A multi-objective optimisation framework for MED-TVC seawater desalination process
based on particle swarm optimisation

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Abstract

Owing to the high specific energy consumption associated with thermal desalination technologies
such as Multi Effect Distillation (MED), there is a wide interest to develop a cost-effective desalination technology. This study focuses on improving the operational, economic, and
environmental perspectives of hybrid MED-TVC (thermal vapour compression) process via optimisation. Application of particle swarm optimisation (PSO) in several engineering
disciplines have been noted but its potential has not been exploited fully in desalination
technologies especially MED-TVC in the past. A multi-objective non-linear optimisation
framework based on PSO is constructed here. Two of our earlier models have been used to predict
the key process performance and cost indicators. The models are embedded within the PSO
optimisation algorithm to develop a new hybrid optimisation model which minimises the total
freshwater production cost, total specific energy consumption and brine flow rate while
maintaining a fixed freshwater production for a given number of effects and seawater conditions.
The steam flow rate and temperature are considered as control variables of the optimisation
problem to achieve the objective function. The PSO has successfully achieved the optimum
indexes for the hybrid MED-TVC process for a wide range of number of effects. It also shows a
maximum reduction of freshwater production cost by 36.5%, a maximum energy saving by 32.1%
and a maximum reduction of brine flow rate by 38.3%, while maintaining the productivity of freshwater.

**Keywords:** Seawater Desalination; Multi Effect Distillation (MED); Thermal Vapour Compression (TVC); Particle swarm optimisation (PSO); Energy consumption.

1. Introduction

Thermal desalination systems such as Multi Effect Distillation integrated with Thermal Vapour Compression (MED-TVC) or Mechanical Vapour Compression (MED-MVC) and Multistage Flash (MSF) are the most common thermal technologies used to desalinate seawater in hot and arid climate countries such as the Kingdom of Saudi Arabia and Kuwait (Ehteram et al., 2020). In this respect, MSF and MED systems have been successfully designed with higher freshwater production compared to membrane technology and are most suitable for desalinating high salinity water. As a penalty, the generation of freshwater at high energy consumption is inevitable for thermal technologies including the MED-TVC process at an elevated freshwater production cost (Al-Obaidi et al., 2019). Moreover, one of the prime concerns of the MED-TVC system is the disposal of large quantities of high-salinity water into the sea, which can have grave consequences for the environment.

Therefore, the choice of improving thermal seawater desalination including MED is a challenging task and must adequately be captured. In this context, process optimisation is a feasible approach to overcome the issue as it has a significant role in increasing the efficiency and reducing energy consumption. It is important to mention that the total freshwater production (related to water demand) of any desalination technology is predominantly related to the total production cost (related to revenue), total energy consumption and quantity of brine disposed (related to
environmental metrics). Therefore, any successful optimisation framework must consider these indexes as interconnected challenges to be resolved.

Several optimisation methods and related studies have been carried out to ascertain the reliability of water supply infrastructure of MED system and to cope with these challenges. Some examples are outlined below.

Esfahani et al. (2012) used multi objective optimisation based genetic algorithm (GA) based on an artificial neural network (ANN) model to minimise total annual cost, maximise gain output ratio, and freshwater flow rate of MED-TVC process. The optimisation concluded that 6 effects of MED system can attain the favorable objective functions compared to other systems of 3, 4, and 5 effects.

An optimisation based nonlinear model was used by Druetta et al. (2013) to accurately optimise the superstructure of the MED system. A superstructure includes all possible configuration of a process (e.g., forward feed, parallel feed configurations of MED process) and optimisation method is applied to determine the best configuration. Druetta et al. (2013) obtained the best configuration based on the optimal stream flow patterns, size of each stage and the operating conditions. Their results showed a reduction of 5% in the total heat transfer area compared to the conventional one.

A superstructure optimisation methodology was proposed by Dahdah and Mitsos (2014) to optimise and adjust the flow routing of each component, sizing and connection of MED and MSF processes in a thermal hybrid system. In this regard, the selection of the final process, the optimal operating conditions and routing of vapour were investigated.

A genetic algorithm (GA) optimisation strategy was embedded in a validated mathematical dynamic model of the MED process of a heat source based on hot water instead of vapour by Carballo et al. (2018) to optimise the process and determine optimal operating conditions. This resulted in an improvement of MED process by reducing the specific thermal consumption at low
steam temperature. Moreover, the effect of changing the operational parameters on the energetic and exergetic performance was also analysed for the optimisation tasks. More importantly, a new exergetic approach was suggested in their study that considered electrical and thermal consumption.

Al-Obaidi et al. (2019) used a single-objective non-linear optimisation framework to minimise the freshwater cost of a hybrid system of MED and RO processes by investigating the optimal values of specified operating conditions of the RO process. Their results showed an economic feasibility of the suggested hybrid system. Moreover, an optimal value of 0.66 $/m^3, was obtained for the total cost of freshwater production.

Al-hotmani et al. (2020) formulated an optimisation problem as a Nonlinear Programming problem to explore the optimal operating conditions of permeate reprocessing RO process integrated with MED-TVC system based on the model developed by Al-hotmani et al. (2019). The aim was to reduce the total energy consumption of the hybrid system. Their results showed a reduction in the total energy consumption whilst maintaining high-quality of freshwater.

The above studies addressed the optimisation of MED system with a focus on enhancing the process design, or on key aspects of process performance indicators or tackling with a principal challenge. To the best knowledge of the authors, a comprehensive optimisation framework based on particle swarm optimisation (PSO) considering the freshwater production, water product cost, total utilised energy and brine flow rate of MED system has not yet been considered for MED-TVC process, which shows the novelty and the scope of this work.

PSO is a popular optimisation method that has been characterised by its reliability as a strong nature tuning algorithm. Furthermore, PSO is characterised by its simple parameter setting, fast convergence, and easy execution (Yaseen et al. 2018). It has thus been used by several scholars to
improve industrial processes (Shirazian and Alibabaei, 2017; Zhang et al., 2019; Sreedhara et al. 2019). The optimisation of MED system using PSO can result to a plethora of optimal solutions that enable the decision makers to select the appropriate one. Some successful studies are collected from the open literature to exhibit the potential of PSO in water treatment and are described below.

The effectiveness of PSO as a superior optimisation method to find global optimal network design of water distribution systems has been established by Hul et al. (2007). This is specifically included in the solution of mixed integer non-linear programming problem for water network synthesis.

Mategaonkar and Eldho (2012) improved an evolutionary algorithm of GA and PSO linked to a simulation model to obtain an effective design of selected groundwater wells in an aquifer system by optimising the pumping rate at a reduced cost.

Ehteram et al. (2020) conducted an intensive study using a hybrid data intelligence (DI) model and PSO to predict the performance of RO process based on total dissolved solids (TDS) and permeate flowrate. This in turn explained the capacity of PSO of low uncertainty, which required an accurate prediction and optimisation of RO process.

There is no doubt that the potential of PSO to support process modelling and to improve the process’s responses via optimisation strategy is huge. However, the hybridization of a robust model and PSO has not yet been considered to optimise a set of operating conditions of MED-TVC system and solve a constructive multi-objective optimisation (MOO) problem to enhance the operational, economic and environmental aspects of the thermal desalination system.

In the above scenario, the main aim of this research is to apply PSO to improve the design, economic and operational parameters of MED-TVC system due to its superiority. The earlier two mathematical models developed by the same authors (operational and cost models) (Filippini et al., 2018 and Al-Obaidi et al., 2019) were embedded with PSO and coded and solved in C++. The
optimisation constitutes multi objective functions of minimising the freshwater production cost, total energy consumption and brine flowrate. Thus, the optimum values of motive steam flowrate and its temperature at fixed feed seawater conditions will be explored. Also, a constraint of fixed freshwater productivity is employed. In this regard, the optimisation methodology has been carried out on a set of different numbers of MED stages to find the optimal conditions and the upper and lower values of control variables (steam flowrate and temperature) are used, corresponding to the ones used in industry. The optimisation results were also tested against simulation results at the same feed seawater conditions to explore the potential of PSO at different number of stages of MED process.

The findings of this research are anticipated to create a relevant method for the enrichment of reliability and sustainability of MED system as one of the most viable option for seawater desalination worldwide.

2. **Description of MED-TVC process**

The MED system was originally designed with several connected distillation stages to desalinate seawater with an external steam supplier (motive steam) to raise the seawater temperature. Fig. 1 shows a schematic diagram of the forward feed MED linked to thermal vapour compression (TVC) process. The TVC is an external steam supplier. Each stage comprises of feed pre-heater, spray nozzle, demister, and an evaporator. The desalination process starts with feeding seawater into the last condenser to preheat it and condense the vapour of the last stage. The heated seawater is then pumped to the first stage at its top brine temperature to instantly evaporate at its boiling temperature with the aid of supplied high-pressure steam. The evaporation is carried out by spreading the feed water using the spray nozzle over the horizontal heat exchanger at reduced
pressure. Then, the evaporated water is condensed in an upper condenser and the majority of the condensed vapour is kept in the flash box as a distillate of the first stage. However, the other portion of condensed vapour is flashed due to its low temperature and then fed to the pre-heater to increase its temperature before sending it to the subsequent stage as the feed steam. The remaining brine of the first stage is simultaneously directed to the second stage for further evaporation using the high energy vapour of the first stage. Therefore, it is expected that less quantity of evaporated water will be produced in the subsequent stages as there is a decrease in evaporation temperature per stage. Finally, the distillate of minimal salinity from all the stages is merged to form the product stream while the high salinity brine leaves the last effect and is disposed to seawater.
Fig. 1. MED-TVC desalination system (Adapted from Druetta et al., 2013)
3. **Modelling of MED-TVC process**

Modelling of the MED-TVC seawater desalination process is necessary for process screening and appraising of operating conditions via simulation. Moreover, the optimisation of thermal desalination plant relies on an existing accurate model. **In other words, the accuracy and robustness of any mathematical model developed is of importance before utilising the model to carry out simulation and optimisation studies. Specifically,** it helps to have the appropriate design of the desalination plant to produce water of desired quality and quantity.

A robust model for MED-TVC was developed by Filippini et al. (2018) and is presented in Table A.1 of Appendix A. In this regard, they have basically combined the models of Darwish et al. (2006) and Dessouky et al. (2002) that characterised MED and TVC systems, respectively. Though, Filippini et al. (2018) developed a new technique to de-linearise the temperature profiles of all the stages. **It can be stated that the model of Filippini et al. (2018) has obtained the lowest deviation of performance indicators between 1.13–1.85 % compared to the latest literature models.** Thus, the model of Filippini et al. (2018) is of high accuracy to estimate the metrics of MED-TVC system. Moreover, Al-Obaidi et al. (2019) presented a reliable costing model for estimating the cost parameters of MED-TVC system including the total freshwater production cost. The model equations are presented in Table A.2 of Appendix A. To carry out this study, an integrated model was developed from the above two models of Filippini et al. (2018) and Al-Obaidi et al. (2019) to predict the operational, economic and performance parameters of MED-TVC.

Therefore, we think that using this model to characterise the MED-TVC system is fair for such deviation of errors to be integrated to PSO method in order to carry out optimisation study. Accordingly, the results will be more reliable and acceptable than using another model of low accuracy available in the literature.
The integrated model was coded in gPROMS software suits. Afterwards, the integrated model has been embedded in an optimisation method to enhance performance and economic perspectives of MED-TVC system as will be described later.

4. Simulation of MED-TVC process and seawater operating conditions

The simulation of MED-TVC process is carried out using an integrated model extracted from the models of Filippini et al. (2018) and Al-Obaidi et al. (2019) as presented in Tables A.1 and A.2 in Appendix A, respectively. The model has considered a fixed set of seawater conditions of 39 kg/m³ (39000 ppm) and 25 °C of seawater salinity and temperature, respectively, and simulated for a set of between 8 to 25 stages of the MED-TVC system. The inlet conditions and design parameters of MED system are shown in Table 1. The cost parameters of MED-TVC are shown in Table A.3 in Appendix A.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seawater salinity and temperature</td>
<td>39 kg/m³, 25 °C</td>
</tr>
<tr>
<td>Steam flow rate, steam pressure, and steam temperature</td>
<td>10 (kg/s), 1300 (kPa), and 75 (°C)</td>
</tr>
<tr>
<td>Disposed brine salinity and temperature</td>
<td>60 (kg/m³) and 40 °C</td>
</tr>
</tbody>
</table>

The simulation results are listed with the optimisation results in Table 3 for the purpose of comparison.
5. **Optimisation of MED-TVC process**

   **a) Problem description and formulation**

In the MED desalination system, traditional optimisation usually considers the freshwater production flowrate or freshwater production cost as the main targets. In this study, a set of different objective functions has been constructed to meet the necessity of a reliable thermal desalination technology of MED including the maximum revenue (minimising the freshwater production cost), and minimum total energy consumption. Moreover, the lowest possible disposed brine flowrate (brine stream) is the objective here to minimise impact on the environment. To appropriately investigate the goal of optimisation, the selection of the most important decision variables that have the largest effect on the system performance and easy to be controlled is crucial. The optimisation has considered the steam flowrate and steam temperature as the main control variables to be adjusted to fit the objective functions. Moreover, a fixed production flowrate of fresh water is constrained to fulfil the main target of any seawater desalination plant operation of a specified number of stages (fixed production of freshwater). In other words, the simulation value of MED-TVC system at the specified number of stages will be considered as the restricted designed value. Furthermore, fixed values of environmental variables of seawater salinity and temperature are taken as 39000 ppm and 25 °C respectively. The optimisation based PSO was carried out for a set of different numbers of stages. This in turn would comprehensively meet different optimal values of constructed MED-TVC plants around the world. In this regard, a hybrid optimisation model was developed from the integration of the two models (described in section 3) and POS that embedded a MOO problem to obtain the optimal values of MED-TVC system at a given set of operating seawater conditions and a selected number of stages of MED. In other words, this optimisation will determine the optimal performance indicators of MED-TVC system at a
given number of stages. The optimisation results will then be compared against the simulation
results and the benefits will be evaluated. The principles of PSO are thoroughly described in the
next section.

The mathematical expression of the optimisation problem is as follows:

Given:          Seawater properties at 39,000 ppm, 25 °C, MED-TVC specifications, fixed number
of stages and 60,000 ppm as the brine salinity.

Determine:      Optimal flowrate ($M_s$) and temperature ($T_s$) of motive steam (decision variables)

So as to simultaneously minimise:

The freshwater production cost ($FWC_{MED-TVC}$),
The energy consumption ($EC$) and brine flowrate ($M_b$) of the MED system

Subject to:     Equality, inequality constraints and end-point constraint: Process model, upper and
lower bounds of decision variables and fixed simulation value of freshwater
production flowrate, respectively

Therefore, the mathematical expression of the optimisation will be as follows:

$$\min_{M_s, T_s} FWC_{MED-TVC}, EC, M_b$$

Subject to:

Equality constraints: Process model: $f(x, u, v) = 0$

Inequality constraints: $6 \text{ kg/s} \leq M_s \leq 10 \text{ kg/s}, 60 \degree C \leq T_s \leq 80 \degree C$

End-point constraint: Fixed simulation value of $M_d$

\textbf{b) Particle swarm optimisation}

The PSO is a popular population based stochastic intelligence optimisation technique, which was
originally proposed by \textit{Kennedy and Eberhart (1995)} based on the social behaviors of flocking
birds or schooling fish. PSO simulates the fights of a group of particles in a multi-dimension space, in which each particle in a population presents a potential solution (called swarm) of an optimisation problem. PSO has been demonstrated to be an effective optimisation method for solving complex science and engineering optimisation problems (Clerc, 2006).

A PSO is normally designed to find an optimal solution to maximise an optimisation problem:

\[
\text{maximise } f(x) \\
x
\]

Subject to:

\[
g(x) \geq 0
\]

\[
h(x) = 0
\]

Typically, a PSO employs a population, \( P = \{x_1, x_2, \cdots, x_N\} \), of particles, \( x_i = (x_{i1}, x_{i2}, \cdots, x_{in})^T \)
called swarms, to search space simultaneously. Here \( N \) is the population size and \( n \) the dimension number of the problem. Each particle is randomly initialised in the search space. At each iteration of the optimisation process, each particle will move to a new position with an adaptive velocity, \( v_i = (v_{i1}, v_{i2}, \cdots, v_{in})^T \), which will be influenced by

• its current position \( x_i \);

• its own search experience, the personal best position (pBest), \( x_i^p \), found by the current particle;

• the population experience, the global best position (gBest), \( x^g \) found by all the particles in the population.

Mathematically, the new position and velocity of a particle \( i \) at the \( t \)-th generation can be calculated as:

\[
x_i(t + 1) = x_i(t) + v_i(t + 1) \tag{1}
\]

\[
v_i(t + 1) = v_i(t) + r_1 \phi_p [x_i^p - x_i] + r_2 \phi_g [x^g - x_i] \tag{2}
\]
where \( r_1 \) and \( r_2 \) are random numbers between 0 and 1. \( \phi_p \) and \( \phi_g \) are the cognitive and social acceleration coefficients, respectively. In this paper, \( \phi_p = \phi_g = 2.05 \).

At each iteration, a particle \( x_i \) will update its velocity and position. The new velocity, \( v_i(t + 1) \), is the sum of three terms: the previous velocity, random proportion of the distance to the local best and the global best. This means that a particle’s movement is influenced by its personal best experience, but it is also guided towards the best-known position in the search space, which is found by all the particles. The process of a typical particle swarm optimisation is illustrated in Table 2. As PSO is easy to converge to a local optimal solution, a uniform mutation is used to keep its diversity so that the proposed PSO can find the global solution. A mutation probability, \( p_m \), is used to select particles to uniformly mutate. This means that there is \( p_m \times N \) particles, which are randomly allocated in the feasible region.
Table 2. The process of a classical particle swarm optimisation algorithm

\begin{itemize}
\item \textbf{Inputs:} \_\_ \text{N (population size),}
\item \_\_ \text{\(N_G\) (Number of generations)}
\item \_\_ \text{\(p_m\) (mutation probability)}
\end{itemize}

\textbf{Output:} \(x^g\)

\begin{algorithmic}
\State \(t = 0\);
\State Randomly initialise the population.
\State Evaluate the fitness value \(F_i(0)\) for each particle.
\State \(v_i = 0, \quad x_i^p = x_i\)
\State Find the global best \(x^g\) from the population
\While{\(t < N_g\) not satisfy the criterion of termination}
\While{\text{for each} \(x_i\) \text{in the population}}
\State Update the velocity, \(v_i(t + 1)\) using Eq. 2
\State Update the new position, \(x_i(t + 1)\) using Eq. 1
\State Evaluate \(F_i(t + 1) = F[x_i(t + 1)]\) of particle \(i\);
\If{\(F[x_i(t + 1)] > F[x_i^p]\)}
\State \(x_i^p = x_i(t + 1)\)
\EndIf
\If{\(F[x_i(t + 1)] > F[x^g]\)}
\State \(x^g = x_i(t + 1)\)
\EndIf
\EndWhile
\State \text{Uniform Mutation according to} \(p_m\)
\State \(t = t + 1;\)
\EndWhile
\end{algorithmic}

The usefulness of PSO is characterised by its simplicity in solving complicated optimisation problems, its fast convergence with easy implementation and has no crossover and mutation like GA techniques. Many researchers have applied PSO to solve single optimisation problem, multi objective optimisation problem, neural network training and pattern recognition (Kennedy and Eberhart, 1995).

Fig. 2 shows a schematic diagram of the optimisation model that integrates two models of Filippini et al. (2018) (operational model) and Al-Obaidi et al. (2019) (cost model) and PSO. More specifically, the process model is used to simulate the process at fixed seawater conditions and a
selected number of stages between 8 to 25 (Table 3) to predict three operational indexes including the freshwater production cost ($FWC_{MED-TVC}$), total energy consumption ($EC$) and brine flowrate ($M_b$). Then, PSO is used to generate the optimal values of the control variables of MED-TVC process including mass flowrate ($M_s$) and temperature ($T_s$) of motive steam that guarantee the optimal values of the operational indexes except the freshwater productivity ($M_d$) that has been taken as a constraint of the optimisation model. Furthermore, it is fair to expect that changing the mass flowrate of motive steam would subsequently change the areas of heat exchanger and condenser. Thus, the calculation of related average area of evaporators and condenser area will be provided as optimisation output metrics for each selected number of effects.

The PSO has been characterised by a set of parameters including the initial swarm particle size of 50, maximum number of iterations ($N_G$) of 100, and $p_m = 0.05$. Normally, the larger of the population size and the more of the iteration, the larger chance for the algorithm to find the solutions. Due to the dimension of this problem is not very high, our experiences show that it is good enough to use $N=50$, $N_G = 100$ and $p_m = 0.05$ to find the solutions in each case.

The PSO has been constructed with the following weight factors:

- $w_{Tac} = 3$
- $w_{Mb} = 0.01$
- $w_{Power\ Consumption} = 0.5$

The selection of the above weight factor is to give each factor the same importance in the process of optimisation based on their average values. Thus, the PSO has gained considerable benefits of the objective functions that ensure safe and successful operation of MED-TVC system.
## 6. Optimisation results and discussion

The optimisation problem has been solved using PSO for each selected number of stages of MED system. The simulation (non-optimisation) and optimisation results of the selected performance indicators are depicted in Figs. 3 – 5 and the overall calculations of the optimal values of mass flowrate and temperature of motive steam, optimisation constraints, optimisation output parameters and acquired %benefits in the freshwater production cost, total energy consumption, and brine flow are provided in Table 3 for each number of effects of MED system. In this respect, 6 kg/s and 60 °C of mass flow rate and temperature respectively are mostly required to optimise the operation by improving the economic and environmental perspectives of the MED-TVC system.
The benefit is basically calculated by the difference between simulation and optimisation values.

Fig. 3 – 5 and Table 3 show that the PSO has deduced lower values of the total freshwater production cost, total energy consumption and brine flowrate whilst keeping the same values of freshwater production for each tested number of stages of MED-TVC system (selected between 8 to 25).

Apparently, the simulation results of Fig. 3 confirm the existence of an optimal number of effects of 17 that demonstrates the lowest fresh water production cost. However, the optimisation results has entailed the most optimal number of effects of 25 that hits the lowest possible fresh water production cost. More importantly, Fig. 3 presents the improvement made by applying PSO in the optimisation of MED system. This improvement is more noticed when the number of effects exceeds 21. This can be attributed to the improvement of fresh water productivity.

Fig. 4 shows the reduction of specific energy consumption as a result to increasing of the number of effects. Apparently, the behavior of the specific energy consumption against the number of effects for both simulation and optimisation is same. The implication of the optimised variables of PSO has introduced a considerable reduction of the power consumed. This is clearly noticed within a small number of effects compared to the large number of effects.

Fig. 5 depicts the improvement of brine flow rate for a set of number of effects between (8 – 25) using the optimisation of PSO compared to the simulation results. As far as the number of effects increases, the improvement of brine flow rate becomes more pronounced. This in turn elaborating the importance of utilising the optimisation towards the improvement of disposed brine into the sea that commensurate a considerable negative impact on the environment.
The recorded benefits of PSO range between (27.56% – 36.5%), (19.38% – 32.1%), and (32.54% – 38.3%) in the freshwater production cost, total energy consumption, and brine flowrate, respectively, for the selected number of stages between (8 – 25) (Table 3). Therefore, it is fair to claim the success of the optimisation framework that respects a quantitative constraint of freshwater production. In this regard, the PSO has opened a superior opportunity to simultaneously enhance both economic and environmental perspectives of the thermal desalination. It can be stated that lowering the mass flowrate and temperature of the motive steam is important (compared to the simulation values given in Table 1) in achieving the main goals. The optimal values of the control variables were selected within the feasible limits that can be applied in the MED-TVC plants. The physical explanation behind achieving the simultaneous objective functions at lower values of mass flowrate and temperature of steam is that these conditions are appropriate to increase the performance ratio and gain output ratio GOR (see Eq. 20 in Table A.1 of Appendix A) of the MED system. However, the selection of low values of mass flowrate and temperature of motive steam whilst constraining the freshwater production flow rate (simulation value) requires higher values of total capital cost (TCC) and annual operating cost (AOC) associated with the construction cost and material of MED system. Specifically, much higher area of the heat exchangers and condenser are required to fulfil fixed freshwater flowrate in case of lowering the mass flowrate and temperature of motive steam that incorporates a higher value of total annualised cost (TAC). This is clearly noticed in Table 3. Table 3 provides the related average area of evaporators and condenser area as they denoted as the optimisation output parameters in the PSO optimisation. Despite this, the overall freshwater production cost was reduced due to acquiring high productivity of freshwater. This is also confirmed by Al-Obaidi et al. (2019) who noticed an improvement of the economy aspect of MED-TVC at values of steam temperature lower than 70
°C. Also, an exponential relationship was deduced between the freshwater production cost and the steam temperature. In other words, lowering the steam temperature would reduce the temperature difference available for heat exchangers. Also, low temperature of steam requires low mass flowrate, and this would decrease the cost of the steam utility (see Eq. 11 in Table A.2 of Appendix A).

It should be noted that the reduction of mass flowrate and temperature of motive steam has the advantage of lowering the total energy consumption (EC). Specifically, Eqs. 25 and 26 in Table A.1 of Appendix A present the relationship between the freshwater production flowrate ($M_d$) and energy consumption of MED system. Basically, an improvement of $M_d$ means lower energy consumption with reduced brine flowrate. In this regard, it is important to mention that controlling mass flowrate and temperature of motive steam can be carried out via adjusting the high pressure steam from boiler shown in Fig. 1.

Comparative analysis of the optimisation results of Table 3 demonstrates several important considerations. Firstly, the application of 15 stages in the MED system provides one of the lowest optimal freshwater production costs. Secondly, 24 stages are appropriate to maintain the MED system with the lowest optimal energy consumption. However, 8 stages are required to fulfil the best environmental perspectives of the lowest optimal disposed brine into the sea. From an engineering viewpoint, the 15 stages option is a compromise solution to quantify the best operation, economic and environmental aspects. Apart from this, the simulation results of Table 3 indicate the same optimal behaviors of the tested parameters.

The optimisation results presented in this section show the possibility of improving MED-TVC system as there is considerable reduction of freshwater production cost, total energy consumption,
and brine flow rate. Therefore, it is also fair to expect that the findings of this research have investigated the requirements of a successful thermal desalination technology.

**Fig. 3.** The simulation and optimisation results of fresh water production cost for different number of effects
Fig. 4. The simulation and optimisation results of specific energy consumption for different number of effects.

Fig. 5. The simulation and optimisation results of brine flow rate for different number of effects.
Table 3. Simulation and optimisation results of MED_TVC process at fixed seawater conditions (39 kg/m³ and 25 °C) and calculated benefits.

<table>
<thead>
<tr>
<th>Number of stages</th>
<th>$M_s$ (kg/s)</th>
<th>$T_s$ (°C)</th>
<th>Fresh water productivity ($M_{fe}$ m³/day)</th>
<th>Average area of evaporators (m²)</th>
<th>Area of condenser (m²)</th>
<th>Fresh water production cost ($FW_{MED−TVC}$, $/m³)</th>
<th>Specific energy consumption – MED ($EC$, kWh/m³)</th>
<th>Benefit%</th>
<th>Benefit%</th>
<th>Benefit%</th>
<th>Brine flowrate ($M_b$, m³/day)</th>
<th>Benefit%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Simulation</td>
<td>Optimisation</td>
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<td>Optimisation</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>60</td>
<td>4725.365</td>
<td>2276.56</td>
<td>646.64</td>
<td>0.732</td>
<td>0.510</td>
<td>30.35</td>
<td>21.734</td>
<td>14.746</td>
<td>8775.673</td>
<td>5914.454</td>
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<td>6</td>
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<td>9.146</td>
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</table>

* Please note: The operating conditions of simulation results are given in Table 1.
7. Conclusions

In this paper, the operational and cost models of the MED-TVC system were introduced into the multi-objective non-linear particle swarm optimisation (PSO) to build an optimisation model. The optimisation model was used to investigate the feasible operating conditions of mass flowrate of motive steam and its temperature to simultaneously establish the lowest values of total freshwater production cost, total energy consumption and brine flowrate under fixed operating seawater conditions. In this respect, the optimisation has been carried out for different number of stages of MED system from 8 to 25 while constraining the freshwater productivity of each number of stages. This research has outlined the superiority of PSO as a fast global optimisation method. The PSO has achieved a considerable reduction of all the objective functions of around 30% while maintaining the MED-TVC at its original productivity of freshwater.

Nonetheless, the presented method in this research suggested that it would be useful to optimise the number of stages of MED-TVC process besides the optimisation of steam characteristics. In this regard, it is recommended to lower the mass flowrate and temperature of the motive steam to attain the main goals. Furthermore, it was affirmed that a 15 stages MED-TVC system is more suitable to produce the best operational, economic, and environmental conditions. Further enhancement of these parameters is expected to be analysed in the future for different seawater conditions.

References


### Table A.1. Model equations of MED process (Filippini et al., 2018)

<table>
<thead>
<tr>
<th>No</th>
<th>Title</th>
<th>Unit</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Temperature drop among effects first attempt</td>
<td>°C</td>
<td>$\Delta T = \frac{T_{i-1}-T_{n-1}}{n} or \Delta T = \frac{T_{s}-T_{b}}{n}$</td>
</tr>
<tr>
<td>2</td>
<td>Temperature drop among pre-heaters first attempt</td>
<td>°C</td>
<td>$\Delta T = \Delta t$</td>
</tr>
<tr>
<td>3</td>
<td>Mean temperature in the plant</td>
<td>°C</td>
<td>$T_{\text{mean}} = \frac{T_{1}+T_{b}}{2}$</td>
</tr>
<tr>
<td>4</td>
<td>Mean salinity</td>
<td>ppm</td>
<td>$x_{\text{mean}} = \frac{xf + xb}{2}$</td>
</tr>
<tr>
<td>5</td>
<td>Fraction of flashed distillate</td>
<td>(-)</td>
<td>$\alpha = \frac{cp(T_{\text{mean}}, x_{\text{mean}})\Delta T}{\lambda(T_{\text{mean}})}$</td>
</tr>
<tr>
<td>6</td>
<td>Fraction of total distillate boiled in each evaporator</td>
<td>(-)</td>
<td>$\beta = \frac{\alpha[xb(1-\alpha)^n - xf]}{(xb - xf)[1 - (1 - \alpha)^n]}$</td>
</tr>
<tr>
<td>7</td>
<td>Heat load in i-th effect</td>
<td>(kJ/s)</td>
<td>$Q_{i} = D_{\text{boiled},i-1} \lambda(T_{v,i-1})$</td>
</tr>
<tr>
<td>8</td>
<td>Sensible heat used in first effect</td>
<td>(kJ/kg)</td>
<td>$Q_{\text{sensible}} = Mf \int_{T_{1}}^{T_{1}} cp(T_{1}, x_{1})dT$</td>
</tr>
<tr>
<td>9</td>
<td>Feed flowrate</td>
<td>(kJ/s)</td>
<td>$Mf = \frac{Q_{\text{sensible}} + Q_{\text{latent}}}{Ms \lambda(T_{s})}$</td>
</tr>
<tr>
<td>10</td>
<td>Latent heat in first effect</td>
<td>(kJ/s)</td>
<td>$Q_{\text{latent}} = D_{i} \lambda(T_{v,i})$</td>
</tr>
<tr>
<td>11</td>
<td>Rejected brine flowrate</td>
<td>(kg/s)</td>
<td>$Mb = Mf - Md$</td>
</tr>
<tr>
<td>12</td>
<td>Feed flow rate</td>
<td>(kg/s)</td>
<td>$Mf = Md - \frac{xb - xf}{xb}$</td>
</tr>
<tr>
<td>13</td>
<td>Distillate produced by boiling in i-th evaporator</td>
<td>(kg/s)</td>
<td>$D_{\text{boiled},i} = \beta Md$</td>
</tr>
<tr>
<td>14</td>
<td>Total distillate produced in i-th effect</td>
<td>(kg/s)</td>
<td>$D_{i} = D_{\text{boiled},i} + D_{\text{flash},i}$</td>
</tr>
<tr>
<td>15</td>
<td>Brine rejected in the i-th effect</td>
<td>(kg/s)</td>
<td>$B_{i} = B_{i-1} - D_{i}$</td>
</tr>
<tr>
<td>16</td>
<td>Mean salinity in the plant</td>
<td>ppm or w/w%</td>
<td>$x_{i} = \frac{x_{i-1}B_{i-1}}{B_{i}}$</td>
</tr>
<tr>
<td>17</td>
<td>Feed temperature in first effect</td>
<td>°C</td>
<td>$t_{1} = t_{n} + (n-1)\Delta t$</td>
</tr>
<tr>
<td>18</td>
<td>Temperature of the vapour phase in i-th effect</td>
<td>°C</td>
<td>$T_{v} = T - BPE(T, x)$</td>
</tr>
<tr>
<td>19</td>
<td>Driving force for heat exchange in i-th pre-heater</td>
<td>°C</td>
<td>$\Delta t_{\log,i} = \frac{\Delta t}{\log \left( \frac{T_{v,i} - t_{i+1}}{T_{v,i} - t_{i}} \right)}$</td>
</tr>
<tr>
<td>20</td>
<td>Gained Output Ratio</td>
<td>(-)</td>
<td>$GOR = \frac{M_{s}}{2330 \lambda(T_{s})}$</td>
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<tr>
<td>21</td>
<td>Performance Ratio</td>
<td>(-)</td>
<td>$PR = GOR$</td>
</tr>
<tr>
<td>22</td>
<td>Specific total area</td>
<td>(m²/s/kg)</td>
<td>$Atot_{s} = \frac{Md}{Mw}$</td>
</tr>
<tr>
<td>23</td>
<td>Specific seawater intake</td>
<td>(-)</td>
<td>$M_{w_{s}} = \frac{Md}{Mw}$</td>
</tr>
<tr>
<td>24</td>
<td>Area of i-th effect</td>
<td>(m²)</td>
<td>$A_{ev,mean} = \frac{U_{ev,i} \Delta T_{ext,i}}{E_{s}}$</td>
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<tr>
<td>25</td>
<td>Energy consumption</td>
<td>(kWh/m³)</td>
<td>$\text{Power consumption} = \left( \frac{E_{s}}{11.88} \right) + 2$</td>
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<tr>
<td>26</td>
<td>Specific energy consumption</td>
<td>(kJ/kg)</td>
<td>$E_{s} = \frac{M_{m} \lambda(T_{s})}{M_{d}}$</td>
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Table A.2. The economic model (Al-Obaidi et al., 2019)

<table>
<thead>
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<th>No.</th>
<th>Title</th>
<th>Unit</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Total capital cost</td>
<td>($)</td>
<td>( TCC = \text{CAPEX}<em>{\text{dir}} + \text{CAPEX}</em>{\text{indir}} )</td>
</tr>
<tr>
<td>2</td>
<td>Indirect CAPEX</td>
<td>($)</td>
<td>( \text{CAPEX}<em>{\text{indir}} = 0.25 \text{CAPEX}</em>{\text{dir}} )</td>
</tr>
<tr>
<td>3</td>
<td>Civil work cost</td>
<td>($)</td>
<td>( \text{CAPEX}<em>{\text{civil,work}} = 0.15 \text{CAPEX}</em>{\text{equipment}} )</td>
</tr>
<tr>
<td>4</td>
<td>MED plant cost</td>
<td>($)</td>
<td>( C_{\text{med}} = K_{\text{MED}} C_{\text{mat,MED}} A_{\text{MED}}^{0.64} )</td>
</tr>
<tr>
<td>5</td>
<td>Fresh water cost</td>
<td>($/m^3)</td>
<td>( FWC_{\text{MED}} = \frac{TAC}{M_{\text{fresh,MED}} T_{\text{HY}3600}} )</td>
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<tr>
<td>6</td>
<td>Annual operating cost</td>
<td>($/yr)</td>
<td>( AOC = AOC_{\text{chem}} + AOC_{\text{lab}} AOC_{\text{pow}} + AOC_{\text{man}} + AOC_{\text{steam}} )</td>
</tr>
<tr>
<td>7</td>
<td>Seawater intake and pre-treatment cost</td>
<td>($)</td>
<td>( C_{\text{intake}} = \frac{K_{\text{intake}} 24360 M_{\text{seawater,MED}}}{2a} )</td>
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<td>8</td>
<td>Capital recovery factor</td>
<td>(1/yr)</td>
<td>( CAF = \frac{\text{Ir}}{\left(1 + \frac{\text{Ir}}{\text{Ir}_{\text{lift}}}\right)} )</td>
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<tr>
<td>9</td>
<td>Cost of human labour</td>
<td>($/yr)</td>
<td>( AOC_{\text{lab}} = \frac{c_{\text{lab}} T_{\text{HY}3600} M_{\text{fresh,MED}}}{\rho} )</td>
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<tr>
<td>10</td>
<td>Cost of manutention</td>
<td>($/yr)</td>
<td>( AOC_{\text{man}} = 0.002 TCC )</td>
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<tr>
<td>11</td>
<td>Cost of external steam</td>
<td>($/yr)</td>
<td>( AOC_{\text{steam}} = \frac{c_{\text{steam}} T_{\text{HY}(T_s-40)} M_{\text{steam}}}{s_0} + 0.005 TCC )</td>
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<tr>
<td>12</td>
<td>Total annual cost</td>
<td>($/yr)</td>
<td>( TAC = AOC + CRF \times TCC )</td>
</tr>
<tr>
<td>13</td>
<td>Equipment cost</td>
<td>($)</td>
<td>( \text{CAPEX}<em>{\text{equipment}} = C</em>{\text{intake}} + C_{\text{MED}} + C_{\text{cond}} )</td>
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<tr>
<td>14</td>
<td>Direct CAPEX</td>
<td>($)</td>
<td>( \text{CAPEX}<em>{\text{dir}} = \text{CAPEX}</em>{\text{equipment}} + \text{CAPEX}_{\text{civil,work}} )</td>
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<tr>
<td>15</td>
<td>Cost of power for pumps</td>
<td>($/yr)</td>
<td>( AOC_{\text{pow}} = \frac{c_{\text{pow}} T_{\text{HY}100} M_{\text{fresh,MED}}}{\rho s} f(\Delta P) )</td>
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<tr>
<td>16</td>
<td>Final condenser cost</td>
<td>($)</td>
<td>( C_{\text{cond}} = K_{\text{cond}} C_{\text{cond}} C_{\text{mat,cond}} A_{\text{cond}}^{0.8} )</td>
</tr>
<tr>
<td>17</td>
<td>Cost of chemical treatment</td>
<td>($/yr)</td>
<td>( AOC_{\text{chem}} = \frac{c_{\text{chem}} T_{\text{HY}3600} M_{\text{seawater,MED}}}{\rho} )</td>
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<tr>
<td>18</td>
<td>Cost of TVC section</td>
<td>($)</td>
<td>( C_{\text{TVC}} = 7912 M_{\text{ev}} \left(\frac{T_{\text{ev}}}{P_{\text{ev}}^{0.005}}\right)^{0.75} )</td>
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</table>

525 526 527 528 529 530 531 532 533 534 535

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Table A.3. Parameters used in the economic model of MED (Al-Obaidi et al., 2019)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
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<tr>
<td>$C_{mat-MED}$</td>
<td>Material of MED</td>
<td>3644</td>
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<td>$K_{MED}$</td>
<td>Coeff. for MED</td>
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<tr>
<td>Ir</td>
<td>Interest rate</td>
<td>0.07</td>
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<td>$C_{Lab}$</td>
<td>Labour</td>
<td>0.05</td>
<td>($/m^3$)</td>
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<tr>
<td>$C_{mat-cond}$</td>
<td>Material of condenser</td>
<td>500</td>
<td>($/m^2$)</td>
<td>THY</td>
<td>Total hour per year</td>
<td>8760</td>
<td>hr/yr</td>
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<tr>
<td>$f(\Delta P)$</td>
<td>Pressure losses</td>
<td>3571</td>
<td>(-)</td>
<td>$C_{chem}$</td>
<td>Chemical treatment</td>
<td>0.024</td>
<td>($/m^3$)</td>
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<tr>
<td>$\mu$</td>
<td>Efficiency of power generation</td>
<td>0.75</td>
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<td>$C_{pow}$</td>
<td>Power</td>
<td>0.09</td>
<td>$/kWh$</td>
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<td>Life</td>
<td>Life of the plant</td>
<td>25</td>
<td>(year)</td>
<td>$K_{intake}$</td>
<td>Seawater intake</td>
<td>50</td>
<td>$/day/m^3$</td>
</tr>
<tr>
<td>$C_{steam}$</td>
<td>External steam</td>
<td>0.004</td>
<td>($/kg)</td>
<td>$K_{cond}$</td>
<td>Coeff. for condenser</td>
<td>2.8</td>
<td></td>
</tr>
</tbody>
</table>

Nomenclature

$A_{ev,i}$: Exchange area of i-th evaporator (m²)

$A_{ph,i}$: Exchange area of i-th pre-heater (m²)

$A_{cond}$: Exchange area of final condenser (m²)

$A_{ev,mean}$: Mean exchange area of evaporators (m²)

$A_{ph,mean}$: Mean exchange area of pre-heaters (m²)

$B_i$: Brine rejected by the i-th effect (kg/s)

CR: Compression ratio in the steam ejector (-)

$D_i$: Total distillate produced in i-th effect (kg/s)

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

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

$Mb$: Rejected brine flowrate (kg/s)
$M_{\text{COND}}$: Flowrate of steam in the final condenser (kg/s)

$M_d$: Distillate from MED process (kg/s)

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

$M_m$: Motive steam flowrate (kg/s)

$M_s$: Total steam flowrate (kg/s)

$M_w$: Intake water flowrate (kg/s)

$M_{\text{TVC}}$: Vapor flowrate entrained in TVC section (kg/s)

$n$: Number of effects of MED process (-)

$p_{\text{cri}}$: Critical pressure of water (kPa)

$p_{\text{ev}}$: Pressure of saturated entrained vapor (kPa)

$p_{\text{m}}$: Pressure of saturated steam at temperature $T_m$ (kPa)

$p_s$: Pressure of saturated steam at temperature $T_s$ (kPa)

$p_v$: Pressure of saturated steam at temperature $T_v$ (kPa)

$Q_{\text{COND}}$: Thermal load in final condenser (kW)

$Q_{\text{sensible}}$: Sensible heat used in first effect (kJ/kg)

$Q_{\text{latent}}$: Latent heat used in first effect (kJ/kg)

$Q_i$: Thermal load at $i$-th evaporator (kW)

$Q_s$: Thermal load of steam (kW)
Ra: Entrainment ratio (-)

\( t_i \): Feed temperature after i-th pre-heater (°C)

\( t_n \): Feed temperature after final condenser (°C)

\( T_l \): Top brine temperature (Ttop) (°C)

\( T_b \): Temperature of rejected brine (°C)

\( T_s \): Steam temperature (°C)

\( T_{vi} \): Temperature of the vapor phase in i-th effect (°C)

\( T_w \): Temperature of the cooling water (°C)

\( T_{mean} \): Mean temperature in the plant (°C)

\( T_{crit} \): Critical temperature of water (°C)

\( U_{ev,i} \): Global heat exchange coefficient in i-th evaporator (kW/m² °C)

\( U_{ph,i} \): Global heat exchange coefficient in i-th pre-heater (kW/m² °C)

\( U_{cond} \): Global heat exchange coefficient in final condenser (kW/m² °C)

\( x_i \): Salinity in i-th evaporator (ppm or w/w%)

\( x_b \): Salinity in rejected brine (ppm or w/w%)

\( x_f \): Salinity in the feed (ppm or w/w%)

\( x_{mean} \): Mean salinity in the plant (ppm or w/w%)
Greek

\( \alpha \): Fraction of rejected brine from previous effect flashed in the associated pre-heater (-)

\( \beta \): Fraction of total distillate boiled in each evaporator (-)

\( \Delta A_{ev}, \% \): Percentage error on evaporators’ areas (%)

\( \Delta A_{ph}, \% \): Percentage error on pre-heaters areas (%)

\( \Delta T_{e,i} \): Driving force for heat exchange in i-th evaporator (°C)

\( \Delta T_{ph,i} \): Driving force for heat exchange in i-th pre-heater (°C)

\( \Delta T_{kg,cond} \): Driving force for heat exchange in final condenser (°C)

\( \Delta T \): Temperature drop between two evaporators (°C)

\( \Delta T_i \): Temperature increase between two pre-heaters (°C)

\( \lambda \): Latent heat of evaporation (kJ/kg)

\( \eta_{pump} \): Pump efficiency (-)

\( \eta_{ERD} \):

Efficiency of energy recovery device (-)