EFFECT OF SOME DESIGN AND OPERATION PARAMETERS ON THE PERFORMANCE OF A WATER DESALINATION UNIT USING HUMIDIFICATION – DEHUMIDIFICATION

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ABSTRACT
This paper investigates the performance of an H-DH desalination unit with an extra condensing surface on the evaporator of a refrigeration unit. Different parameters were studied. The water flow rate was seen to inversely impact the desalinated water production. The increase in air temperature increases the water production. The HDH unit showed the same trends with all the packing materials used. The use of cellulose paper led to the highest performance followed by the clay-balls packing. Finally, the poorest performance was attained when saw-dust was used as packing.

Key words: Humidification; Dehumidification; HDH; Packing Materials; Refrigeration Unit.


1. INTRODUCTION

Fresh water is the key requirement for human presence on our planet. It is very important to all activities of mankind. The lack of uncontaminated water causes the death of millions annually (out of which 3900 infants [1]) either from famine, or from lack of sanitation. Future wars are expected to be over water resources. Despite that earth is covered mainly by water, fresh water represents only less than 3% [2]. In the light of this water sacristy, desalination comes into the scene as the best solution to obtain fresh water. Several methods are used to obtain fresh water. These methods are generally classified into membrane methods, and thermal methods [3], [4].

Thermal methods such as multi-effect distillation (MED), multistage flash (MSF), and vapor compression (VC) are the most known and widely used. These technologies were the
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Interest of several researches in the past; these researches resulted in improved performance that made them the main thermal technologies in the market.

Humidification dehumidification, HDH, is a modern technology that appeared in the literature, in the last few decades. This method has the advantage of being suitable for Small scale units. This advantage makes the HDH technology the subject of several investigations. This method basically imitates the natural way of rain formation where air passes first over a humidifier to gain water then it passes through a dehumidifier to reject this fresh water.

This Paper studies a humidification dehumidification cycle using an experimental setup to investigate the effect of several parameters. The first parameter studied is the packing material. Three different packings are used, namely: cellulose paper, fire clay balls, and saw dust. The second factor studied is the temperature of inlet air. Air temperature is changed as 37, 65, and 90 °C. Moreover, the effect of sprayed water temperature and quantity is tested. The water temperatures used are: 27, 50, and 80 °C. The water quantity varied from 150 m$^3$/hr to 600 m$^3$/hr. This represents a water to air ratio of 8.88 to 14.48.

2. LITERATURE REVIEW

There are many previous papers that discussed this technology experimentally and theoretically. The following paragraphs will review some of the recent works in this area.

Farid et. al [5]; constructed an HDH unit based on direct contact between air and solar heated water. They found that the unit yielded 12 L/m$^2$ of the collector which is 3 times the production of a solar still. They found the best performance at water and air mass flow rates of 80 and 50 kg/hr, respectively. At this ratio of 1.6 the GOR (called performance factor in their paper) was 1.35.

Dai et. al [6]; constructed a solar HDH with a solar water collector. They found that the perfect temperature range from 70 - 90 °C extracting fresh water from 30 to 105 (kg /hr). They found that the GOR of the system is about 0.85 under optimal operating conditions.

Yamali et. al [7]; found that the productivity of the system increased with an increase of feed water and air mass flow rates. They also found that the productivity of the system increased with an increase in cooling water flow rate. Furthermore, they found that the productivity of the system increased with an increase of initial water temperature.

Narayan et. al [8]; optimized the performance of HDH. They found that the varied pressure systems have better performance than single pressure systems. Also, they found that the air heated cycle is more efficient than even the water heated cycle. And they found that the air heated cycles (GOR is roughly 2.5 times larger for the water heated case).

Farrag et.al [9]; used HDH unit with closed air open water. They found that efficient contact between water and air will be accomplished by atomizing the hot saline water through air stream. From the results, they found that the productivity of fresh water increases by increasing air mass flow rate. Besides, the water productivity of the system increases with an increase in the amount of water and inlet air temperatures. They calculated the GOR for the system to be 4.2.

A. El-Haroun [10]; found that, using sponge as packing material will be better than sawdust and clauses. Also, he found that, the productivity of the unit increased with the enlargement in surface area of heat transfer of the humidifier. From the results, they also found that the water productivity of the system decreases with an increase in the flow rate of water.

Niroomand et. al [11]; found that increasing air flow rate has negative effect on the production and energy consumption of the system. Also, they found that increasing the cold-
water flow rate will increase the water production. Also, by increasing the air flow rate the amount of evaporation in the humidifier will increase. Additionally, by increasing the air flow rate the amount of water production will decrease. They found that the optimum value of water production is between 3 to 25 kg/hr.

Enaatollahi et. al [12]; found that, the water productivity of the system increases with an increase in the inlet water temperature. Also, they found that the water production rate initially increases with increasing air flow rate to an optimum value 1.7 m$^3$/sec, and beyond that it decreases. In addition, they found that increases in the ambient air temperature increase the desalinated water production up to an optimum value of 295 K, and beyond that a reduction in the production was observed.

Khalil et. al [13]; constructed an HDH unit. In humidifier, the air passes through the orifices of a sieve plate at the bottom of a hot water pool to generate bubbles. They found that, as inlet water temperature increases from 56.5 $^\circ$C to 62.2 $^\circ$C for air flow rate of 11 Kg/hr, GOR values increases from 0.31 to 0.37. Furthermore, they found that as sieve hole's diameter increased, the amount of extracting water decreased and a 5-mm orifice diameter gave the check productivity. Increasing of air mass flow rate led to a slight increase in the amount of extracted water.

Chehayeb et. al [14]; used a numerical model to simulate the operation of HDH at various feed water flowrates. They compared between the performance of the single-stage system and the two-stage system of the same size at different values of feed water. They found that, the gain output ratio increases from 2.5 to 3.7. Also, they found that the two stage system results in the highest GOR. Furthermore, they found the optimal water to air mass flow rate ratio from 4.2 to 4.7.

J. S. Yassin [15]; found that the water productivity of the system increases with both the increase in air to feed water mass ratio and with the increase of the air and water temperatures. Also, they found that the water productivity of the system increase with an increase the amount of water.

Table 1 shows a list of the packing materials used in HDH and Table 2 shows the range of water to air mass ratio covered experimentally in several researches and it classifies their findings according to the effect of mass ratio on the GOR. The last column titled comment indicates whether increasing the mass ratio will increase or decrease. If an optimum was found this is indicated and the optimum value is listed.

Table 1 Packing materials used in previous researches

<table>
<thead>
<tr>
<th>Packing Type</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose</td>
<td>[16], [17], [18], [19]</td>
</tr>
<tr>
<td>Ceramic Raschig Rings</td>
<td>[20], [21], [22]</td>
</tr>
<tr>
<td>Wooden shaving</td>
<td>[5], [23], [24]</td>
</tr>
<tr>
<td>Honey Comb Paper</td>
<td>[6], [25], [26]</td>
</tr>
<tr>
<td>Thorn Trees</td>
<td>[27]</td>
</tr>
<tr>
<td>Canvas</td>
<td>[28]</td>
</tr>
<tr>
<td>Wood covered with cotton textile</td>
<td>[29]</td>
</tr>
<tr>
<td>Porous Plastic</td>
<td>[30], [31]</td>
</tr>
<tr>
<td>Plastic Rings</td>
<td>[32]</td>
</tr>
<tr>
<td>Saw Dust</td>
<td>[33]</td>
</tr>
</tbody>
</table>
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Table 2 Effect of water flow rate on the unit performance

<table>
<thead>
<tr>
<th>Reference</th>
<th>(m'<em>w/m'</em>\text{air})</th>
<th>Optimum Value</th>
<th>GOR</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farrag et al, [9]</td>
<td>0.1187 to 0.089</td>
<td>----</td>
<td>4.2</td>
<td>decrease</td>
</tr>
<tr>
<td>Narayan et al, [19]</td>
<td>1 to 7</td>
<td>----</td>
<td>2.6-4</td>
<td>increase</td>
</tr>
<tr>
<td>Thiel et al, [33]</td>
<td>1 to 3</td>
<td>----</td>
<td>4.84-5.65</td>
<td>increase</td>
</tr>
<tr>
<td>Kang et al, [34]</td>
<td>1.65 to 0.9</td>
<td>----</td>
<td>2.44</td>
<td>decrease</td>
</tr>
<tr>
<td>Khalil et al, [13]</td>
<td>----</td>
<td>----</td>
<td>0.53</td>
<td>----</td>
</tr>
<tr>
<td>Hamed et al, [26]</td>
<td>0.000057 to 0.0266</td>
<td>----</td>
<td>1.85-2.1</td>
<td>Increase</td>
</tr>
<tr>
<td>Orfi et al, [29]</td>
<td>0.4 to 4</td>
<td>1.8</td>
<td>-----</td>
<td>Increase-then decrease</td>
</tr>
</tbody>
</table>

3. SYSTEM DESCRIPTION

The current humidification–dehumidification desalination system consists of a blower, three air heaters, humidifier, and two dehumidifiers. The first dehumidifier uses the incoming water to cool the air the second is the evaporator of a 1/3 HP refrigeration unit. The system is based on an open cycle for water and air stream. The unit is operated in a forced draft mode using the blower. A packing material is used in to increase the mass transfer area in the humidifier for efficient humidification of air. The saline water is pumped from saline water tank through the dehumidifier tubes. Gaining sensible and latent heat of condensation of water vapor, the saline water is preheated before entering the humidifier. In some experiments this water passes through an auxiliary heater to reach a specified temperature before the humidifier. The desalinated water is collected from the bottom of the dehumidifier, while the brine water is rejected from the bottom of the humidifier. A schematic View of the experimental set up is shown Fig (1) where three line types are used to illustrate the paths of air, water, and refrigerant. Fig. (2) is a photograph of the setup to complement the description of the experimental setup.
Figure 1 A schematic View of the experimental set up Water desalination unit HDH
4. RESULTS AND DISCUSSION

The experimental setup discussed in the previous section was used to perform experiments using several packing materials. Also, an analytical estimation was implemented using EES. Water temperature and water flow rates were recorded with and without the operation of refrigeration cycle. The packing materials used were sawdust, clay balls and cellulose paper. The water temperature introduced to the shower was 27 °C, 50 °C and 80 °C. The temperature of air was varied to be 37 °C, 65 °C and 90 °C, using a set of heaters.

The water produced was plotted against time and the production rate was calculated at steady state. The measured slope of the relation is the production rate. Figure 3 is an example of the total production rate calculated in case of air at 27°C, water at 50°C at a rate of 300 L/hr, Clay balls as packing material, and with the operation of the refrigeration unit.

Results obtained were used to study the effect of four parameters on the performance of the cycle. These parameters are the type of packing materials, the amount of water flow rate, the temperature of water and the air flow rate. Each parameter is discussed in detail in the remainder of this section.
4.1. Water to air mass ratio

Figure 4(a, b, and c) presents the effect of water to air mass ratio on the rate of production at different air temperature for different packing materials. A general trend seen in the three figures is that the desalinated water production rate decreases with the increase in the water to air mass ratio. This inverse relation is almost linear. The production rate increases with the increase in air temperature. This effect, of air temperature, is more pronounced at low humidifier water flow rate (low mass ratios).
4.2. Air temperature
To further discuss the effect of the air temperature, the variation of production rate (same results of fig 4) are plotted against the air temperature in figure 5 for clay balls (as an example). The graph shows the variation at all tested water flows. The results show the positive impact of the air temperature on the production rate of potable water. The same trend is witnessed with the other two packing materials.

**Figure 4** Variation of the production rate of desalinated water with the flowrate of humidifier water at different air temperatures a) for cellulose packing, b) for clay-balls packing, and c) for saw-dust packing.
4.3. Packing material

Measurements clearly show that the cellulose packing is much superior than the other two packing materials. The difference is more pronounced at high water mass flow rate, and low temperatures. For example, at air temperature of 90°C and water flow of 150 L/hr: unit production with cellulose, clay balls, and sawdust packings are 35 L/day, 28.8 L/day, and 21.1 L/day, respectively. While at air temperature of 37°C and water flow rate of 600 L/hr the production using the three packings are: 9, 9.6, and 7.2 L/day respectively. Figure 6 shows samples of these variations. Figure 6 (a) shows the variation of water production with air temperature for different packing materials at water flow of 150 L/hr, while Figure 6 (b) shows the production variation with the water flux at 90°C.
4.4. The operation of the refrigeration unit

As explained in the description of the setup, humid air passes over two consecutive condensing surfaces. The first is cooled by the feed water and the second is the evaporator of a refrigeration unit. All the results displayed in the previous sections were obtained from condensate collected from both surfaces. Due to the poor humidity content of the air leaving the humidifier, the apparatus dew point of the first condenser was not cold enough to condensate water in some of the experiments. The operation of the refrigeration unit was key to obtain most of the unit production of desalinated water because of the colder surface temperature it provides. Figure 7 shows the produced desalinated rate with and without the operation of the refrigeration unit at two different air temperatures (65°C and 90°C).
6. CONCLUSION
This paper studied experimentally the performance of a desalination unit with refrigeration unit integrated to enhance its production. Several design and operational parameters were investigated. It is concluded that the production of desalinated water is inversely related to the amount of water sprayed in the humidifier. The increase in the air temperature at the inlet of the humidifier increases the water production. Cellulose paper proved to be superior to the clay balls and saw dust as a packing material in such applications. Finally, the operation of the refrigeration unit was essential to the production of desalinated water from the current setup.

For future work, we recommend redesigning the humidification tower to better humidify the air. Besides, the refrigeration unit could be better integrated to the unit so that the condenser is subjected to the inlet air to serve in heat addition. Moreover, this unit could be integrated to large Air conditioning systems to condition the fresh air supply and obtain desalinated water along with the cold dry fresh air.

REFERENCES


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