

The Performance Research and Orthogonal Analysis of Humidification-dehumidification Technology (HDH) System

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Abstract. HDH seawater desalination technology has characteristics of flexible scale, small investment, and suitable for decentralized fresh water demand. This paper designs a HDH seawater desalination system, and based on the principles of energy conservation and mass conservation, a theoretical calculation model is established, and the influence of spray liquid flow and temperature, airflow, cooling water temperature and flow on the system water production and Gained output ration (GOR) is studied. And the orthogonal analysis method is used to study the influence of different parameters on water production and GOR. The results show that: water production and GOR are positively related to temperature of the spray liquid, when spray liquid or air flow is large, fresh water output is negatively correlated with air flow, system water production and cooling water flow are positively correlated at first, then system fresh water production tends to be stable, GOR and cooling water flow are first negatively correlated, and then GOR become stable, water production is negatively correlated with cooling water temperature, GOR is positively correlated with cooling water temperature. The spray liquid flow rate has the greatest influence on water production, and spray liquid temperature has the greatest influence on GOR.

1 Introduction

The survival and development of human society are inseparable from water. The earth is rich in water resources, with a total water storage of approximately 1.4 billion cubic kilometers. However, sea water, brackish water and other water that cannot be directly used for drinking and irrigation account for more than 97% of the earth's total water storage, and the remaining less than 3% of fresh water, but most of them are frozen in the glaciers at the poles and alpine regions of the earth, and the remaining fresh water is distributed more underground than surface water. The fresh water that exists in rivers, lakes and other places on the earth is less than 0.36% to directly be used by humans [1].

At present, the mainstream seawater desalination technologies include low-temperature multi-effect distillation (LT-MED), multi-stage flash evaporation (MSF) and reverse osmosis (RO), etc. However, these technologies and equipment require large investment,

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high energy consumption, and high maintenance costs. The requirements of pre-treatment processing are strict, and it is necessary to reduce the cost of fresh water through the large-scale production of fresh water. And most of the seawater desalination devices with mature technology and commercial production are traditional large-scale devices, are suitable for energy-rich economically developed regions [2], which cannot effectively solve the shortage of fresh water in remote and scattered areas. HDH avoids the above-mentioned problems. Its main characteristics are: flexible scale, small investment, suitable for decentralized fresh water demand, the vaporization process takes place at the gas-liquid interface instead of the heat transfer surface, which avoids scaling on the heat transfer surface and reduces the pretreatment requirements for seawater. The initial form of HDH seawater desalination system is a solar distiller. Humidifier and dehumidifier are its two most important components. Air is used as the carrier to bring water vapor from the humidifier to the dehumidifier for condensation. And concentrated brine is also obtained in the vessel, which shows that HDH technology can not only be applied to seawater desalination, but also can be applied to the concentration of waste liquid.

The development of HDH devices has gone through three stages. The first is the natural convection HDH process based on the development of solar distiller. Muller-Hois [3] built a natural convection HDH seawater desalination system. The seawater sprayed from the humidifier transfers heat and mass with the countercurrent air conduct. In this system, the energy utilization rate is not very ideal, because the HDH processes are not separated, and the difference between the evaporation temperature and the condensation temperature is small. In the second stage, the natural convection of the air in the first stage is replaced by forced convection. The flow velocity of the air becomes larger, and improves the efficiency of heat and mass transfer, thereby increasing the production of fresh water. Veza [4] built a HDH seawater desalination device, which adopts forced air convection, and the efficiency of system have been greatly improved. The third stage is the separation of the humidification process and the dehumidification process. Most scholars use this form of HDH device for experimental research, and build various systems on the basis of this structure [5-10]. AI-Hallaj[11] established a typical representative of a separate HDH device, the latent heat of condensation is recovered in the water, and the fresh water output of the device is 2 to 5 times that of the distiller under the same conditions. Albers [12] proposed the dew point evaporation seawater desalination technology. The heat of the condensation chamber is directly transferred to the evaporation chamber, and the energy utilization rate is improved. After that, in the system that adopted the falling film mass transfer method in the vertical falling film dew point evaporator [13], after the sea water fell into the evaporation chamber, it contacted the surface of the evaporator. The results showed that it was different from the conventional device, the water production and energy recovery coefficient can be increased by 1.5 times. Rajaseenivasan [14] analyzed the bubbling tower HDH seawater desalination system with different combinations of solar collectors. The results showed that the performance of the system improved with the increase of air flow and cooling water flow. Lawal [15] experimentally studied the performance of the HDH system driven by the heat pump. The proposed integrated unit can produce fresh water, and the cooling effect is adjusted by the heat exchange unit by water heating or cooling. Srihar[16] used HDH process to recover the waste heat of the condenser and the evaporator, and improved the performance of the refrigeration system by circulating the humid air around the condenser coil and condensing humid air on the surface of the evaporator coil.

In terms of theoretical analysis, Nafey [17-18] first established mathematical models of different heating methods for HDH systems. For the analysis of a heat pump-driven HDH desalination system shows that the influence of temperature on the system productivity is not obvious [19]. Moumouh [20] studied a mathematical model for the design of a

humidification-dehumidification desalination device based on air HDH. The mathematical model predicted the heat exchange of the desalination device and calculated the outlet temperature of each device. For the study of multi-effect mathematical models for humidifiers, dehumidifiers and heat exchangers showed that: the water production rate of the system is higher than the one-effect system and the three-effect system [21]. And the influence of different parameters on the performance of a dual heat and mass coupled HDH system is studied. The results showed that when other parameters are constant, as the amount of feed seawater increases, fresh water production and heat input increase, but GOR decreases.

In summary, the HDH seawater desalination technology has greater practical application prospects, and has become a research hotspot in recent years. But there isn't systematic conclusions have been formed, and further research is still needed. This paper proposes a HDH system based on the plate tower humidifier, and conducts theoretical analysis and calculations to provide guidance for subsequent experimental research and practical engineering applications.

2 Mathematical model and solution of HDH system

According to the operating characteristics of the actual system, the model is simplified for the convenience of analysis:

- No heat loss.
- The humid air is saturated at the inlet and outlet of the humidifier.
- The processes involved are all working conditions under the stable operation of the system.

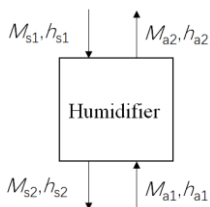


Fig. 1. Humidifier model

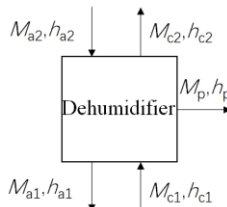


Fig. 2. Dehumidifier model

According to the work process, the energy conservation equation and mass conservation equation in the humidifier are established [23-24].

In the humidifier, according to the conservation of energy, the heat released by the liquid is equal to the heat absorbed by the humid air, the energy conservation equation is as follows:

$$M_{s1}h_{s1} - M_{s2}h_{s2} = M_a(h_{a2} - h_{a1}) \tag{1}$$

Where M_{s1} is the mass flow of the liquid spray, kg/s, h_{s1} is the specific enthalpy of the liquid at the top of the humidifier, kJ/kg, M_{s2} is the mass flow of the liquid from the humidifier outlet kg/s, h_{s2} represents the specific enthalpy value of the liquid at the outlet of the humidifier, kJ/kg, M_a is the mass flow of dry air, kg/s, h_{a2} represents the specific enthalpy of the humid air at the outlet of the humidifier, kJ/kg, h_{a1} represents the specific enthalpy of humidity air at the inlet of the humidifier, kJ/kg.

The mass of humid air in the humidifier changes with the liquid, so the mass conservation equation must be used in theoretical calculations. The mass conservation equation is as follows:

$$M_{s1} - M_{s2} = M_a(d_{a2} - d_{a1}) \tag{2}$$

Where d_{a1} and d_{a2} are the moisture content of the humidifier inlet and outlet, kg/kg.

In the dehumidifier, according to the conservation of energy, the heat released by the humid air is equal to the heat absorbed by the cooling water. The energy conservation equation is as follows:

$$Mch_{c2} - Mch_{c1} = M_a(h_{a2} - h_{a1}) + M_p h_p \tag{3}$$

Where M_p is the water production rate, kg/s; h_p is the latent heat of condensation of fresh water, kJ/kg.

Water vapor is condensed into fresh water in the dehumidifier, so the mass conservation equation is as follows:

$$M_p = M_a(d_{a2} - d_{a1}) \tag{4}$$

Reference HDH related literature [25-26], the main research performance parameters are as follows:

- System water production

The water production of the system characterizes the ability of the system to produce fresh water. The unit generally adopts kg/s, kg/h or kg/d. This article adopts the unit of kg/s.

- GOR

The definition of GOR is as follows:

$$GOR = \frac{M_p h_p}{Q_w} \tag{5}$$

In this paper, a mathematical model of the HDH system is established, and the iterative method is used to calculate unknown parameters by MATLAB program. The calculation flow chart is shown in Figure 3. The flow M_{s1} and temperature t_{s1} of the liquid at inlet of the humidifier are known. And the temperature t_{a1}' of the humid air at inlet of the humidifier is assumed, so that the state of the humidified air at inlet of the humidifier is also known. The actual heat exchange can be obtained from efficiency formula, and then the temperature of the humid air at the outlet of the humidifier and various parameters can be obtained. Regarding the obtained state parameters of humidifier outlet as the state parameters of the humid air at inlet of the dehumidifier. Then the humid air temperature t_{a1}'' at outlet of the dehumidifier is calculated according to the actual heat exchange, replacing t_{a1}' until the difference between t_{a1}' and t_{a1}'' meets the convergence condition, and end the iteration work.

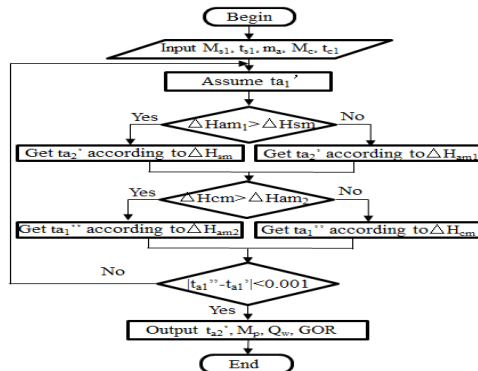


Fig. 3. Calculation flow chart of humidification and dehumidification system

3 Results and discussion

3.1 The influence of spray liquid and air

The temperature of the spray liquid is a key factor of affecting the performance of the entire HDH system. At this time, the air flow M_a is 0.018 kg/s, the cooling water flow M_c is 0.03 kg/s, and the dehumidifier inlet cooling water temperature t_{c1} is 20°C. Figure 4 shows that the water production is positively correlated with the temperature of spray liquid. This is because the humidification capacity of the humidifier has been improved, so the fresh water production promotes. When the flow of the spray liquid is constant, as the temperature of the spray liquid increases, the GOR increases (Figure 5). This is because the temperature of the spray liquid increases, the heat released by the humid air in the dehumidifier increases more than the increase of the input heat, and the GOR increases. GOR increases with the increase of the spray liquid flow.

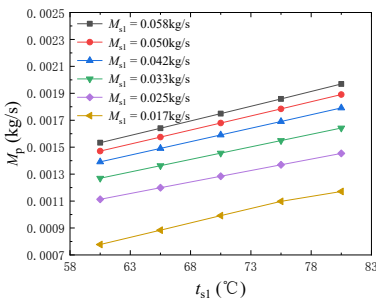


Fig. 4. The system water production varies

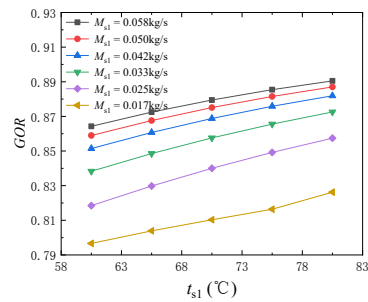


Fig. 5. The GOR varies with spray liquid temperature

With seawater spray temperature

Besides, as a carrier of water vapor, the flow of air also has an important impact on the performance of the system. At this time, the spray liquid temperature t_{s1} is 70°C, M_c is 0.03 kg/s, and t_{c1} is 20°C.

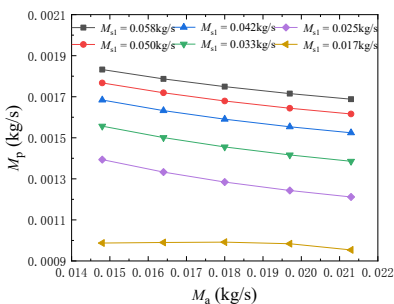


Fig. 6. The system water production

Varies with air flow

Figure 6 shows the variation curve of the system water production with air flow. The water production of the system is determined by the difference of moisture content of the humid air at inlet and outlet of dehumidifier and air flow. Under high spray liquid flow, the

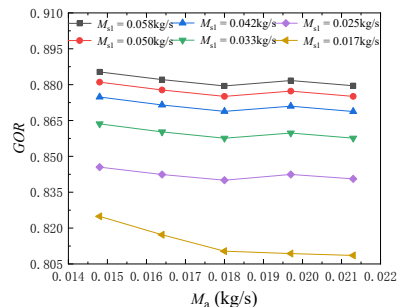


Fig. 7. The GOR varies with air flow

difference of moisture content changes more than air flow; it has a greater impact on the system water production, resulting in a decrease of the system water production. Under the low spray liquid flow, the difference of moisture content is smaller than the other working conditions, so the system water production is not basically change with influence of air flow increasing. Figure 7 shows the change of GOR with the air flow rate. It can be seen that under low fluid flow conditions, the heat input to system increases while the system water production is basically unchanged, resulting in a decrease of GOR. In the other case of other spray liquid flow, as the air flow rate increases, GOR shows a trend of decreasing at first, then increasing, and then decreasing. This is because the changes of fresh water production and heat input to system are different.

3.2 The influence of cooling water

At this time, the spray liquid temperature is 70°C, the air flow rate is 0.0180kg/s, and the cooling water temperature is 20°C.

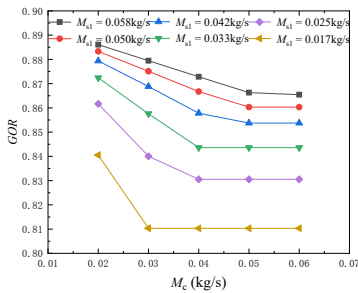


Fig. 8. GOR varies with cooling water flow

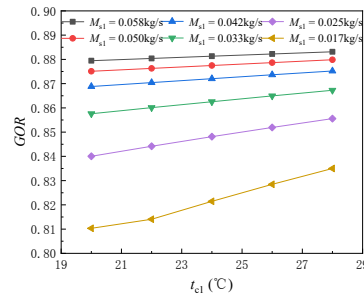


Fig. 9. GOR varies with cooling water temperature

Figure 8 shows the change of GOR with the cooling water flow. After the critical cooling water flow rate, the system water production and heat input to system no longer change with the cooling water flow rate, so the GOR does not change. Before the critical value, GOR decrease as the cooling water flow increases. This is because the flow of cooling water increases, heat input to system increases more than heat released by humid air in the dehumidifier. From Figure 9, it can be seen that the dehumidification capacity of the dehumidifier is relatively large when spray liquid flow is small. The water production is constant; more heat must be input to maintain the operation of the system. Therefore, when the cooling water temperature increases, the dehumidification capacity reduced, so that GOR increases.

3.3 Orthogonal analysis

The above content analyzes the key parameters that affect the performance of the HDH system, and obtains the change law of the influence of a single parameter on the system performance, but different parameters have mutual influence. This paper uses orthogonal analysis to determine the best engineering condition.

Orthogonal experiment is a design method for studying multiple factors. According to the orthogonally, the most representative operating point is selected from all operating conditions for analysis, and the optimal one is found through the analysis of these operating conditions [27].

Table 1. Orthogonal analysis table of water production

Factor Level	Spray liquid flow (kg/s)	Spray liquid temperature (°C)	Air flow (kg/s)	Cooling water flow (kg/s)	Cooling water temperature (°C)
K1	0.004511	0.006145	0.007876	0.004558	0.008047
K2	0.006056	0.006247	0.007140	0.006443	0.006443
K3	0.007435	0.007493	0.006974	0.007920	0.007920
K4	0.008552	0.007580	0.006803	0.008942	0.007275
K5	0.009868	0.008957	0.007629	0.008559	0.006894
k1	0.000902	0.001229	0.001575	0.000912	0.001609
k2	0.001211	0.001249	0.001430	0.001289	0.001289
k3	0.001487	0.001499	0.001395	0.001584	0.001584
k4	0.001710	0.001516	0.001361	0.001788	0.001455
k5	0.001974	0.001791	0.001526	0.001712	0.001379
the extreme difference	0.000562	0.000562	0.000214	0.000876	0.000320

It can be seen from Table 1 that the effects of various factors on the water production are arranged in descending order: spray liquid flow, cooling water flow rate, spray liquid temperature, cooling water temperature, and air flow.

Table 2. Orthogonal analysis table of GOR

Factor Level	Spray liquid flow(kg/s)	Spray liquid temperature(°C)	Air flow(kg/s)	Cooling water flow(kg/s)	Cooling water temperature(°C)
K1	4.127	4.194	4.285	4.354	4.241
K2	4.123	4.242	4.269	4.292	4.292
K3	4.137	4.267	4.288	4.234	4.234
K4	4.133	4.314	4.246	4.233	4.291
K5	4.158	4.325	4.254	4.229	4.288
k1	0.8254	0.8388	0.8570	0.8708	0.8482
k2	0.8246	0.8484	0.8538	0.8584	0.8584
k3	0.8274	0.8534	0.8576	0.8468	0.8468
k4	0.8266	0.8628	0.8492	0.8466	0.8582
k5	0.8316	0.8650	0.8508	0.8458	0.8576
the extreme difference	0.0070	0.0262	0.0084	0.0250	0.0114

It can be seen from Table 2 that effects of various factors on GOR are arranged in descending order: spray liquid temperature, cooling water flow, cooling water temperature, air flow, and spray liquid flow.

4 Conclusions

This paper studies the influence of different parameters such as spray liquid flow rate and temperature, air flow rate, cooling water flow and the humid air temperature at the inlet and outlet of the system on fresh water production and water production ratio. Get the following conclusions:

- As the temperature of the spray liquid increases, the system water production and GOR increase.
- When the spray liquid flow and the air flow are small, the system water production does not change much with the increase of the air flow. When the spray liquid flow rate or air flow rate is large, the fresh water production will increase with the increase of the air flow rate.

- Before the critical cooling water flow rate, GOR decrease as the cooling water flow increases. Above the critical value, the GOR does not change.
- When the cooling water temperature increase, the dehumidification capacity reduced, so that GOR increases.
- By orthogonal analysis, it is also concluded that the spray liquid flow has the greatest influence on the water production, and the spray liquid temperature has the greatest influence on GOR.

5 Acknowledgments

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6 Nomenclature

Symbols

Ms_1	liquid mass flow of humidifier inlet (kg/s)
Ms_2	liquid mass flow of humidifier outlet(kg/s)
hs_1	liquid specific enthalpy of humidifier inlet (kJ/kg)
hs_2	liquid specific enthalpy of humidifier outlet (kJ/kg)
Ma	mass flow of dry air(kg/s)
ha_1	specific enthalpy of air at inlet humidifier(kJ/kg)
ha_2	specific enthalpy of air at outlet humidifier(kJ/kg)
Mc_1	mass flow of cool water (kg/s)
hc_1	specific enthalpy of inlet cool water(kJ/kg)
hc_2	specific enthalpy of outlet cool water(kJ/kg)
Mp	water production rate(kg/s)
hp	latent heat of condensation fresh water(kJ/kg)
Qw	heat input to system(kJ)
ts_1	liquid temperature of humidifier inlet(°C)
tc_1	cool water temperature of humidifier inlet(°C)
ta_1	temperature of air at inlet humidifier(°C)
ta_1'	assume temperature of air at inlet humidifier(°C)
ta_1''	temperature of air at inlet humidifier after iteration (°C)
ΔHam_1	maximum theoretical heat exchange of air at humidifier(kJ)
ΔHam_2	maximum theoretical heat exchange of air at dehumidifier(kJ)
ΔHsm	maximum theoretical heat exchange of liquid at humidifier(kJ)
ΔH_{cm}	maximum theoretical heat exchange of cool water at dehumidifier(kJ)
ta_2'	temperature of air at outlet humidifier(°C)

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