Performance Simulation of an Air-Heated Humidification Dehumidification Desalination System

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Abstract. This paper focuses on an air-heated humidification dehumidification (HDH) desalination system driven by low grade waste heat. The working processes within the air-heated HDH desalination system are demonstrated, and the performance of the HDH desalination unit is gained and analyzed on the basis of the building mathematical models. In addition to the energy analysis, the entropy generation of the desalination system is also obtained to validate the energy efficiency. The simulation results show that the performance of the HDH desalination system is especially sensitive to the mass flow rate ratio between the working seawater and humid air. It was found that the actual maximum value of gained output ratio (GOR) is $\text{GOR} = 1.80$ at the case of $m_{sw}/m_{da} = 0.68$. Furthermore, the maximum value of GOR is consistent with the minimum entropy generation within the desalination, which validates the performance analysis in some extent. The obtained results provide some significant references for the design and optimization of the HDH desalination system.

1. Introduction
In the light of the water shortage all over the world, extensive attentions were paid on the desalination methods to produce freshwater. However, traditional systems [1, 2], were not suitable for small scale requirements of freshwater because of the relevant low efficiency. Recent years, a high-performance desalination method, called HDH desalination method, was proposed [3], and investigations have been achieved on the system constitution and the relevant performance analysis.

Al-Sulaiman [4] gave out a parabolic trough solar collector to power the open air, open water desalination system, and the related thermodynamic performance of two different specific configurations were simulated, acquiring the influences from the structures of the solar heater on the performance of the HDH system. It was discovered that the solar collector was very suitable for the air heated HDH systems in the places with high radiation, and the configuration with the air heater between the humidifier and the dehumidifier is more efficient with a higher freshwater production.

A theoretical simulation model of a water-heated solar desalination unit was also suggested by Hamed [5], and energy equations of each component within such unit considered were solved to evaluate the relevant performance as well as the freshwater yield. Two periods were designated to calculate the freshwater production of the proposed system. The final simulated results told that the highest freshwater production was found in the second period, after preheating before entering the humidifier at 13 pm to 17 pm. Furthermore, according to validate the accuracy of the theoretical results for the proposed desalination system, the relevant experimental platform was built to test the heat and mass transfer process within the system, and a good agreement of the comparison between experimental and theoretical results presented the significance of the new water-heated solar desalination system.

In addition of the energy analysis of the HDH desalination system, entropy generation was also calculated to optimize the system characteristics for better operation parameters [6-8]. Mistry [9]
assessed the entropy generation with the HDH desalination system both with humid air and water heated, was accomplished. The mathematical models to obtain entropy generation and exergetic were built. In view of the results both from the energy and entropy generation analysis, it was validated that the minimization of the entropy generation was necessary and significant to fixed the components and the relevant operating conditions in order to get an optimal performance.

In the paper, the waste heat powered air-heated HDH desalination unit is proposed. The corresponding working principles of the air-heated HDH system are illustrated, and the performance for the HDH desalination unit is calculated and analyzed in view of the mathematical models with the analysis of energy and entropy generation. The research method as well as the corresponding obtained results provides the principles to define the configuration of the coupled HDH desalination system, and the entropy analysis also gives out the optimization orientation to reduce the final investments.

2. Numerical model and computing method

2.1. System description

Configurations of the air-heated HDH desalination system are presented in Fig. 1. It is found that the desalination system is mainly made up of the direct contact humidifier, the dehumidifier and the heat exchanger, and there existing two cycles, including the open seawater cycle and the closed humid air cycle. The initial seawater first enters the dehumidifier to cool the hot humid air, and the steam in the air condenses to freshwater. As a result, the initial seawater is heated to a higher temperature, and then the solvent of the hot seawater is carried by the dehumidified air in the humidifier, and the obtained concentrated seawater is exhausted to the environment direct while the humidified air flows into the heat exchanger to close the air-cycle.

![Figure 1. Configurations of the air-heated HDH desalination system](image)

2.2. Mathematical models

In the heat exchangers, the saturated humid air out of the humidifier absorbs the released heat from the waste heat sources with a counter flow pattern. The relevant energy balance and entropy generation can be expressed:

\[ Q_e = m_e (h_{e,3} - h_{e,1}) = m_{ds} (h_{ds,3} - h_{ds,2}) \]

\[ S_{gen,p} = m_{ds} (s_{ds,3} - s_{ds,2}) + m_p (s_{p,3} - s_{p,1}) \]

For the dehumidifier process, the related conservation equations and entropy generation in the surface heat exchanger are demonstrated as:

\[ m_w = m_{ds} (w_3 - w_1) \]
For the humidification process, the corresponding equations are respectively expressed as:

\[
\begin{align*}
    m_{sw} (h_{sw,1} - h_{sw,0}) + m_{h} h_{w} &= m_{da} (h_{u,3} - h_{w,1}) \\
    S_{gen,d} = m_{sw} (s_{sw,1} - s_{sw,0}) + m_{da} (s_{u,1} - s_{u,2}) + m_{h} s_{w}
\end{align*}
\]

(4)

(5)

2.3. Assessment

In the HDH desalination system, freshwater is separated from the humid air continuously with a mass flow rate of \( m_{sw} \). As a result, the definition of gained-output-ratio (GOR) is defined to indicate the efficiency of the energy utilization.

\[
GOR = \frac{m_{ps,\gamma}}{m_{e} \cdot (h_{e,1} - h_{e,0})}
\]

(9)

Furthermore, specific generation, \( s_{gen,t} \), is applied to illustrate the irreversible loss within the desalination thermal cycle.

\[
s_{gen,t} = \frac{S_{gen,t}}{m_{w}}
\]

(10)

3. Results and Discussion

The investigated HDH desalination system is powered at the air aspect by the waste exhaust through the heat exchangers, and the corresponding performance is simulated and presented. The thermal parameters of the waste exhaust from a furnace, are listed in Table 1. Furthermore, for the humidification and dehumidification processes, the definition of the effectiveness, \( \varepsilon \), and modified heat capacity ratio, HCR, are used to characterize the relevant performance, and all the designed parameters of the HDH desalination system during the simulation are listed in Table 2.

After the energy analysis of the HDH desalination system, the freshwater production and the humidity ratio of the humid air with the mass flow rate ratio from \( m_{sw}/m_{da} = 0.68 \) to \( m_{sw}/m_{da} = 1.68 \) are presented in Fig. 2. For the air-heated HDH desalination system, it is apparent the seawater solvent is first carried by the air during the humidification process. Thus, the freshwater is acquired after the carried steam condenses under the cooling effect of the feed seawater in the dehumidifier. It is seen that corresponding to the change principles of the humid air temperature, the difference of the humidity ratio between the inlet and outlet of the humidifier decreases continuously from \( \varphi = 0.31 \, \text{kgkg}^{-1} \) to \( \varphi = 0.006 \, \text{kgkg}^{-1} \) with the increase of the mass flow rate ratio, \( m_{sw}/m_{da} \). According to the calculation method of freshwater production, the final flow rate of the freshwater production drops from \( m_{w} = 73.56 \, \text{kg/h} \) to \( m_{w} = 12.42 \, \text{kg/h} \). It was verified that the performance of the HDH desalination will alternate at the balance condition of the dehumidifier, HCR=1[10-12]. Hence, it is shown that the balance condition of the humidifier, HCR=1, changes the variation trend for the freshwater production, which drops more sharply after the balance point.

| Table 1. Parameters of the low grade heat source |
|-----------------------------------------------|
| Term | Unit | Value |
|------|------|-------|
| \( T_{e,i} \) | K | 413.15 |
| \( m_{e} \) | kg/s | 0.4 |
| \( x \) | % | 31.2 |
| CO₂ | % | 68.8 |
| N₂ | % | 86.8 |
As previous statement, gained-output-ratio is considered to characterize the energy conversion efficiency within the air-heated HDH desalination system, and the relate values with the elevation of the mass flow rate ratio are demonstrated in Fig. 3. It is obvious that the peak value, $GOR=1.88$, emerges at the balance condition of the dehumidifier, $HCR_d=1$, and it is inferred that the characteristics of the desalination system is more sensitive to the performance of the dehumidification process. Nevertheless, due to the negative entropy generation of the dehumidification process at the case of $HCR_d=1$, the correspond working point is impossible to arrive. Hence, the actual peak value, $GOR=1.80$, is realized at $m_{sw}/m_{da}=0.68$. In spite of the smaller top value of GOR, the proposed air-heated HDH desalination still shows great advantages compared to the traditional methods with lower energy consumption in response of the fixed water production. It is evident that the driving energy from the heat exchangers is first obtained through the seawater flow during the dehumidification process. Then the heated seawater releases the obtained energy to heat the humid air. Therefore, the thermal cycle in the HDH desalination system is accomplished with a GOR value farther larger than 1.

As the scale of the irreversibility loss within the HDH desalination system, the total specific entropy generation is also simulated and presented in Fig. 3. Obviously, it seems that the values of the total specific entropy generation for all the cases are positive. Actually, the negative region for the specific entropy generation for of the dehumidifier exists. Furthermore, It is gained that the variation trend of GOR is completely consistent with that of the total specific entropy generation. Taking the balance condition of the dehumidifier, $HCR_d=1$, for example, a minimum irreversibility loss within the HDH desalination system arises when the bottom value of the total specific entropy generation is $s_{gen,t}=1.21 \text{kJkg}^{-1}\text{K}^{-1}$, corresponding to the maximum value of GOR, $GOR=1.88$ at $HCR_d=1$, and the actual maximum GOR case has the value, $s_{gen,t}=1.26 \text{kJkg}^{-1}\text{K}^{-1}$, of the total specific entropy generation.
4. Conclusions
In this paper, the mathematical models of the air-heated HDH desalination system powered by waste heat is established, and the corresponding performance is iteratively calculated in the platform of Matlab. The simulation results show that the analysis based on the first and second law should be simultaneously completed to verify the practical operation cases. An actual top value of $GOR=1.80$ at $m_{sw}/m_{da}=0.68$ appears despite the impossible maximum value, $GOR=1.88$, at the balance condition, $HCR_d=1$, during the dehumidification process. The variation laws of GOR are completely consistent with the total specific entropy generation of the HDH desalination system. The obtained results and the relevant research method give some significant references for the further design of the HDH desalination system. Moreover, the thermo-economic and relevant optimization analysis should be achieved in the future.

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Reference
[1] M. A. Al-Weshahi, A. Anderson, G. H. Tian. Organic Rankine Cycle recovering stage heat from MSF desalination distillate water. Applied Energy, 130 (2014): 738-747.
[2] S. Lu, Y.H. Zhou, M.S. Bi, J.J. Ren, Z. Cai. An integrated optimization model and application of MEE-TVC desalination system. Desalination, 371 (2015): 1-8.
[3] V. G. Gude, Energy storage for desalination process powered by renewable energy and waste heat sources. Applied Energy, 137 (2015): 877-898.
[4] F. A. Al-Sulaiman, M.I. Zubair, M. Atif, P. Gandhidasan, S.A. Al-Dini, M.A. Antar, Humidification dehumidification desalination system using parabolic trough solar air collector. Applied Thermal Engineering, 75 (2015): 809-816.
[5] M. H. Hamed, A.E. Kabeel, Z.M. Omara, S.W. Sharshir, Mathematical and experimental investigation of a solar humidification-dehumidification desalination unit. Desalination, 358 (2015): 9-17.
[6] C. Muthusamy, K. Srinath, Energy and exergy analysis for a humidification dehumidification desalination system integrated with multiple inserts. Desalination, 367 (2015): 49-59.
[7] F. A. Al-Sulaiman, G. P. Narayan, J. H. Lienhard, Exergy analysis of a high-temperature-steam-driven, varied-pressure, humidification-dehumidification system coupled with reverse osmosis. Applied Energy, 103 (2013): 552-561.
[8] K. H. Mistry, Second law analysis and optimization of humidification-dehumidification desalination cycles. Master Thesis, Massachusetts Institute of Technology, 2010.
[9] K. H. Mistry, J. H. Lienhard, S. M. Zubair, *Effect of entropy generation on the performance of humidification-dehumidification desalination cycles*. International Journal of Thermal Sciences, 49 (2010): 1837-1847.

[10] G. P. Narayan, K.H. Mistry, M. H. Sharqawy, S. M. Zubair, J. H. Lienhard, *Energy effectiveness of simultaneous heat and mass exchange devices*. Frontiers in Heat Mass Transfer, 023001 (2010): 1-13.

[11] W. F. He, D. Han, L. N. Xu, C. Yue, and W. H. Pu, *Performance investigation of a novel water-power cogeneration plant (WPCP) based on humidification dehumidification (HDH) method*. Energy Conversion and Management, 110 (2016): 184-191.

[12] W. F. He, D. Han, C. Yue, and W. H. Pu, *A parametric study of a humidification dehumidification (HDH) desalination system using low grade heat sources*. Energy Conversion and Management, 105 (2015): 929-937