Multi-objective Optimization of a Solar Humidification Dehumidification Desalination Unit

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Abstract. In the present paper, a humidification–dehumidification desalination unit integrated with solar system is considered. In the first step mathematical model of the whole plant is represented. Next, taking into account the logical constraints, the performance of the system is optimized. On one hand it is desired to have higher energetic efficiency, while on the other hand, higher efficiency results in an increment in the required area for each subsystem which consequently leads to an increase in the total cost of the plant. In the present work, the optimum solution is achieved when the specific energy of the solar heater and also the areas of humidifier and dehumidifier are minimized. Due to the fact that considered objective functions are in conflict, conventional optimization methods are not applicable. Hence, multi objective optimization using genetic algorithm which is an efficient tool for dealing with problems with conflicting objectives has been utilized and a set of optimal solutions called Pareto front each of which is a tradeoff between the mentioned objectives is generated.

1. Introduction

Water demand already exceeds supply in many parts of the world and as the world population continues to rise, so does the water demand. It is expected that by 2025, more than 60% of world’s population will have water shortages [1]. Regarding the fact that seawater is one of the most convenient sources of water, desalination can be a practical solution to this concern.

Desalination refers to a process which removes salt and other minerals from water resulting in having fresh water. The required energy for this purpose can be provided by different sources including refrigeration cycle [2], combined cogeneration cycle, heat pump [3] or solar system. Limitation of natural gases and oil in addition to their undesired effect on environment arises more interest in application of renewable sources of energy. Due to the fact that solar energy has a good consistency with climatic conditions in regions which need potable water, it can be considered as an appropriate source of energy. It is noteworthy that among the various desalination technologies in use, only those based on a thermal principle of operation must be considered in combination with solar ponds [4].

Additionally, many of the remote arid areas need low capacity desalination systems, while conventional desalination methods such as MSF, MEE, VC and RO are suitable for large and medium capacity of fresh water production; therefore utilizing mentioned methods for small capacity systems is not economical. Humidification-dehumidification desalination is a suitable choice for production of fresh water when the demand is decentralized [5]. A significant advantage of the HD technology
besides its simplicity of operation is that it provides a means for low pressure, low temperature desalination that operates off of waste heat and is potentially very cost competitive [6].

In addition, HD operates at low temperature; therefore choosing solar system as the source of energy is an ideal decision. Solar desalination based on the HD principle results in an increase in the overall efficiency of the desalination plant and is therefore considered as a promising technique for small capacity, solar-driven desalination plants [7]. Several studies have been performed on solar driven HD desalination systems considering different objective functions and design parameters.

Ben Bacha et al. [8] conducted a work including modeling, simulation and experimental validation of a solar HD system and showed that that elevated flow rate at the entrance of evaporation tower, low temperature of water at the entrance of condenser, and hot water recycling can improve operation and production of the system. Soufari et al. [9] optimized the performance of HD desalination using mathematical programming and found the productivity seems to be the best objective function. Al-Hallaj et al. [10] studied the solar-based processes from an economic point of view. The result of the research was that the solar HD process is a suitable replacement to all other forms of solar desalination techniques in the smaller capacity range. Hermosillo et al. [1] analysed a desalination system working under the air humidification and dehumidification principle by comparing mathematical model and experimental results and a sufficient agreement was shown, although no optimization was carried out in this study. Gude et al. [11] studied the advantages and opportunities for enhanced utilization of solar energy using theoretical and experimental approaches. It was indicated that solar energy is best utilized when the source is integrated with energy-efficient desalination process. Zamen et al. [12] instead optimized the cost of a complete solar HD process.

The main purpose of the present project is to optimize the operation of a solar HD desalination process by defining suitable objective functions such as the area of the humidifier and dehumidifier and thermodynamic parameters. Since the objective functions are conflicting, global optimum cannot be achieved by the means of conventional optimization methods. Multi-objective method is a suitable choice in such cases in which both the thermodynamics and economic objectives can be considered simultaneously and a set of optimal solutions, called Pareto solutions can be achieved. As a result, based on the project limits and available investments, the optimal solution for each case can be chosen by the designer. In other words, a reasonable solution to a multi-objective problem is to investigate a set of solutions, each of which satisfies the objectives at an acceptable level without being dominated by any other solution [13]. Multi-Objective optimization has been successfully utilized for optimizing many different thermodynamic systems. Baghernejad et al. [14] successfully used multi-objective evolutionary algorithms in order to find solutions that simultaneously satisfy exergetic as well as economic objectives for an integrated solar combined cycle system. Najafi et al. [15] used multi-objective optimization in order to maximize the performance and minimize the cost of an SOFC-Gas Turbine hybrid cycle coupled to an MSF Desalination unit.

In the present work, multi-objective optimization of the plant is carried out while the required areas of the subsystems of the HD unit, as an indicator of the cost, and also the specific energy of the solar energy source, indicating the energy efficiency, are considered as objective functions. Although the considered system in the present work is a well-established technology, the main contribution of the present work, compared to the previous studies, is providing a set of optimal system designs, each of which can be utilized by the user depending on the project requirements and the corresponding available investment. Simulation and optimization procedures have been carried out using MATLAB™.

2. Model Description

The humidification dehumidification process is based on the fact that the capability of air in carrying vapor increases progressively with temperature. The HD unit is the distillation under atmospheric conditions by an air loop saturated with water vapor, and has three main sections: the humidifier (evaporator), dehumidifier (condenser) and solar heat source. A schematic representation of the plant has been demonstrated in Fig. 1.
2.1 Solar source
In the solar heater, the sea water leaving the condenser is heated and will enter the evaporator with higher temperature. In comparison with other desalination systems, considering the fact that HD unit requires lower water temperature; solar heater is an appropriate choice for the heat source of this type of units.

2.2. Humidifier
In the humidifier, air and water, where the water has been heated by an external heat source, are in contact and a certain amount of vapor is absorbed by air. The temperature of air will increase and water temperature will decrease during this process.

In the presented model, packing bed evaporator is used. Usually, packings are used when a liquid is in contact with a gas or vapor. It is desired to have the greater liquid surface contact with the vapor or gas. As the liquid flows over the packings, essentially wetting the latter, the area in contact between the two fluids is related to the area of the packing. Packings can also be used in liquid–liquid systems to assist in removing the wake from the dispersed liquid and increasing the heat transfer [16].

3. Mathematical Model
In order to establish the thermal transfers and mass balances of the evaporation tower for the liquid phase, the gas phase and the liquid-gas interface the following hypotheses are made [8]:

- Steady state conditions
- The tower is adiabatic.
- Head losses in the tower column are low and it can be assumed that the density of the air mass flux is constant, since the evaporation rate is small compared to the water flow rate, then the water mass flux remains constant throughout the column.
- The water distribution over the packed bed is uniform; hence there is only a vertical gradient of temperature and humidity.

3.1. Solar source
The rate of heat transferred from the solar collector to water is expressed as:

$$ \dot{Q} = \dot{m}C_p\Delta T_w $$.  \hspace{1cm} (1)

Hence, the energy per unit of time radiated on the surface of the collector is equal to:
can be obtained from the empirical relation [17].

\[ \eta_{col} = 0.8 - 6.8 \left( \frac{T_{col,in} - T_{amb}}{I} \right) \]  

Finally, the required surface area for collector is given by:

\[ A_{col} = \frac{\dot{Q}}{I} \]  

3.2. Humidifier

As demonstrated in Fig. 2 for modeling the humidifier, a volume element with height of \( dz \) containing three control volumes is considered: 1) C.V.1: total system, 2) C.V.2: water side, 3) C.V.3: air side

![Figure 2. Element of humidifier volume](image)

The mass rate balance for C.V.1 can be written as:

\[ \dot{m}_{we} = \dot{m}_{ae} \]  

The heat rate balance for C.V.2 results in Equation 2.

\[ \frac{dT_{we}}{dz} = \frac{\dot{h}_{we}a_{He}(T_{we} - T_{ie})}{m_{we}C_{we}} \]  

\( h_{we} \) is obtained from Equation (7) [8].

\[ h_{we} = \frac{5900 m_{ae}^{0.5894} m_{we}^{0.169}}{a_{He}} \]  

For C.V.3 the heat and mass rate balances can be expressed respectively as:

\[ \frac{\dot{m}_{ae}}{dz} = \frac{k_{ae}a_{Me}(\omega_e - \omega_e)}{m_{ae}} \]  

\[ \frac{dT_{ae}}{dz} = \frac{h_{ae}a_{He}(T_{ae} - T_{ae})}{m_{ae}C_{ae} + \omega_eC_{ae}} \]  

Where \( h_{ae} \) and \( k_{ae} \) are obtained using Lewis relation [8]:

\[ k_{ae} = \frac{2.09 m_{ae}^{0.11515} m_{we}^{0.45}}{a_{Me}} \]
Finally heat rate balance for interface per unit of surface is as follows:

\[ h_{we}\alpha_{He}(T_{we} - T_{ie})dz = h_{ae}\alpha_{He}(T_{ic} - T_{ac})dz + L_{we}k_{ac}\alpha_{Me}(\omega_{ie} - \omega_{e})dz \]  

(12)

The interface is assumed to be a film of saturated air. Therefore \( T_{ie} \) and \( \omega_{ie} \) are dependent variables. \( T_{ie} \) with respect to \( \omega_{ie} \) can be calculated using an experimental relation [18].

\[ \omega_{ie} = f_{exp}(T_{ie}) = 2.19 \times 10^{-6} \times T_{ie}^3 - 1.85 \times 10^{-4} \times T_{ie}^2 + 7.06 \times 10^{-3} \times T_{ie} - 0.077 \]  

(13)

### 3.3. Dehumidifier

As demonstrated in Fig. 3 using the same procedure as the one applied on the humidifier, the dehumidifier volume element contains C.V.1 (total system), C.V.2 (water side) and C.V.3 (air side).

![Figure 3. Element of dehumidifier volume](image)

Mass rate balance for C.V.1 can be written as:

\[ dm_d = dm_{vc} = \dot{m}_{ac}d\omega_c \]  

(14)

The heat rate balance for C.V.2 can be calculated as:

\[ \frac{dT_{we}}{dz} = \frac{h_{wc}\alpha_{He}(T_{ic} - T_{we})}{\dot{m}_{wc}\alpha_{wc}} \]  

(15)

For C.V.3 heat and mass rate balances can be expressed respectively as:

\[ \frac{d\omega_c}{dz} = \frac{k_{ac}\alpha_{Me}(\omega_c - \omega_{ic})}{\dot{m}_{ac}} \]  

\[ \frac{dT_{ac}}{dz} = \frac{h_{ac}\alpha_{He}(T_{ac} - T_{ic})}{\dot{m}_{ac}(\alpha_{ac} + \omega_c\alpha_{wc})} \]  

(16) \hspace{1cm} (17)

Finally, for the interface:

\[ h_{we}\alpha_{He}(T_{we} - T_{ic}) = h_{ac}\alpha_{He}(T_{ic} - T_{ac}) + L_{we}k_{ac}\alpha_{Me}(\omega_{ic} - \omega_c) \]  

(18)

And the experimental relation for \( T_{ac} \) and \( \omega_{ic} \):

\[ \omega_{ic} = f_{exp}(T_{ic}) = 2.19 \times 10^{-6} \times T_{ic}^3 - 1.85 \times 10^{-4} \times T_{ic}^2 + 7.06 \times 10^{-3} \times T_{ic} - 0.077 \]  

(19)

The mean values of \( h_{sc} \) and \( h_{wc} \) calculated and \( k_{ac} \) is obtained from Lewis relation.
\[ k_{ae} = \frac{h_{ae}}{C_{ae}} \]  

It is important to note that the mass transfer coefficient of the air in the humidifier should satisfy a constraint which is related to the ratio of mass velocity of water to air and also geometrical parameters. For this purpose, the characteristic curve of selected packing is formed as mathematical relations [12].

\[ \frac{k_{ae}aV}{L} = (1.222H + 0.3667) \times \left( \frac{m_{we}}{m_{ae}} \right)^{-0.62} \]  

4. Mathematical programming model

Finite element method has been implemented in order to model the air and water behaviour in the humidifier and dehumidifier units. Based on the discretization which is carried out in FEM, the governing equations of each element which are in the format of differential equations are converted into a set of algebraic relations; hence, the water and air properties of each element is determined by solving above mentioned system of equations. In order to perform the FEM discretization both the humidifier and dehumidifier are divided into n and m vertical elements respectively.

4.1. Solar collector equations

The heat transfer rate and surface area of the solar collector can be determined using the following equations:

\[ \dot{Q} = m_{wc}A_{cross}C_{wc}[T_{we}(1) - T_{wc}(1)] \]  

\[ A_{col} = \frac{\dot{Q}}{l \left[ 0.8 - 6.8 \left( \frac{T_{col,in} - T_{amb}}{T_{amb}} \right) \right]} \]  

4.2 Humidifier finite difference equations

\[ T_{we}(i + 1) = T_{we}(i) \left( 1 - \frac{\Delta z_{e}h_{we}a_{e}}{m_{we}C_{we}} \right) + T_{ie}(i) \frac{\Delta z_{e}h_{we}a_{e}}{m_{we}C_{we}} \]  

\[ T_{ae}(i + 1) = T_{ae}(i) \left( 1 + \frac{\Delta z_{e}h_{ae}a_{e}}{m_{ae}C_{e}} \right) - T_{i}(i) \frac{\Delta z_{e}h_{ae}a_{e}}{m_{ae}C_{e}} \]  

\[ \dot{m}_{we}(i + 1) = \dot{m}_{we}(i) + \dot{m}_{ae}[\omega_{ae}(i + 1) - \omega_{ae}(i)] \quad 1 \leq i < n \]  

\[ L_{we}k_{ae}[\omega_{ie}(i) - \omega_{ae}(i)] = h_{we}[T_{we}(i) - T_{ie}(i)] + h_{ae}[T_{ae}(i) - T_{ie}(i)] \quad 1 \leq i < n \]  

\[ \omega_{e} = f_{exp}[T_{ae}(i)] \quad 1 \leq i < n \]  

\[ \omega_{ie} = f_{exp}[T_{ie}(i)] \quad 1 \leq i < n \]  

4.3 Humidifier finite difference equations

\[ T_{wc}(j + 1) = T_{wc}(j) \left( 1 + \frac{\Delta z_{e}h_{wc}a_{c}}{m_{wc}(i)C_{c}} \right) - T_{ic}(j) \frac{\Delta z_{e}h_{wc}a_{c}}{m_{wc}(i)C_{c}} \quad 1 \leq j < m \]  

\[ T_{ac}(j + 1) = T_{ac}(j) \left( 1 - \frac{\Delta z_{e}h_{ac}a_{c}}{m_{ac}C_{c}} \right) + T_{ic}(j) \frac{\Delta z_{e}h_{ac}a_{c}}{m_{ac}C_{c}} \quad 1 \leq j < m \]  

\[ L_{wc}k_{ac}[\omega_{ic}(j) - \omega_{c}(j)] = h_{wc}[T_{wc}(j) - T_{ic}(j)] + h_{ac}[T_{ac}(j) - T_{ic}(j)] \quad 1 \leq j < m \]
The constraints regarding the closed air cycle and water flow rate are as follows:
\[
\omega_c(j) = f_{\exp}[T_{ae}(j)] \quad 1 \leq j < m
\]
\[
\omega_{ic}(j) = f_{\exp}[T_{ic}(j)] \quad 1 \leq j < m
\]

The constraints regarding the closed air cycle and water flow rate are as follows:
\[
\dot{m}_{we}(1) = \dot{m}_{wc}
\]
\[
\dot{m}_{ae} = \dot{m}_{ac}
\]
\[
T_{ae}(1) = T_{ac}(1)
\]
\[
T_{ae}(n) = T_{ac}(m)
\]

Another constraint of the system is the pinch temperature difference. Humidifier and dehumidifier towers can be considered as two heat exchangers. An important factor in design of heat exchangers is pinch temperature difference. In practice, the outlet temperature of the hot stream cannot reach the inlet temperature of the cold stream and vice versa.

Pinch temperature difference for the dehumidifier occurs at the inlet or outlet of the tower, but for the humidifier it may occur at each point of the tower. Thus, the following constraints should also be considered [9].
\[
T_{ac}(1) - T_{wc}(1) < \Delta T_p
\]
\[
T_{ac}(m) - T_{wc}(m) < \Delta T_p
\]
\[
T_{ae}(i) - T_{we}(i) < \Delta T_p
\]

The heat recovery can be obtained by
\[
Heat \ Recovery = \frac{T_{wc}(1) - T_{we}(m)}{T_{we}(1) - T_{wc}(m)}
\]

Finally, the objective functions are calculated as follows:
\[
Specific \ Energy = \frac{\dot{Q}}{\dot{m}_d}
\]

Where the distilled water flow rate:
\[
\dot{m}_d = \dot{m}_{we}(1) - \dot{m}_{we}(n)
\]

And the areas which can represent the cost if the HD:
\[
\frac{A}{\dot{m}_d} = \frac{A_e + A_c}{\dot{m}_d}
\]

5. Optimization procedure
Optimization of the objective functions based on mentioned parameters is conducted employing multi-objective using genetic algorithm. Most of the real-world problems deal with multiple objectives which are often in conflict with each other. Therefore, any effort to optimize the problem with respect to a single objective, will lead to improper results regarding the rest of objectives. The fact which necessitates using methods which can satisfy all objective functions concurrently. Vividly, a perfect solution which can satisfy all of the objectives at the same time, does not exist. Therefore, a logical alternative for dealing with a multi-objective problem is to determine a set of solutions, each of which satisfies the objectives at a suitable level while not being dominated by any other solution [19]. In case
all of the objective functions should be minimized, a feasible solution \(x\) is said to dominate another feasible solution \(y\) \((x \succ y)\), if and only if \(Z_i(x) \leq Z_i(y)\), for \(i = 1, \ldots, K\) and \(Z_j(x) < Z_j(y)\) for least one objective function \(j\). A solution is called Pareto optimal if it is not dominated by any other solution in the considered space [19]. Evolutionary algorithms, specifically genetic algorithm (GA), with their unique capabilities for this kind of problems, are promising methodologies for dealing with multi-objective optimization problems [19-20].

6. Results and discussion

Considered input conditions of the regarded case are given in Table 1 [9]. The inlet mass velocity and temperature of water entering the condenser and also the air mass velocity have been imposed as input conditions. Optimization parameters include the collector outlet temperature (with the range of 68-80 °C), Pinch temperature difference (1.0-6.0 °C) and condenser length (with the range of 0.7-1.5 m).

| Parameter                                   | Value  |
|---------------------------------------------|--------|
| Inlet water temperature to the condenser (°C)| 15     |
| Water mass velocity in to the condenser \(\frac{kg}{m^2\cdot s}\) | 0.132  |
| Air mass velocity \(\frac{kg}{m^2\cdot s}\)   | 0.043  |

Multi-objective optimization using genetic algorithm is applied in order to find a set of optimal parameters. In this method, the population size is adjusted to 40 and mutation and Pareto fractions are 0.8 and 0.35, respectively. After 80 generation, the optimization procedure was terminated when the average change in the spread of Pareto solutions was less than the considered termination tolerance \((10^{-6})\). Final Pareto optimal set generated by multi-objective genetic algorithm is depicted in Fig. 4. Parameters of a few of the determined optimal points are given in Table 3.

As can be observed in Table 3 each solution includes the corresponding optimum parameters which include the collector outlet temperature, the pinch point temperature difference and the length of the condenser. For each optimal solution, the value of the considered objective functions which are the required specific energy (required thermal power for production of unit mass flow rate of distilled water) and the required specific area (for a unit mass flow rate of distilled water) are given. Accordingly, the efficiency of the collector, the required area of collector (for a unit mass flow rate of
distilled water) and heat recovery percentage for each optimum solution is determined and is also demonstrated in Table 2. As was previously explained, each of the achieved solutions can be chosen based on the requirements of a specific project. It is worth noting that the required specific energy employing HD desalination is significantly larger than that of other desalination methods including reverse osmosis (RO). Nevertheless, HD desalination unit has a notably simpler configuration compared to other desalination systems and consequently required a lower investment which makes it a suitable candidate for small scale applications. Accordingly, the main contribution of the present work, is providing a set of optimal system designs each of which can be selected based on the available capital. Hence, it further facilitates the implementation of HD based small scale solar driven applications.

| Optimization Parameters | Objective Functions |
|-------------------------|---------------------|
| $T_{col-out}$ ($^\circ$C) | Specific Energy ($\frac{Wh}{kg}$) |
| $\Delta T_m$ ($^\circ$C) | $\frac{A}{m_d}$ ($m^2.h/kg$) |
| $L_e$ (m) | $\frac{A_{col}}{m_d}$ ($m^2.h/kg$) |
| HR % |
| 68.0 | 340.07 | 14.02 | 0.63 | 44.69 |
| 71.0 | 377.72 | 10.87 | 0.70 | 41.68 |
| 79.6 | 833.52 | 7.35 | 1.53 | 21.91 |
| 68.8 | 413.79 | 7.47 | 0.76 | 39.14 |
| 78.3 | 355.45 | 12.09 | 0.65 | 43.46 |
| 74.4 | 676.14 | 7.70 | 1.24 | 26.64 |

7. Conclusion
In the present work, a humidifier-dehumidifier (HD) desalination plant integrated with a solar heat source was simulated. Specific required energy provided by the solar source, as an indicator of the energy efficiency of the plant, and the areas of the humidifier and dehumidifier, indicating the capital cost of the plant, were taken into account as objective functions. Since the considered objective are in conflict, multi-objective optimization using genetic algorithm was employed to carry out the optimization procedure and a set of optimal solutions each of which is a trade-off between the objectives was achieved. It is worth mentioning that the humidifier-dehumidifier desalination system is a well established technology and the corresponding mathematical model is comprehensively studied and validated in the literature. Hence, an experimental validation procedure was not necessary and thus was not conducted. Furthermore, although HD desalination is a less efficient method compared to other desalination technologies, it has a simpler configuration and requires lower investment which makes it a more promising alternative for decentralized small scale applications. In this context, the main contribution of the present work, is providing a set of optimal system designs each of which can be selected by the designer based on the available capital along with the specific requirements and the limitations of the project.

8. Nomenclature
$A$ — Surface area, $m^2$
$a$ — Specific area, $m^2/m^3$
$C$ — Specific heat, $J/kg.K$
FEM—Finite element method
$h$ — Heat transfer coefficient, $W/m.K$
$H$ — Height of evaporator, m
HD—Humidification dehumidification
$I$ — Total solar energy incident on the collector
MEE—Multi effect evaporation
MSF—Multi Stage Flash
RO—Reverse Osmosis
$\dot{Q}$ — Heat transfer rate, $W$
$T$ — Temperature, K, $^\circ$C
$V$ — Volume, $m^3$
VC—Vapor compression
$z$ — Height, m
aperture W/m²
\( k \) — Mass transfer coefficient, kg/m².s
\( L_v \) — Evaporation latent heat, J/kg
\( \dot{m} \) — Mass velocity, kg/m².s

Greek
\( \eta \) — Efficiency
\( \omega \) — Specific humidity, kg vapor/kg dry air

Subscripts
\( a \) — Air
\( amb \) — Ambient
\( c \) — Condenser (dehumidifier)
\( col \) — Collector
\( cross \) — Cross section of HD unit
\( d \) — Distillated water
\( e \) — Evaporator (humidifier)
\( i \) — Interface
\( H \) — Heat
\( in \) — Inlet
\( M \) — Mass
\( p \) — Pinch
\( sol \) — Solar
\( v \) — Vapor
\( w \) — Water

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