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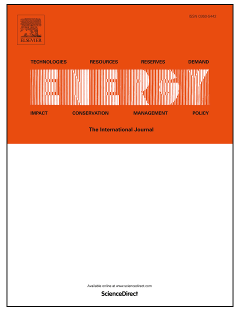

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Performance Analysis and Optimization of Hybrid Multi-Effect Distillation Adsorption Desalination System Powered with Solar Thermal Energy for High Salinity Sea Water

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Abstract

Performance analysis, parametric study and response surface methodology (RSM) based optimization of hybrid Multi-Effect Distillation Adsorption Desalination (MEDAD) system powered with solar energy is presented in this paper. The goal is to develop innovative and cost-effective technology for high salt concentration sea water desalination using renewable energy technologies. The main objectives are to develop sustainable methods and strategies to enhance the quality and quantity of freshwater production; and reduce the energy consumption during the desalination process. The effect of number of stages for the Multi Effect Distillation (MED) system, the addition of the adsorption desalination (AD) stage and the heat recovery from the residual brines on the performance of the MEDAD system for high salinity sea water under hot and humid climatic conditions are investigated. The analytical analysis and an optimization method are used in this study to determine the system's optimum operating conditions to maximize the freshwater production, reduce the energy consumption and performance ratio. Four input factors are selected for the parametric study: Heat transfer fluid temperature and Reynolds number; and sea water temperature and total dissolved solids TDS. The results show that the production rate of fresh water was improved by 2.68 times, achieving a 57.78% lower specific energy consumption by adding the adsorption desalination stage. For the heat recovery from the residual brine, the results show that the freshwater production rate and the performance ratio increased by respectively 14.73% and 12.86%, and the specific energy consumption decreased by 11.34%. New correlations for the variation of the inverse of the specific energy consumption (m^3/kWh) and the performance ratio versus the four input factors and the order of importance of the input factors are presented.

Key Words: *Solar Thermal, Hybrid Desalination, Multi-Effect Distillation Adsorption Desalination (MEDAD), Optimization, Parametric Study.*

Nomenclature

A	Surface area (m^2)
Cp	Specific heat (J/kg. K)
hfg	Latent heat of evaporation or condensation (J/kg)
k_0	Adsorption constant (1/Pa)
m	Mass flow rate (kg/s)
n	Number of stages
P	Pressure (Pa)
Q	Required energy (W)
Q_{isos}	Isosteric adsorption heat (J/kg)
quant	the amount of adsorbate in the adsorbent.
Re	Reynolds number
R_v	Gas constant of water vapor (J/kg K)
T	Temperature (°C)
t_{cycle}	Time needed to complete one cycle of adsorption/desorption (s)
U	Overall heat transfer coefficient (W/m^2 K)
V	Volumetric flow rate (m^3/h)
X	Total dissolved solids (ppm)

ρ Density (kg/m^3)

Subscripts

ads Adsorption

b Brine

cond Condenser

d Desalinated fresh water

des Desorption

evap Evaporator

ex Exit

i Intermediate stage

in Inlet

isos Isosteric

lm Logarithmic mean

loss Loss in temperature

sat Saturation

sep separator after each stage

sep, v vapor separated after each stage's separator

sg	Silica gel
sw	Seawater
tot	Total
v	Vapor

Abbreviations

AD	Adsorption Desalination
ETC	Evacuated Tube Solar Collector
FPC	Flat Plate Solar Collector
HE	Heat Exchanger
HTF	Heat Transfer Fluid
MED	Multi-Effect Distillation
MEDAD	Multi-Effect Distillation Adsorption Desalination
PR	Performance Ratio
PTC	Parabolic Trough Solar Collector
PV	Photovoltaic
SEC	Specific Energy Consumption
TDS	Total Dissolved Solids

1. Introduction

Thermal desalination systems uses heat source to separate the salts from seawater by evaporation and condensation processes to produce distilled water [1]. The sources of heat vary based on the amount of energy required by the desalination process, and the operating temperature of the system. It can either be thermal energy from a conventional source such as the burning process of fossil fuels, or from a renewable resources, such as solar thermal sources [2]. One of the most common thermal desalination methods is Multi-Effect Distillation (MED). This method requires a temperature of a medium grade [1], which can be supplied using solar collectors. For a small-scale system, a flat plate collector (FPC) or evacuated tube solar collector (ETC) can be used, whereas a collector that concentrates the solar power such as a parabolic trough solar collector (PTC) is more efficient for a large-scale system [3]. Moreover, electrical energy is required for pumping the heat transfer fluid (HTF), especially when a storage system is used. This can be supplied to the system using solar PV panels, in order to have the system fully disconnected from the grid. MED systems utilize the heat in the first stage to evaporate seawater, producing steam. Then, the latent heat of the steam is used in the following stage to evaporate more seawater, and the condensed steam exiting from each stage is collected in a tank of distilled water. Finally, the outlet steam of the final stage condenses, ending the desalination process. However, in such configuration, a limitation arises in the final stage where the steam must be at a temperature higher than the ambient, which is 25 °C on average, in order to condensate naturally [4].

In order to break the limit that obstructs the progression of the MED process into additional stages following the last one, a new technique is introduced to reduce the saturation temperature of the last stage. Adsorption Desalination (AD) is a new technology that has been attracting the researchers' attention in the recent years, and it can be integrated with the MED system. The AD system uses an adsorbent material to collect the particles of vapor at a low temperature, then it utilizes a small amount of energy which can be the waste heat of other thermal processes in order to desorb, or release, the collected vapor at a temperature higher than the ambient. Hence, when an AD system is added to the final stage of the MED arrangement, it collects the generated vapor out of the last stage. This allows the saturation temperature of the vapor from the last MED stage to fall below the atmospheric temperature and reach around 5 °C [5] after which the vapor is adsorbed, then desorbed at a temperature higher than the atmospheric, at which it can condensate normally. This addition to the conventional MED system creates a Multi Effect Distillation Absorption Desalination (MEDAD) hybrid system. The number of stages in the MEDAD system increases above the number of stages of a traditional MED system [6], which in turn raises the production rate of fresh water for the same amount of used energy, and reduces the energy consumption per cubic meter of produced fresh water.

The recent development of desalination technologies for meeting the environment discharge requirements using more efficient and sustainable energy systems for water production was reviewed by Ng et al. [7-8] . It was stated in this paper that one of the immediate solutions to improve the energy efficiency of the desalination systems is to develop a hybridization desalination process through the combination of thermally driven and adsorption desalination (AD) cycles. The advantage of hybrid desalination system is the use of low temperature of the working fluid temperature (60^{o}C-80^{o}C) which can be accomplished by waste exhaust or renewable solar thermal heat. In this paper, the author reported the results and the benefits of using the MEDAD system through theoretical analysis and experimental studies. In Addition, the use of co-generation system (electricity and fresh water through MEDAD desalination process) and the corresponding cost of the MEDAD system were highlighted in this study. Sadri et al [9] developed a thermo-economic modeling approach to investigate the performance of an adsorption desalination system. A thermo computational model based on heat and mass balance was used to determine the performance of the AD desalination system. In addition, an irreversibility analysis using chemical and physical exergy and exergoeconomic analysis was developed . The results showed an increase in the water production using the AD system and the cost of water production was found to be 0.57$/m^3. Qian Chen et al [10] investigated the use of self-sustainable solar desalination system. The system combines a spray-assisted low-temperature desalination system, solar thermal collectors, and heat storage tanks. A mathematical model was first developed and validated with laboratory pilot for the proposed large-scale solar-powered desalination system. Ibrahem Altarawneh et al. [11] used experimental and theoretical investigation on solar desalination using parabolic trough solar collector. The results of solar desalination showed enhanced performance in obtaining salt free water. The results show that the productivity of parabolic trough under reduced pressure was of about 58% greater than that of the same PTC under atmospheric pressure. Abdelfattah El Mansouri et al. [12] developed an autonomous desalination system fully powered by solar energy. This system mainly consists of a salt gradient solar pond coupled to an organic Rankine cycle that drives the pumps of a reverse osmosis desalination unit. Alireza Rafiei et al. [13] investigated the performance of a desalination system consisting of photovoltaic thermal (PV) panels and Humidification Dehumidification Desalination (HDD) systems. The effect of nanofluid application as the solar working fluid on the desalination performance was investigated as the main objective of this study. Abdellah Shafieian et al. [14] investigated the improvement of the performance of thermal-driven membrane-based solar desalination systems using nanofluid in the feed stream.

The main objective of this study was to implement nanofluid in the feed stream of a heat pipe solar membrane-based desalination system, which not only aims to improve the freshwater productivity of the system, but also has the capability of decreasing its specific energy requirement.

Few studies can be found in the literature on the performance and the optimization of the MEDAD system for water production. The originality of the proposed research is to investigate the performance of the MEDAD desalination system using high salinity sea water from the GCC countries. The MEDAD system is evaluated highlighting the advantage of the AD unit addition and brine recirculation as a heat recovery technique. An optimization procedure is also presented in order to enhance the performance and production of the system based on its optimal operating conditions and input variables. New correlations are presented in this study for the first time to show the variation of the inverse of the specific energy consumption (m^3/kWh) and the performance ratio (distillate mass flow rate to the mass flow rate of the steam used) versus four input factors (working fluid temperature, Reynolds number, sea water temperature and the total seawater dissolved solids TDS).

2. Hybrid Multi-Effect Distillation and Adsorption Desalination System

2.1. Multi-Effect Distillation (MED)

The distillation process occurs with the aid of a heat source, which evaporates the water particles from seawater, separating them from the salt particles to end with distilled water vapor and brine. The MED stages follow the same technique of distillation, with slight modifications on the multiple stages the process follows.

Only the first stage of the system requires external heat, which can either be direct heating, or through a pipe in which a hot fluid flows, representing a heat exchanger (HE). This heat is required to evaporate the water out of the seawater that is sprayed from the top of the tank, representing the first stage. The spray usually releases small droplets of seawater, and the evaporation process occurs due to convection and conduction as the droplets fall through the tank [15].

The process inside each tank is regulated by the pressure in the tank. The pressure has to be at the saturation point, matching the temperature of the fluid entering the tank, considering it is the temperature at which water vaporizes. However, since the heat source is only linked to the first stage, the vapor that gets evaporated from the seawater in each stage is used as a heat source in the subsequent stage. Moreover, some heat losses occur inside each stage as well as between the stages, as the actual system is not adiabatic, and the friction in the connecting pipes causes pressure losses. These losses reduce the temperature of vapor passing from one stage to another; thus, the saturation temperature decreases through the stages [16].

As the water evaporates in the first stage inside the tank, it rises up due to its relatively low density, leaving brine at the bottom of the tank. Afterwards, the vapor moves through a pipe into the second stage and condenses as it evaporates new water droplets, which in turn flows into the following stage, and so forth. However, as the vapor out from the first stage condenses towards the end of the second stage, it turns into a mixture, including water in both the liquid and gaseous states. Therefore, the pipe through which the vapor condenses is linked with a separator at the end of the second stage in order to separate the two states. The gaseous state joins the vapor that got evaporated from the seawater, and they both flow into the following tank in one pipe, and the liquid state is collected in a tank which contains the distilled water. Moreover, the brine that is left at the bottom of each tank holds excess heat, so it gets pumped into the next stages in order to retrieve this heat [1]. The system in this study is designed requiring a temperature of 50 ˚C in the first stage, and a cross-section schematic of the first stage and an intermediate stage are shown in *Figure 1*.

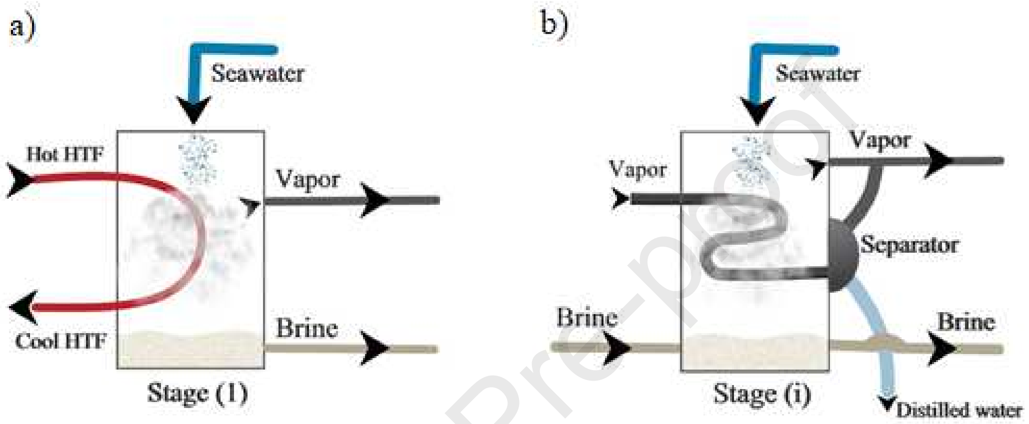


Figure 1: a) The schematic of the first MED stage. b) The schematic of an intermediate stage (i)

2.2. Adsorption Desalination (AD)

The AD unit utilizes a low temperature heat source to generate desalinated water based on an adsorption-desorption process [17]. This system includes three main components: an evaporator, two adsorption beds in between, and a condenser. Typically, the evaporator operates at a very low pressure in order to evaporate seawater at a low saturation temperature, while the condenser operates at a higher pressure that is maintained at the cooling seawater temperature. Also, the adsorption beds, usually two units, are responsible for vapor generation as they contain an adsorbent material, which becomes hydrophilic and hydrophobic when it is cooled down and heated up, respectively. Various adsorbents can be used, i.e. silica gel, activated alumina, and activated carbon, each of which has different properties as shown in *Table 1*. The appropriate type of adsorbent should have a high adsorption capacity, an average pore diameter of about 2 – 4 nm, and a low regeneration temperature, which has to match with the heating fluid temperature. These specifications best fit the silica gel RD type in comparison with other widely used adsorbents [18].

Table 1: Properties of different types of adsorbents [19], [20].

	Silica Gel RD	**Activated Carbon**	**Activated Alumina**
Regeneration temperature (°C)	55 – 140	100 – 140	120 – 260
Maximum acceptable temperature (°C)	400	150	500
Specific heat capacity (kJ/kg K)	0.921 – 1.09	1.13 – 1.51	0.879 – 1.05
Bulk density (kg/m^3)	704.8 – 897.0	352.4 – 544.6	608.7 – 672.8
Average pore diameter (nm)	2.2	1.5 – 2.5	1.8 – 4.8
Pore volume (cm^3/g)	0.37	0.56 – 1.20	0.29 – 0.37
Surface area (m^2/g)	750	600 – 1600	210 – 360

In order to control the flow of water vapor between the three components, valves are used. *Figure 2* describes the process which commences when the valve between the evaporator and adsorption beds opens, permitting the vapor to flow to the adsorbent. Meanwhile, a cooling seawater flow is circulating in a pipe to cool down the adsorbent, allowing the vapor to be adsorbed. Afterwards, a heating fluid circulation provides heat to the adsorbent, forcing it to desorb the vapor at a higher temperature than it was at the exit of the evaporator. Another valve which is placed between the adsorption beds and the condenser opens, releasing the vapor to be condensed, producing desalinated fresh water. Additionally, placing more than two beds will enhance the performance, as they will operate simultaneously in shorter intervals in a continuous manner [21].

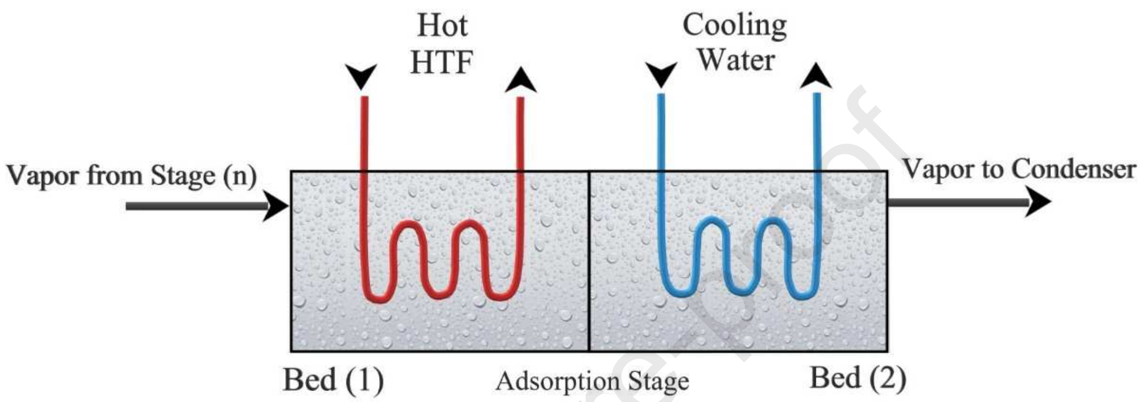


Figure 2: A schematic of AD process

2.3. MEDAD System

As the cold heat transfer fluid (HTF) leaves the storage tank, it passes through the evacuated tube collector (ETC) and gets heated up to a temperature that is sufficient to evaporate the seawater in the first MED stage. Furthermore, in order to break the limit that obstructs the progression of the MED process into additional stages after the last stage, in which the saturation temperature has to be higher than the atmospheric temperature, a new technique is required that reduces the saturation temperature of the last stage. Hence, collecting the generated vapor out of the last stage, increasing its temperature, then sending it to the condenser, is the solution. Here, the need of adjoining an AD stage arises. When the last stage of the MED system is linked to an additional AD stage, the saturation temperature of the vapor from MED's last stage can fall to around 5 ºC, after which the vapor is adsorbed, then desorbed at a temperature higher than the atmospheric, at which it can condensate normally. This addition to the traditional MED system can increase the number of stages significantly; thus, increasing the amount of collected distilled water, reaching up to double the conventional amount in some cases. As the AD stage does not need a high regeneration temperature, depending on the adsorbent type, the HTF that exits the first stage of the MED can be used as an inlet HTF to supply heat to the AD stage, which recovers the heat that would have been otherwise wasted. Afterwards, the cold HTF leaving the AD stage will flow to the storage tank to be resent again to the ETC in another operation cycle, and so forth, as can be seen in Figure 3. The operating conditions of the MEDAD system components s are summarize in Tables 1 and 2.

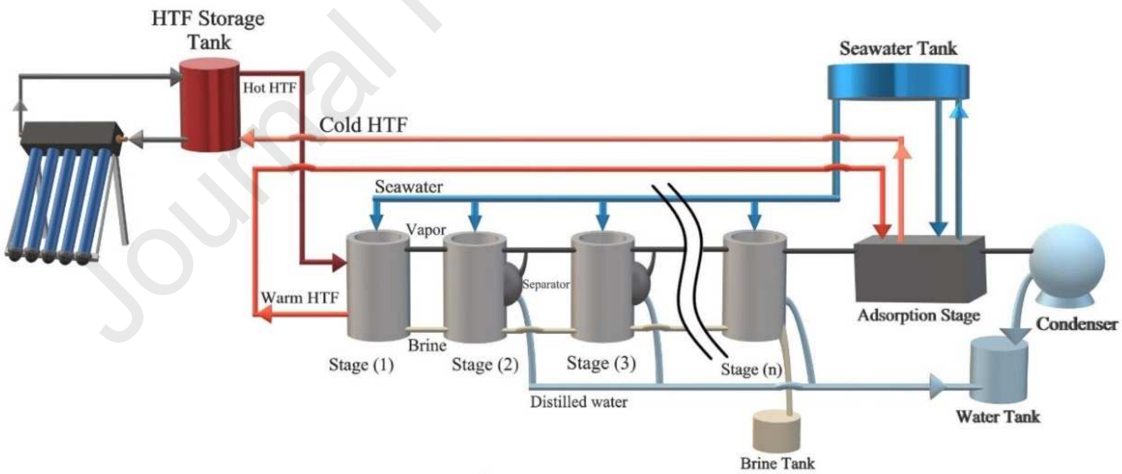


Figure 3: Schematic of the MEDAD System

3. Modeling Analysis of the MEDAD System

3.1. MEDAD System Assumptions

In this study, the steady-state operation of MEDAD system is used for different sea water salinity and under heat transfer working fluid conditions from the solar thermal energy system. The steady-state conservation equations from the mass and energy balance are solved, and iterative solution method is used to solve for the desired or output values. It is noted that this assumption of steady state operation is based on previous MEDAD experimental studies. The results of the experimental investigation of MEDAD hybrid desalination cycle [24] showed that the MED stages reach steady state temperatures for the vapor space, brine pool, and feed and condenser cooling water. The results of the performances of the batch-operated Adsorption Desalination [17] were also discussed in previous study. The transient temperature profiles of the adsorber, desorber, evaporator and condenser of the AD cycle using the 2-bed mode were presented. The results showed that the plant performances attain cyclic steady state after three half-cycles. Cyclic-steady-state conditions can be assumed for the operation of the AD system.

The following assumptions are used for the present analytical analysis of the MEDAD system: (1) steady state operation, (2) adiabatic system, (3) uniform temperature distribution, (4) the connecting pipes between the stages are thermally insulated, (5) the HTF properties are temperature dependent, (6) seawater and brine properties are temperature and TDS dependent, (7) the overall heat transfer coefficient is calculated including the fouling factor of the tubes, (8) the top brine temperature is 50 °C, (9) the temperature loss between the stages is constant and equals to 5 °C, (10) the overall heat transfer area and evaporators size are constant for all stages, (11) the TDS content of the distilled water is zero, and (12) negligible pumping power.

3.2. Modelling Approach

The performance of the system was determined from the analytical solution by solving the steady-state conservation equations of mass and energy and using iterative method. The solution was obtained by solving analytically the mathematical equations using the prescribed constraints and the parametric inputs. The flowchart algorithm shown in Figure 4 summarizes the steps used for the calculation of the hybrid MEDAD desalination system. The number of stages in the MEDAD system reached 9 stages with the addition of an AD stage compared to 5 stages when operating with MED only. The results are reported according to seawater properties of the Arabian Gulf. The coded equations provided the ability of modifying the design by adding parts and customizing the parameters. An RSM-based optimization method is then used to generate correlations for the output responses in terms of four input factors within specified operating ranges of three levels described by low (-1), center (0), and high (1). The following equations are used to model the system, and *Figure 4* shows the parameters that can be plugged into equations according to the illustrated flowchart to find the performance parameters of the system. More information about the equations used to model the MEDAD system can be found in references [22-23].

3.2.1. Multi-Effect Desalination (MED) Modelling Equations

The required energy for the MED stages is only the energy needed in the first stage Q_{MED} which is supplied from the HTF [22-23]:

$$Q_{MED} = m_{HTF} * Cp_{HTF} * \left(T_{in,HTF} - T_{ex,HTF}\right) = A_{HE} * U * T_{lm} \quad (1)$$

Where U is the overall heat transfer coefficient for the tube, and it can be calculated in terms of the saturation temperature inside the first stage $T_{sat,1}$ considering fouling on the inner surface of the tube:

$$U = 1939.4 + 1.40562 * T_{sat,1} - 0.0207252 * {T_{sat,1}}^2 + 0.0023186 * {T_{sat,1}}^3 \quad (2)$$

Also, T_{lm} is the logarithmic mean temperature of the first stage, considering that it represents a crossflow heat exchanger:

$$T_{lm} = \frac{(T_{in,HTF} - T_{sat,1}) - (T_{ex,HTF} - T_{sw})}{\ln(\frac{T_{in,HTF} - T_{sat,1}}{T_{ex,HTF} - T_{sw}})} \quad (3)$$

The energy balance equations of the MED stages [22-23] can be represented as follows:

- For the first stage:

$$m_{HTF} * Cp_{HTF} * (T_{in,HTF} - T_{ex,HTF}) = m_{sw} * Cp_{sw,1} * (T_{sat,1} - T_{sw}) + m_{v,1} * hfg_1 \quad (4)$$

- For the intermediate stages (i) with i = [2 , n]:

$$m_{sep,v,i} * hfg_{sep,i} = m_{v(i+1)} * hfg_{(i+1)} + m_{sw} * Cp_{sw(i+1)} * (T_{sat(i+1)} - T_{sw}) - m_{v,i} * hfg_i - m_{b,i} * Cp_{b,i} * (T_{sat,i} - T_{sat(i+1)}) \quad (5)$$

The mass balance equation for the seawater and brine for a stage (i) with i = [1, n] is as follows [21-22]:

$$m_{b,i} = \frac{(X_{sw} * m_{sw}) + (X_{b(i-1)} * m_{b(i-1)})}{X_{b,i}} \quad (6)$$

Where $X_{b,i}$ is the TDS of brine in parts per million [ppm], and it can be calculated from the following equation in terms of $T_{sat,i}$:

$$X_{b,i} = 0.9 * (457628.5 - 11304.11 * T_{sat,i} + 107.5781 * T_{sat,i}^{2} - 0.360747 * T_{sat,i}^{3} \quad (7)$$

The mass balance equation for the seawater, vapor and brine for a stage (i) with i = [1 , n] is as follows [21-22]:

$$m_{v,i} = m_{sw} + m_{b(i-1)} - m_{b,i} \quad (8)$$

The mass balance equations for the distilled vapor for a stage (i) with i = [2 , n-1], and for the nth stage are as follows [22-23]:

$$m_{d,i} = m_{v(i-1)} + m_{sep,v(i-1)} - m_{sep,v,i} \quad (9)$$

$$m_{d,n} = m_{v(n-1)} + m_{sep,v(n-1)} \quad (10)$$

The number of stages *n* of the MED system before the adsorption stage can be determined as follows:

$$n = \frac{T_{sat,1} - T_{sat,n}}{T_{loss}} + 1 \quad (11)$$

Where $T_{sat,1}$ is limited by the temperature of the HTF from the storage tank, $T_{sat,n}$ is limited by the temperature that the adsorption stage can accept, and T_{loss} accounts for the temperature losses between each two stages, and the losses inside the stage itself.

3.2.2. Adsorption Desalination AD Stage Modelling Equations

The last MED stage represents an evaporator that is connected with the adsorption stage, which receives the vapor later on. Additionally, the HTF that exits the first stage of the MED, after it was used as a heat source for the MED, enters the AD stage in order to utilize the excess heat in the desorption process.

The required energy for the desorption process in the AD stage [22-23]:

$$Q_{des} = \frac{quant_{des} * m_{sg} * Cp_{des,1} + m_{sg} * C_{sg} * (T_{AD,2} - T_{AD,1})}{t_{cycle}} \tag{12}$$

The amount of adsorbate in the adsorbent, which is the water vapor in silica gel is as follows [22-23]:

- At the beginning of the desorption process:

$$quant_{des} = P_{evap} * k_0 * \exp(\frac{Q_{isos}}{R_v * T_{AD,1}}) \tag{13}$$

- At the beginning of the adsorption process:

$$quant_{ads} = P_{cond} * k_0 * \exp(\frac{Q_{isos}}{R_v * T_{AD,3}}) \tag{14}$$

The mass of the adsorbent for two beds that is required to adsorb the vapor exiting the last MED stage in one cycle:

$$m_{sg} = \frac{m_{v,n} * t_{cycle}}{quant_{des} - quant_{ads}} \tag{15}$$

3.2.3. The Overall Hybrid MEDAD System Modelling Equations

The amount of desalinated water $\boldsymbol{m_{d,tot}}$ can be found as follows [22-23]:

$$m_{d,tot} = \sum_{i=2}^{i=n} m_{d,i} + m_{v,n} \tag{16}$$

The volumetric flow rate of the desalinated water over one hour $\boldsymbol{V_d}$ as follows:

$$V_d = \frac{m_{d,tot} * 3600}{\rho_d} \tag{17}$$

The total required energy for the MEDAD system [22-23]:

$$Q_{MEDAD} = Q_{MED} + Q_{AD} \tag{18}$$

The performance ratio of the MEDAD system [22-23]:

$$PR = \frac{m_{d,tot} * hfg_{amb}}{Q_{MEDAD}} \tag{19}$$

The specific energy consumption (kWh/m^3) [22-23]:

$$SEC = \frac{Q_{MEDAD}}{V_d} \tag{20}$$

3.3. Flowchart Algorithm

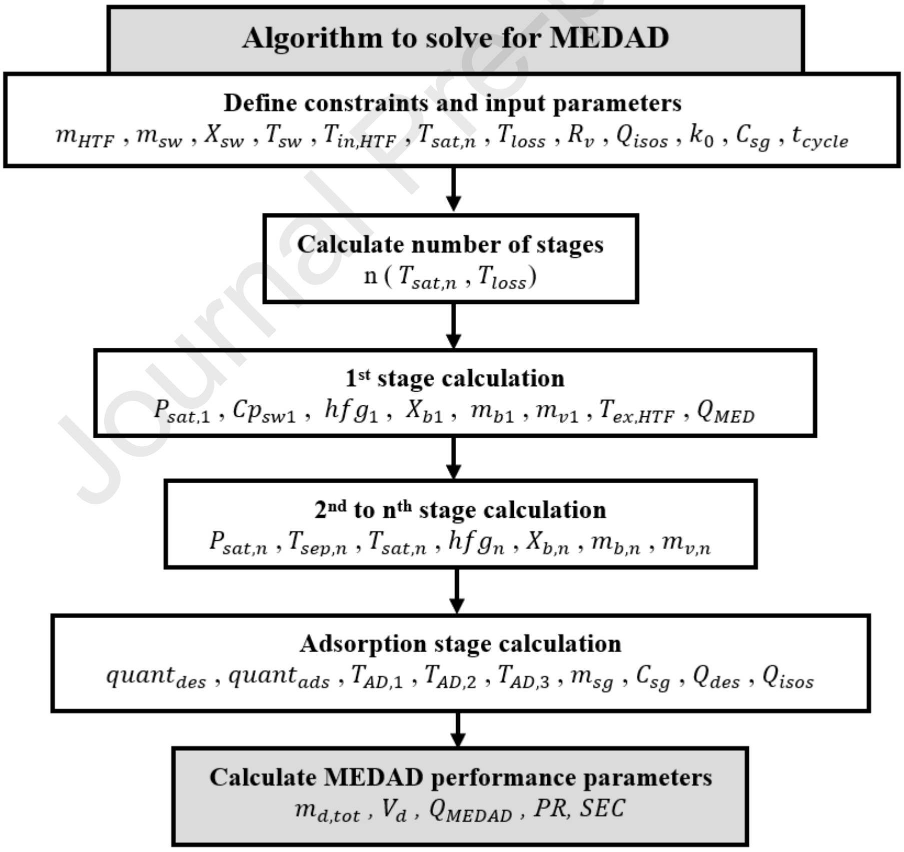


Figure 4: Flowchart Algorithm: Steps for the Calculation of the Hybrid MEDAD Performance Parameters

4. Response Surface Methodology (RSM) based Optimization of MEDAD System

4.1. Introduction

The Response Surface Methodology (RSM) is a statistical technique using a regression analysis based on mathematical relations. These mathematical relations describe the interaction between measured response variable outputs and the important input factors. The RSM-based optimization method is used to investigate the effects of several factors affecting the output and determine the optimum operating conditions to maximize or minimize the responses (output variables). In the present study, the RSM optimization method based on central composite rotatable design (CCD) is used. The CCD method uses 2^n factorial runs with $2n$ axial runs and the error is given by the centre runs n_c. The total number of runs (N) needed for the CCD is given by [25]:

$$N = 2^n + 2n + n_c \tag{21}$$

Where n is the number of independent variables and 2^n are the standard factorial points with its origin at the center. 2n are the points that are fixed axially at a distance α (calculated as $\alpha = (2^n)^{0.25} = 1.6817$) from the center to generate the quadratic terms and replicate the tests at the center. The axial point 2n is used for readability and screening analysis. n_c is the number of central points with replicates or repeated runs at the centre, that are essential for giving an estimation of the error and serve to optimize the results based on the values of the response variables [25].

4.2 Model Estimation

The following quantitative expression describes the response surface showing the relationship between the response and the input factors [26]:

$$Y = f(x_1, x_2, x_3, \ldots x_n) \tag{22}$$

Where y is the response variable of the system, f is the response surface and x_n is the set of independent variables or input factors. The main objective of the design matrix is to optimize the response variables (Y). It is therefore required to use the appropriate approximation for the correlation between factors and response surfaces. A correlation in the form of a second order polynomial (quadratic equation) is used to develop an empirical model that links the response with the input variables and is expressed as follows:

$$Y = \beta_o + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{33} X_3^2 + \varepsilon \tag{23}$$

Where Y represents the response and β_o , β_i , β_{ii} are respectively the constant, linear, and quadratic coefficients. The β_{ij} represents the interaction between the coefficients; and n is the number of factors. X_i and X_j are the coded values of the input variables and ε is the random error.

In this study, the inverse of specific energy consumption (SEC) and the performance ratio (PR) were selected to be the two main responses of the MEDAD system. The main objective is to increase the inverse of the SEC m^3/kWh (reduce the energy consumption and increase the freshwater production) and increase the performance ratio PR. The input factors along with their levels are shown in *Table 2*: (A) Reynolds number of the HTF entering the MEDAD system with the levels of [7000, 110500, and 214000], (B) the total dissolved solids of the inlet seawater with the levels of [20000, 35000, and 50000 ppm], (C) the normalized HTF temperature with the levels of [2.4, 3.4, and 4.4], and (D) the normalized inlet seawater temperature with the levels of [0.4, 1.2, and 2]. In the case of the normalized temperatures, the normalization method was approached by dividing the actual temperatures over a reference temperature of 25 °C.

Table 2: Input Factors and Output Responses

	Variable	Symbol	Levels		
			-1	**0**	**1**
Input factor	**Reynolds number of the heat transfer fluid (Re_htf)**	A	7000	110500	214000
	TDS of the inlet seawater (TDS) [ppm]	B	20000	35000	50000
	Normalized heat transfer fluid temperature (T_htf/Tref)	C	2.4	3.4	4.4
	Normalized inlet seawater temperature (T_sw/Tref)	D	0.4	1.2	2
Output response	**Inverse of specific energy consumption (SEC) [m^3/kWh]**	R1			
	Performance ratio (PR)	R2			

5. RESULTS AND DISCUSSION

5.1. Performance Analysis of MEDAD System and Validation of the Numerical Results

The advantage of adding an AD stage to the MED system is shown through a comparison between the two systems in *Table 3 and* illustrated in *Figure 5.* Unlike the MED system where the final stage is limited by the condensation temperature of the surrounding environment, the MEDAD final stage is controlled by the adsorption unit, allowing it to have a higher number of stages, and to produce 2.68 times the desalinated water compared to an independent MED system. These numerical results for the desalinated water production using MEDAD system are in good agreement with previous numerical [22] and experimental [24] studies. Remarkable improvement (3 or more folds) of the desalinated water using hybridization of MED and AD desalination system compared to only MED system with the same operating conditions is reported in reference [22]. In the experimental study [24], the total water production reported in this study was 2.02 LPM and 5.67 LPM for the MED and MEDAD systems respectively (the water production is 2.81 times for the MEDAD system compared to MED system). These results are in good agreement with the numerical results for the water production reported in the present study.

Also, since the AD unit consumes low energy, the MEDAD system has a lower SEC by 57.78% (See Table 3), which leads to a higher PR (4.68 and 11.07 for MED and MEDAD systems respectively). These results are obtained using the same heat source under the same conditions of seawater temperature at 25 °C, seawater TDS of 42,000 ppm, seawater mass flow rate of 0.0035 kg/s per stage and HTF mass flow rate of 0.2 kg/s. It is noted that the results reported in reference [22] show also a high average performance ratio PR (average PR = 7 -8) for the hybrid 8-stage MEDAD desalination system compared to MED system. The results of the present study (see Table 3) show clearly the advantages of the MEDAD system compared to MED system: higher total desalinated water production (m^3/h), lower specific energy consumption (kWh/m^3) and higher performance ratio RP (see Table 3).

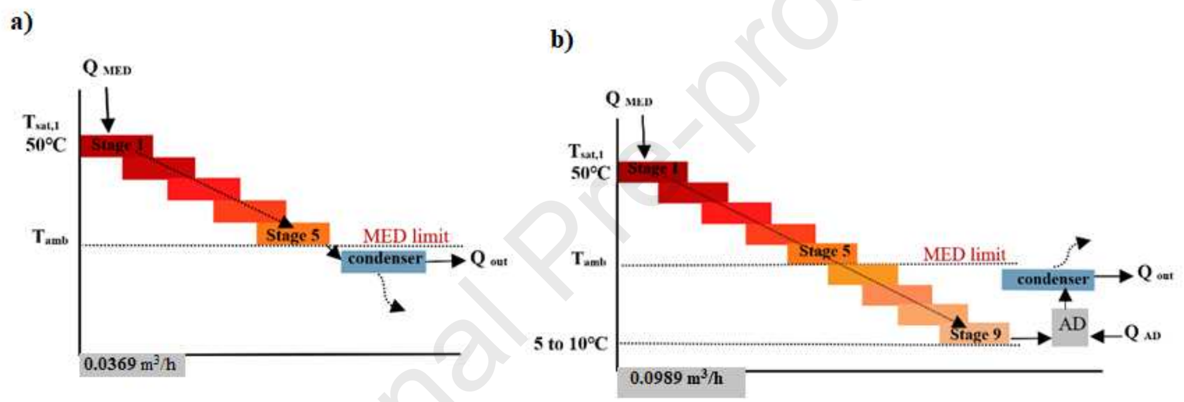


Figure 5: a) MED system - 5 stages, b) Hybrid MEDAD system - 9 stages in addition to an adsorption stage

Table 3: System performance with and without AD unit integration

Parameter	Unit	MED	MEDAD
Number of stages	-	5	9
HTF inlet temperature to the desalination unit	°C	80	80
Volumetric flow rate of desalinated water	m^3/h	0.0369	0.0989
Required Power for the Desalination	kW	5.3311	6.0313
Specific Energy Consumption SEC	kWh/m^3	144.4743	60.9838

Performance ratio PR	-	4.6766	11.0783

5.2. Effect of Heat Recovery - Hybrid MEDAD System

The desalination process in each stage separates the seawater into brine and vapor streams. The vapor moves to the succeeding stage in order for the desalination to resume throughout the MED stages, but the brine can either be collected from each stage separately into one tank, or it can be recirculated into the subsequent stage to provide additional heat for the evaporation process. *Table 4* compares between the two cases, case 1: MEDAD without brine circulation, and case 2: MEDAD with brine circulation. The results highlight the advantage of brine circulation as a heat recovery technique, which reduced the SEC by 11.34%, increased the PR by 12.86%, and increased the production rate by 14.73%.

Table 4: System performance comparison with and without brine recirculation

Parameter	Unit	MEDAD without brine circulation	MEDAD with brine circulation
HTF inlet temperature to the desalination unit	°C	80	80
Volumetric flow rate of inlet seawater	m^3/h	0.1109	0.1109
Volumetric flow rate of desalinated water	m^3/h	0.0862	0.0989
Specific Energy consumption	kWh/m^3	68.7831	60.9838
Performance ratio PR	-	9.8163	11.0783

5.3. Response Surface Methodology-based Optimization Results

Table 5 presents the generated 30 runs (modeling results) including 6 centered-points runs and 24 non-centered-points runs each with set inputs combination.

Table 5: Modeling results - Generated Runs for the RMS-Based Optimization

	Input factors				Output responses	
Run	**Re_htf**	**TDS (ppm)**	**T_htf/Tref**	**T_sw/Tref**	**Inverse of SEC (m^3/kWh)**	**PR**
1	214000	20000	2.4	2	0.01384451	9.3514
2	214000	20000	4.4	2	0.014597773	9.8602
3	110500	35000	3.4	1.2	0.015688391	10.5968
4	214000	50000	2.4	0.4	0.016407429	11.0825
5	110500	35000	4.4	1.2	0.015850649	10.7064
6	7000	50000	2.4	0.4	0.024324923	16.4304
7	110500	35000	3.4	1.2	0.015688391	10.5968
8	214000	50000	2.4	2	0.018065901	12.2027
9	110500	35000	3.4	1.2	0.015688391	10.5968
10	7000	20000	2.4	0.4	0.015088327	10.1915
11	7000	50000	2.4	2	0.034181724	23.0882
12	110500	50000	3.4	1.2	0.018252505	12.3288
13	214000	50000	4.4	2	0.0194901	13.1647

14	7000	20000	4.4	2	0.012970976	8.7613
15	214000	35000	3.4	1.2	0.01570295	10.6067
16	110500	35000	2.4	1.2	0.014854052	10.0333
17	110500	35000	3.4	0.4	0.015049453	10.1652
18	110500	35000	3.4	1.2	0.015688391	10.5968
19	110500	35000	3.4	1.2	0.015688391	10.5968
20	110500	20000	3.4	1.2	0.013926937	9.407
21	214000	20000	4.4	0.4	0.013552633	9.1542
22	7000	20000	4.4	0.4	0.010441923	7.0531
23	7000	50000	4.4	0.4	0.016962665	11.4575
24	110500	35000	3.4	2	0.016386163	11.0681
25	214000	20000	2.4	0.4	0.012895655	8.7104
26	110500	35000	3.4	1.2	0.015688391	10.5968
27	214000	50000	4.4	0.4	0.017583685	11.877
28	7000	20000	2.4	2	0.016575364	11.1959
29	7000	35000	3.4	1.2	0.008219642	5.552
30	7000	50000	4.4	2	0.018940362	12.7934

Table 6 shows the two quadratic correlations of the responses as functions of the four input factors, and they are valid within the previously specified ranges. Additionally, the coefficients of the input factors are presented in *Table 7*. The standard deviation for the inverse of SEC and the PR is 0.0026 and 1.73, respectively, which are considered to be relatively small indicating that the responses data is closely distributed. Also, for both responses, the coefficient of variation (C.V.%), which is a measure of the data dispersion and is defined by the ratio of standard

deviation to the mean, is 15.74%, which is less than 30%. This conveys that the models are in the accepted range. The generated models are significant, as for both the responses the F-value is 5.06, in an acceptable range, and the p-value is less than 0.05. Moreover, the R^2 of 0.8251 implies that the proposed correlations are acceptable and useful for a MEDAD system of 9 stages followed by an adsorption unit as shown in *Table 8*. If the value of R^2 is close to one, then the proposed correlation predictions mirror the true values obtained through the analytical solution. The proposed correlations can be used to predict accurately the inverse of energy consumption and performance ratio of the MEDAD system.

Table 6: New Correlations for the Responses R1 (Inverse of SEC) and R2 (Performance ratio PR)

Response	**Quadratic Correlations for R1 and R2 in terms of input factors A,B,C, and D**
R1 - Inverse of SEC (m^3/kWh)	$0.009175 - 3.86641 \times 10^{-8} * A + 4.52053 \times 10^{-7} * B - 0.001234 * C + 0.002451 * D - 9.12904 \times 10^{-13} * A * B + 2.10538 \times 10^{-8} * A * C - 7.76850 \times 10^{-9} * A * D - 5.48442 \times 10^{-8} * B * C + 4.89026 \times 10^{-8} * B * D - 0.000507 * C * D$
R2 - PR	$6.19718 - 0.000026 * A + 0.000305 * B - 0.833600 * C + 1.65559 * D - 6.16626 \times 10^{-10} * A * B + 0.000014 * A * C - 5.24713 \times 10^{-6} * A * D - 0.000037 * B * C + 0.000033 * B * D - 0.342625 * C * D$

Table 7: Coefficients of the input factors

Coefficients of the input factors		
	Inverse of SEC (m^3/kWh)	**PR**
Constant	+0.009175	+6.19718

[Re_htf]	-3.86641E-08	-0.000026
[TDS]	+4.52053E-07	+0.000305
[T_htf/Tref]	-0.001234	-0.833600
[T_sw/Tref]	+0.002451	+1.65559
[Re_htf] * [TDS]	-9.12904E-13	-6.16626E-10
[Re_htf]* [T_htf/Tref]	+2.10538E-08	+0.000014
[Re_htf] * [T_sw/Tref]	-7.76850E-09	-5.24713E-06
[TDS] * [T_htf/Tref]	-5.48442E-08	-0.000037
[TDS] * [T_sw/Tref]	+4.89026E-08	+0.000033
[T_htf/Tref] * [T_sw/Tref]	-0.000507	-0.342625

Table 8: Analysis table for the output responses

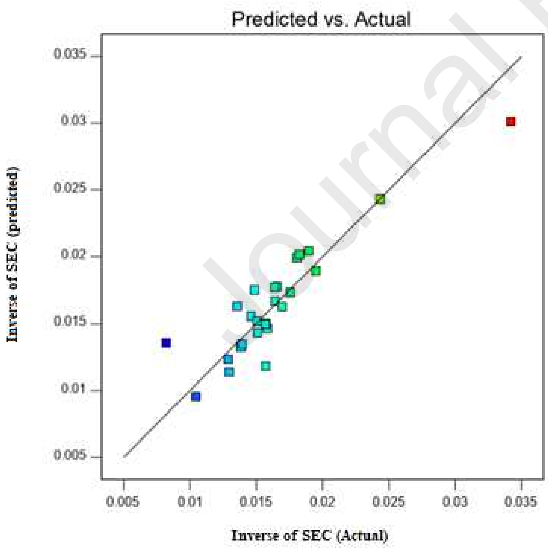
	Output responses	
Parameter	**Inverse of SEC (m^3/kWh)**	**PR**
Standard deviation (Std. Dev.)	0.0026	1.73
Mean	0.0163	10.99
Coefficient of variation (C.V.%)	15.74	15.74
R^2	0.8251	0.8251
Adjusted R^2	0.6619	0.6619
F-value	5.06	5.06
p-value	0.0018	0.0018
	Significant	Significant

5.3.2. Graphical Results

The comparison between the actual results obtained from the analytical analysis and the predicted results from the proposed correlations is shown in *Figure 6*. As the actual and predicted results are relatively close with some insignificant outliers, it can be verified that the generated correlations are valid.

The perturbation plots presented in Figure 7 show the effect of the input parameters (Reynolds number, the total dissolved solids TDS, the normalized temperature of the heat transfer fluid, and the normalized temperature of the sea water) on the two output response (inverse of the specific energy SEC and the performance ratio PR). The perturbation plot compares the effect of all the input factors from a specific point in the design space (reference point - midpoint of all the input factors). The reference point represents the center value of the input variables: Re = 110500, TDS = 35000 ppm, normalized temperature of the heat transfer fluid = 3.4 and normalized temperature of sea water = 1.2. A steep curvature in a factor designates that the response is sensitive to that factor. As shown in Fig. 7, the total dissolved solid TDS (factor B) is the most affecting parameter on the inverse of the energy consumption ECS and the performance ratio PR. The impacts of the input factors on the inverse of the energy consumption and performance ratio by order of importance are respectively the total dissolved solids for the sea water TDS (B), the Reynolds number of the heat transfer fluid (factor A), the normalized temperature of seat water (factor D), and the normalized temperature of the heat transfer fluid (factor C).

Figure 8 presents the 3D response surface plots of the two responses (inverse of the energy consumption and performance ratio) versus only two input factors. Figure 8 shows (a) the combined effects of the total dissolved solid TDS and Reynolds number of the heat transfer fluid and (b) the normalized sea water and heat transfer fluid temperatures. The results of the inverse of the energy consumption and the performance ratio show higher values at high TDS for the sea water (50,000 ppm) and at low Reynolds number (Re = 7000). For the combined effects of the normalized temperatures, higher values of the inverse of the energy consumption and the performance ratio are obtained at higher normalized sea water temperature and lower normalized heat transfer fluid temperature. . The total dissolved solid TDS and the temperature of the sea water play an important role on the energy consumption and performance of the hybrid desalination MEDAD system. The Reynolds number for the heat transfer fluid is also an important parameter that can affect the performance of the desalination system.



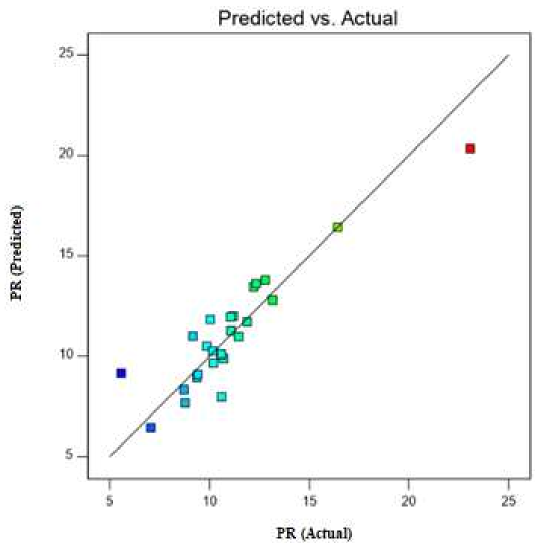


Figure 6: The predicted model data vs. actual data for the inverse of SEC and the PR

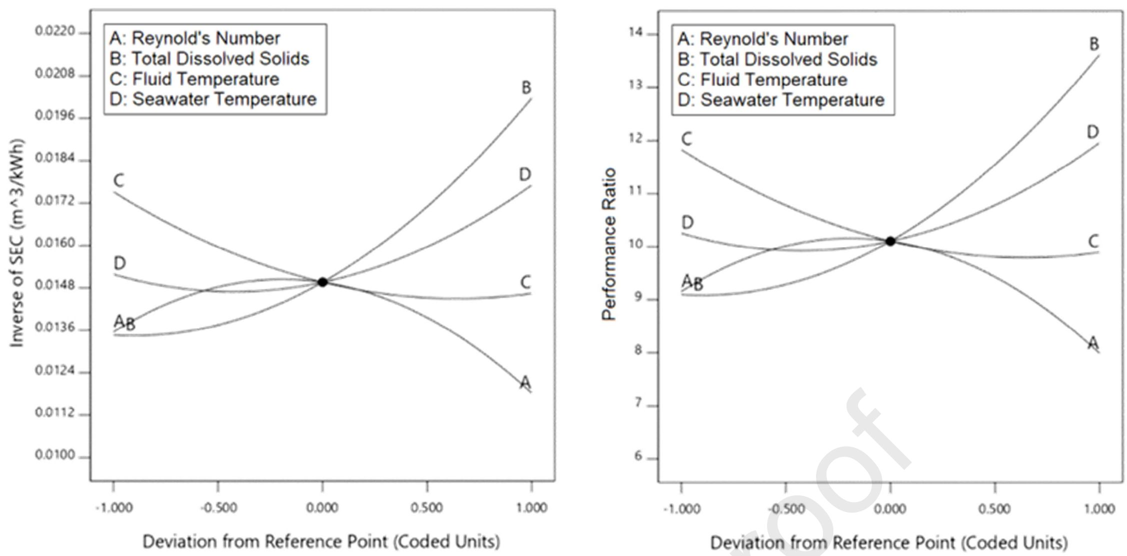


Figure 7: The pertubation plots of the inverse of SEC and the PR

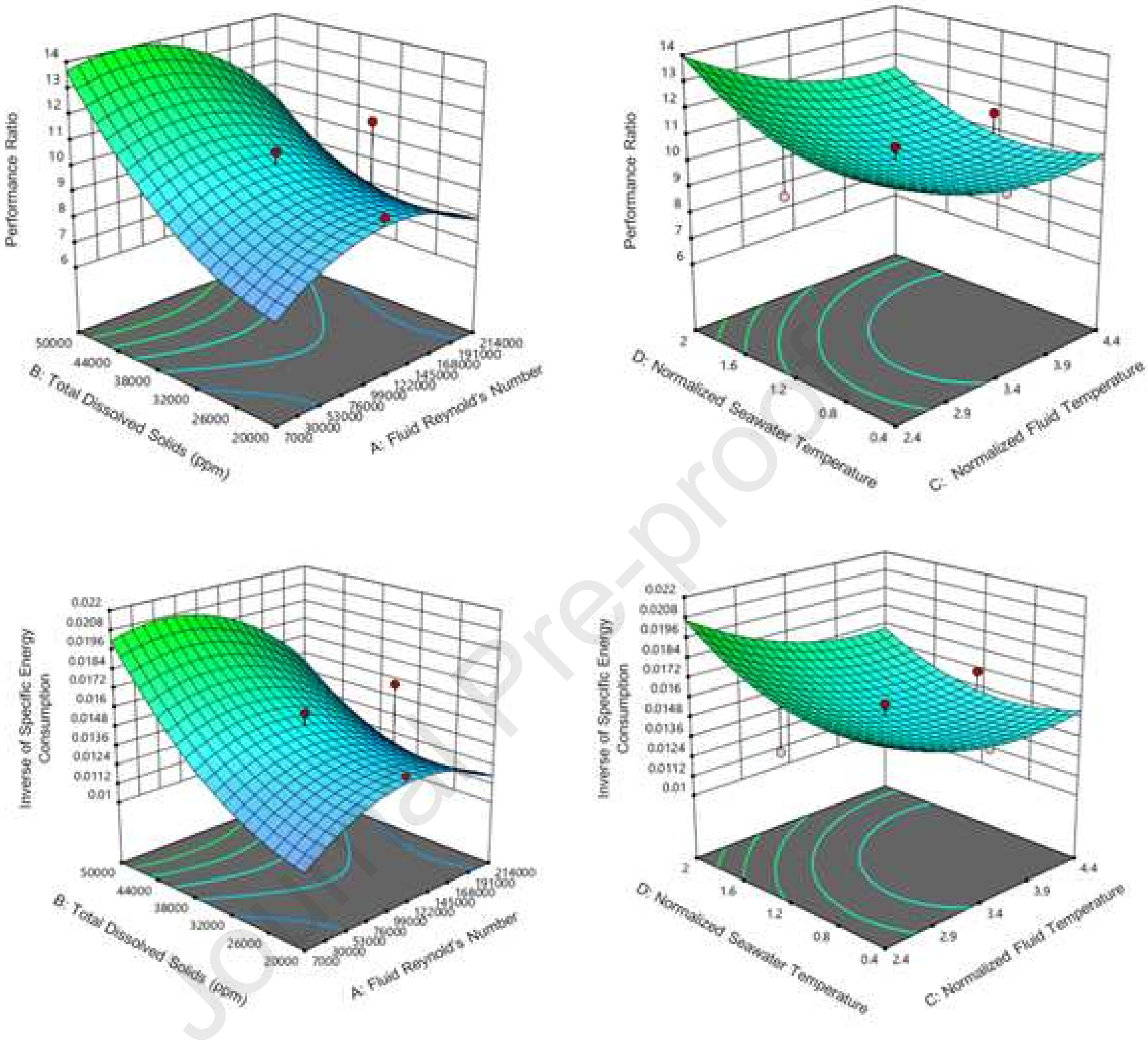


Figure 8: 3-D Surface Plots of the inverse of SEC and the PR

5.3.3. Optimization Results of MEDAD System

The performance of the MEDAD system can be enhanced by selecting the optimal conditions of the input factors to maximize the responses, achieving an inverse of SEC of 0.03 m^3/kWh and a PR of 20.35. *Table 9* presents the optimal operating values of the inputs where the

Reynolds number of the HTF and the normalized temperature are at 7000, and 2.4, respectively, and the seawater TDS and the normalized temperature are at 50000 ppm, and 2, respectively.

Table 9: Optimal operating conditions of the input factors

	Variable	Goal	Optimal Value
Input factors	**Reynolds number of the heat transfer fluid (Re_htf)**	In range	7000
	TDS of the inlet seawater (TDS) – [ppm]	In range	50000
	Normalized heat transfer fluid temperature (T_htf/Tref)	In range	2.4
	Normalized inlet seawater temperature (T_sw/Tref)	In range	2
Output responses	**Inverse of specific energy consumption (SEC) –** [m^3/kWh]	Maximize	0.03
	Performance ratio (PR)	Maximize	20.35

6. CONCLUSION

The integration of a Multi-Effect Distillation system (MED) with an Adsorption Desalination (AD) unit was proven to enhance the production rate of fresh water and decrease the specific energy consumption compared to an independent MED system. An analysis of the system was performed using analytical method and the results were validated using experimental and numerical data. The operating temperature range was found to reach 10 ºC at the final of the 9th MED stage by adding an AD unit to the system. The results show clearly the advantages of the MEDAD desalination system compared to MED system: higher total desalinated water production m^3/h (increased by 2.68 times), lower specific energy consumption kWh/m3 (decreased by 57.78%) and higher performance ratio PR (increased by 2.37 times). The results highlight the advantage of brine circulation as a heat recovery technique for the MEDAD system: the total water production increased by 14.73%, the SEC decreased by 11.34% and the PR increased by 12.86%. Additionally, the hybrid MEDAD system was optimized using the response surface methodology method. The optimal operating conditions of the system as well as the model correlations for each response were determined. New correlations for the inverse of the SEC (m^3/kWh) and the performance ratio PR versus the Reynolds number, heat transfer fluid temperature, the TDS of the inlet seawater, and the inlet seawater temperature are presented. The results observed from the hybridization of MED with AD for high salinity sea water proved its competitive potential compared to other thermal desalination methods and showed that the system can play a major role in decreasing the large energy requirements of conventional systems and mitigating water-scarcity challenges.

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Highlights

- Hybrid multi-effect distillation adsorption desalination (MEDAD) system powered with solar thermal energy.
- RSM-based optimization of the MEDAD system for high salinity seawater.
- The water production increased by 2.68 times, SEC decreased by 57.78% and PR increased by 2.37 times for the MEDAD system.
- Brine heat recovery for MEDAD: water production increased by 14.73%, SEC decreased by 11.34% and PR increased by 12.86%.
- New correlations are proposed for the inverse of the specific energy consumption SEC and performance ratio PR.

Author Statement

The individual contributions to the paper "Performance Analysis and Optimization of Hybrid Multi-Effect Distillation Adsorption Desalination System Powered with Solar Thermal Energy for High Salinity Sea Water":

Chaouki Ghenai: Conceptualization, formal analysis, investigation, methodology, supervision, project administration, validation, writing – review & editing, and funding.

Dania A.M. Kabakebji: Data curation, software, formal analysis, methodology, validation, writing – review & editing

Ikram M.E. Douba: Data curation, software, formal analysis, methodology, validation, writing – review & editing

Amira E. Yassin: Data curation, software, formal analysis, methodology, validation, writing – review & editing

Declaration of interests

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

☒The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

None