 3600 M_{seawater,MED}}{\rho}$

Table A.3. Parameters used in the economic model of MED_TVC system

Parameter	Description	Value	Unit	Parameter	Description	Value	Unit
$C_{mat-MED}$	Material of MED	3644	($\$/m^2$)	K_{MED}	Coefficient for MED	1.4	(-)
Ir	Interest rate	0.07	(-)	C_{Lab}	Labor	0.05	($\$/m^3$)
$C_{mat-cond}$	Material of condenser	500	($\$/m^2$)	THY	Total hour per year	8760	(hr/yr)
f(ΔP)	Pressure losses	3571	(-)	C_{chem}	Chemical treatment	0.024	($\$/m^3$)
μ	Efficiency of power generation	0.75	(-)	C_{pow}	Power	0.09	($/KW h)
Life	Life of the plant	25	(year)	K_{intake}	Seawater intake	50	($\$$ day$/m^3$)
C_{steam}	External steam	0.004	($/kg)	K_{cond}	Coefficient for condenser	2.8	(-)

Highlights

- A package of MED_TVC system model and cost model are considered in this study.
- A lowest fresh water production cost of MED_TVC system is explored via simulation.
- A clear change of fresh water cost is found due to increase the number of effects.
- 17 effects of MED system attains the lowest fresh water production cost.
- Increasing the number of effects improves GOR with a penalty of increasing TAC.