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Experimental study on air bubbling humidification

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ABSTRACT

A new process of solar humidification–dehumidification (HD) desalination by air bubbling humidification is designed. The studies are focused on the air humidifying experiments. The test-bed of air bubbling humidifier with a sieve plate is set up. The main factors affectinf air humidification are studied separately. The results show that the air relative humidity reaches 100% by humidifying in the range of the experiments. As the air flow rate increased, the quantity of air humidification, the pressure drop of air passing though the holes and the water level above sieve plate were all increased; as the temperature of air and water in the humidifier increased, the quantity of humidifying air increased significantly; as the height of water level above the sieve plate increased, the resistance of air passing though the humidifier increased, so that the blower power increased too; when the way of cooling air is improved, the GOR of the system can be enhanced and the cost of freshwater can be decreased. The study provides a basis for design of solar HD desalination with bubbling humidification.

Keywords: Solar, Humidification-dehumidification, Desalination, Bubbling humidification

1. Introduction

Solar HD desalination is one of the methods with high efficiency in solar desalination [1], and it has many advantages, such as simple structures of equipment, operation at normal pressure and at the temperature between 70°C and 90°C, low electrical power consumption, and common flat plate or vacuum tube solar collector available, etc. The humidificationg process takes place on the gas–liquid interface rather than on the heat transfer surface, so that the water scale formed on the surface of the humidifier is low. The pretreatment process needed for seawater is simple, the size of the unit is flexible, and the investment in it is low.

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Humidification is one of the main processes in the solar HD desalination. The method of air humidification by seawater spraying is commonly used at present. A solar HD desalination unit established by Al-Hallaj et al. [2] is a typical one. A batch of flat solar air heaters was used to pre-heat seawater, and then the hot seawater was sprayed on air, and humidified it. The freshwater output in summer in the Middle East was 12 kg/(m^2·d), which was about 3 times of the output of a solar distillation unit under the same conditions of sunlight radiation [3]. The multi-stage spraying humidification desalination process was used by Ben Amara et al. [4], each stage of it included a group of solar heaters and a spraying humidifier. A small pilot plant with four-stage humidification was established by Houcine et al. [5], the freshwater daily output reached 355 kg/d when the yearaverage solar radiation was 590 W/m^2. The researchers of the Northwestern Polytechnic University in China used a kind of a honeycomb structure made of paper as a heat transfer medium, which increased the contact surface and improved the effect of mass transfer [6,7] between air flow and seawater. The pinch technology and exergy analysis method were used for the energy analysis of the multi-stage spraying HD system [8,9].

EI-Agouz et al. [10] first used the bubbling humidifying method in desalination. An air pipe with many holes was set into water to humidify air by bubbling. The test results showed that its humidification efficiency was equivalent to the efficiency of multi-stage spraying humidification [11,12].

To combine bubbling humidification with solar desalination, a new process of solar HD desalination process is designed in this paper. The studies are focused on the air humidification experiments, and the test-bed of a bubbling humidifier with a sieve plate is set up. The main factors affecting air humidification are studied experimentally. The gain output ratio (GOR) of the two process schemes is calculated and compared. The research is aimed to decrease the production cost of freshwater.

2. The process

The new solar HD desalination process is shown in Fig. 1. The main equipment includes the solar seawater heater, solar air heater, bubbling humidifier and dehumidifier etc; auxiliary equipment includes a blower, seawater pump, valves and pipes, etc. All pipelines and the humidifier are wrapped by an insulating layer to decrease the heat loss.

The working process of the system is: the air heated by solar heater enters the bubbling humidifier to be humidified, then gets into the dehumidifier, where a part of vapor is condensed to fresh water. Afterwards, the dehumidified air returns to the solar heater to be heated and is circulated again.

In the dehumidifier, the heat transfer pipes are made of inorganic heat pipes. This kind of pipe is a new heat transfer element. Its heat transfer abilities are 44 kW/m^2 in the radial direction, and 8600 kW/m^2 in the axes direction, which is better than those of a general heat pipe. The inside of the pipe is vacuumed and filled with a mixture powder of several inorganic materials. The two ends of the pipe are closed. The cold and hot fluids exchange heat through the outside of the two ends of the pipe. The heat is transferred quickly from one end to another through the pipe wall.

As the cold seawater is sprayed on the cold end of the heat pipes, it absorbs the heat coming from the hot end of the pipes and is preheated. Meanwhile, at the hot end of pipes, the moist air is cooled down, a part of vapor in the air is condensed to freshwater. The preheated seawater flows from the dehumidifier divided into two

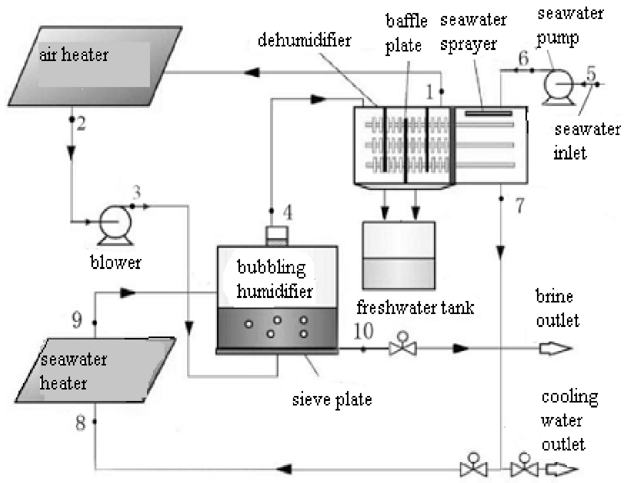

Fig. 1. Scheme of solar HD desalination with bubbling humidification.

parts. One part of it returns the solar heater to make up the evaporated seawater; the other part of the preheated seawater is directly discharged. To maintain the seawater concentration at a certain range in the humidifier, the brine is discharged periodically.

3. Experiment of bubbling humidification

Air bubbling humidifying process is a heat and mass transfer process between air and water. When the air passes through the holes on sieve plate and enters the bubble humidifier, bubbles are formed and moved up by the force of buoyancy and disturbance of seawater.

3.1. Experimental system

The experimental system of bubbling humidification was designed (Fig. 2). The system consists of a sieve bubbling humidifier, blower, air heater, and measuring instruments, such as pressure meters, flow meter, thermometers and moisture meter.

The structure of the humidifier is a single-stage sieve plate, which is shown in Fig. 3. The height of the humidifier is H = 500 mm, the sieve plate diameter is D = 200 mm, the thickness of it is δ = 8 mm, the diameter of a hole is d_0 = 1 mm. The holes are distributed in the form of equilateral triangle, the distance between contiguous holes is s = 18 mm, the number of holes is n = 91, the percentage of opening holes is ϕ = 0.27%.

The photo of the experimental system is shown in Fig. 4.

In the sieve plate design and operation, the problem should be considered and avoided that water in the humidifier would be leaked or mixed with the moist air when the air flow rate is too low or too high. Correspond-

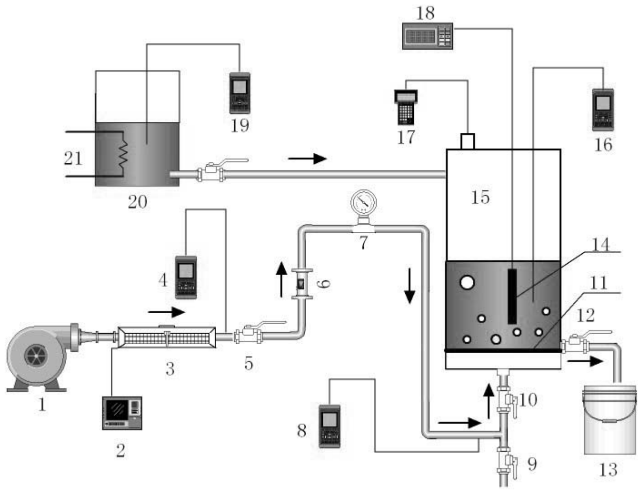

Fig. 2. Test-bed of bubbling humidification. 1 – blower; 2 – voltage transformer; 3 – air heater; 4, 8, 16, 19 – digital thermometer; 5, 9, 10, 12 – valve; 13 – water tank; 6 – flow meter; 7 – pressure gauge; 11 – sieve plate; 14 – heater; 15 – humidifier; 17 – hygrometer; 18 – temperature controller; 20 – hot water tank; 21 – water heater.

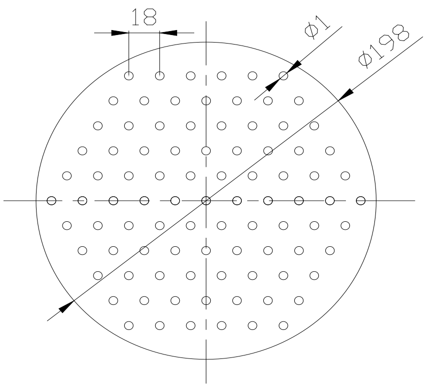

Fig. 3. Structure of a sieve plate.

ing to the above two non-normal states, the critical air flow rates could be obtained by experiment or calculation.

3.2. Experimental results and analysis

The experiments of bubbling humidification were carried out in January–February 2010. It was operated under normal pressure, using tap water instead of seawater, and electric heaters instead of solar air heater and water heater. The temperature of the air in the inlet of the humidifier t_3 and the temperature of water in the humidifier t_w were set equal. The photo of bubbling in the humidifier is shown in Fig. 5. The main factors influencing humidification were experimented and analyzed as follows.

3.2.1. Influence of air flow

As the temperature of ambient air is $t_0 = 16.7°C$, relative humidity of air is $\phi_0 = 16.7\%$, the water level in the humidifier is $h = 6$ cm, $t_3 = t_w = 40°C$, the air flow increased from 0.5 m^3/h to 2.5 m^3/h, the measured temperature of moist air in the outlet of the humidifier is $t_4 = 40°C$, and the measured relative humidity of which is $\phi_4 = 100\%$.

According to the calculation, for the upward force of air in the sieve plate holes is bigger than the static pressure of water layer in operation of humidifier at this air flow rate, so the water leakage would not occur.

Checking the psychometric chart according to air states in the inlet and outlet of the humidifier, the theoretical fresh water production m can be calculated by

$$m = M_0(d_4 - d_3) \quad (1)$$

In Eq. (1), M_0 is the air mass flow rate, kg/s; d_3, d_4 are separately the absolute moisture content of air in the inlet and outlet of the humidifier, kg (water)/kg (air). As d_3 and d_4 are constant, m is proportional to $M0$.

The power consumption of blower is

$$P = M_0\left(h_3 - h_2\right) \quad (2)$$

Fig. 4. Photo of the bubbling humidifying system.

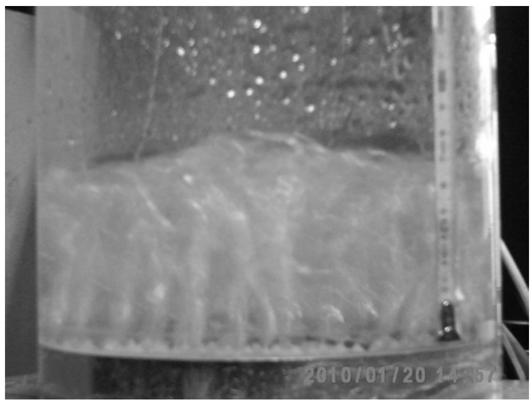

Fig. 5. Photo of bubbling in the humidifier.

Here P is blower power, W; h_2, h_3 are separately the specific enthalpy of air in the inlet and outlet of blower, kJ/kg.

The air pressure drop in the humidifier and the blower power consumption influenced by air flow rate are shown in Fig. 6 separately. When the height of the water level on the sieve plate h = 6 cm, it could be seen from the figure that the pressure drop in the bubbling process and the blower power consumption are all increased when the air flow rate increased.

3.2.2. Influence of water level height

As the air flow rate is 2.5 m^3/h and the other parameters are same with the above experiment, if the height of the water level in the humidifier is increased from 6 cm to 18 cm, it was obtained by experiments that the air relative humidity is entirely 100% in the outlet of the humidifier, but the air pressure drop in the humidifier is increased as shown in Fig. 7. The air relative humidity in the outlet of the humidifier is less than 100% if the water lever height is lower than 6 cm. Therefore, ahead of enough humidifying capacity assured, the lower the water level is, the smaller the pressure drop and blower power consumption are. So in the scope of the experiments, the water level height h = 6 cm is suitable.

3.2.3. Influences by temperature in humidifier

As the air flow rate is q_v = 2.5 m^3/h, the water level height is h = 6 cm, ambient air temperature is t_0 = 9°C, ambient air relative humidity is ϕ_0 = 40.2%, $t_w = t_3$ = 30–80°C, it was obtained by experiments that all the air relative humidity values in the outlet of the humidifier reached 100%.

According to the difference of moisture in air, the total humidification quantity m is calculated as shown in Fig. 8. In Fig. 8, as $t_w = t_3$ is increased from 70°C to 80°C, the slope of the curve increased quicker, the humidification quantity increased from 901 g/h to 1762.7 g/h, its growing rate is 95.6%. So it is concluded that the temperature of water and air in humidifier should be enhanced during bubbling humidification process as much as possible.

3.2.4. GOR and the cost of freshwater

3.2.4.1. GOR

For the system in Fig. 1, supposing the temperature of feed seawater t_5 is 20°C, and the quantity of emission brine is ignored. When the temperature of air entering the humidifier t_3 is taken 40°C, 50°C, 60°C, 70°C, 80°C separately:

For the dehumidifier, the energy balance equation [13] of heat releasing and heat absorbing is

$$-M_0\left[h_1-h_4+\left(d_1-d_4\right)h_{4w}\right]=c_{pw}\,M_w\left(t_7-t_6\right) \quad (3)$$

The freshwater generation rate is

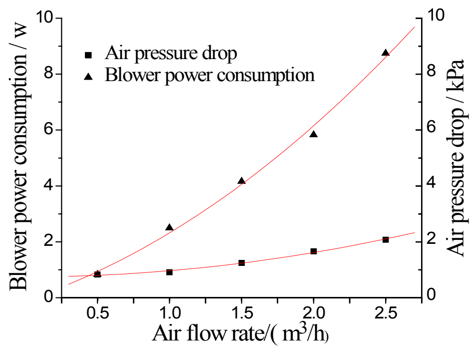

Fig. 6. Air pressure drop in humidifier and blower power consumption changed with air flow rate.

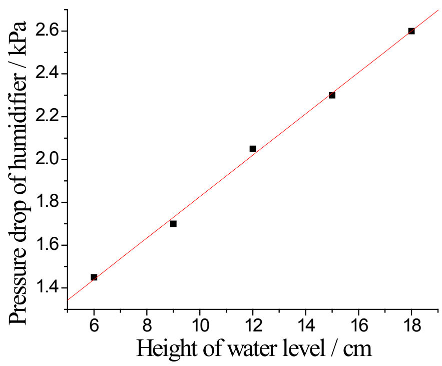

Fig. 7. Air pressure drop changed with the height of water level on sieve plate.

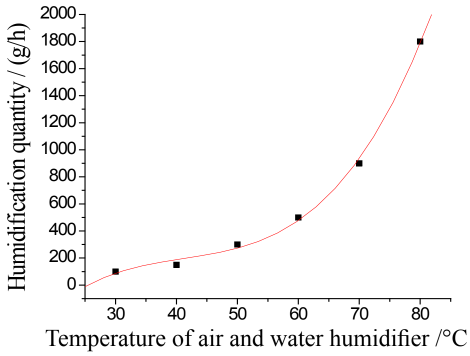

Fig. 8. Quantity of humidification changed with the temperature of air and water in the humidifier.

$$\text{GOR} = \frac{mr}{P+c_{pa}M_0\left(t_2-t_1\right)/\eta_0+c_{pw}m\left(t_9-t_8\right)/\eta_w+M_w\left(h_6-h_5\right)} \quad (4)$$

In the above two equations, h_1, h_4 are separately the dry air enthalpy in the outlet and inlet of the dehumidifier, kJ/kg; d_1 is the absolute water content in the outlet of dehumidifier, kg (water)/kg (air); c_{pa}, c_{pw} are separately the specific heat of air and water, J/(kg K); r is the latent heat of water evaporating, kJ/kg; M_w is seawater flow rate, kg/s; t_1, t_2 are separately the temperature of air in the inlet and outlet of air heater, °C; t_6, t_7, t_8, t_9 are separately the temperature of seawater in the inlet and outlet of the dehumidifier, in the inlet and outlet of water heater, °C; h_5, h_6 are separately the seawater enthalpy in the inlet and outlet of seawater pump, kJ/kg; η_0 is efficiency of air collector; η_w is efficiency of seawater collector.

Referencing the normal efficiency values of collectors, it is taken $\eta_0 = 0.45$, $\eta_w = 0.5$ in the calculation. The results show that in the outlet of the dehumidifier's cold end, there is only 1–4% amount of seawater used to compensate for the humidifier, and most of the seawater is discharged from the system (Fig. 1), that means 96–99% of heat absorbed by seawater from dehumidifier is exhausted. For the seawater pump conveyed a large amount of water and consumed a large amount of energy, which is taken about 67–75% of the whole energy consumed by the system, so the GOR of the primitive system is too low, which is shown in Fig. 10. Therefore the system can be improved (Fig. 9): according to the performance of the inorganic heat pipe, the pipes' cool-ends in the dehumidifier are immersed into a seawater pool which is large enough; a seawater pump is used to supply water for the humidifier to compensate evaporated and discharged water. On the other hand, the inorganic heat pipes of seawater collectors are inserted into the humidifier to heat seawater directly. Supposing the temperature of water in pool is 20°C as constant, and t_1 is 30°C, the GOR′ of this improved scheme is calculated as follows:

$$\mathrm{GOR}' = \frac{mr}{P + c_{pa}M_0\left(t_2 - t_1\right)/\eta_0 + c_{pw}m\left(t_w - t_6\right)/\eta_w + M'_w\left(h_6 - h_5\right)} \quad (5)$$

In this scheme, for the seawater flow rate M'_w conveyed by pump is the sum of water evaporated and brine discharged in the humidifier, the calculation results indicate that the power consumption item M'_w (h_6 – h_5) is only taken 2–3% of the whole energy consumed in Eq. (5), and it is much less than the primitive scheme, therefore the GOR′ is improved much more than GOR, which is shown in Fig. 10.

In Fig. 10, when tw is 80°C, GOR′ of the improved system is 2.3, which is more than GOR of the primitive system, that is 0.8.

According to [14,15], the GOR of the HD system with closed-air and open-water cycle is generally 1.2–4.5; the GOR of small and medium MSF systems is generally 3–6, the GOR of a big MSF system is more than 10; the GOR of an MED system is generally 9–10.

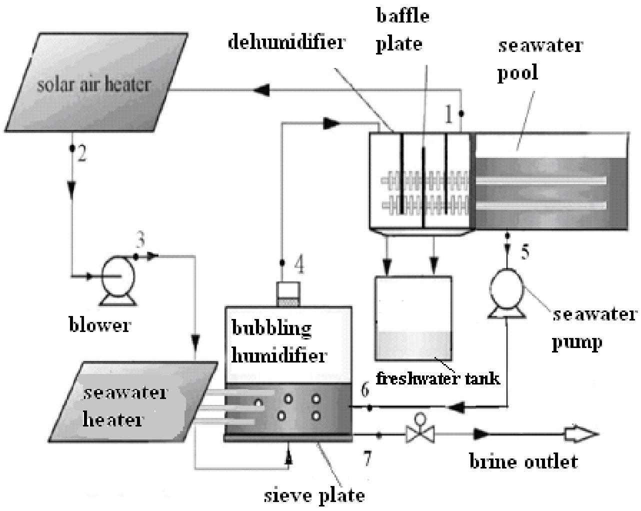

Fig. 9. Scheme of the improved solar HD desalination with bubbling humidifying.

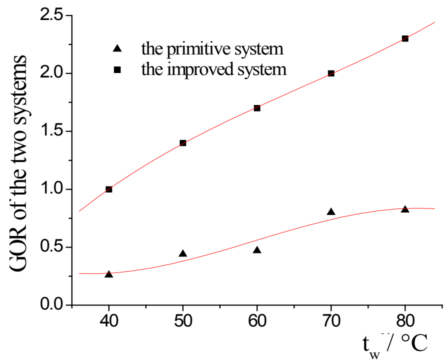

Fig. 10. GOR changed with the temperature of air and water in the humidifier.

3.2.4.2. Cost of freshwater production

Supposing the electricity price is 0.05 Yuan/degree, the cost of freshwater production of system in Fig. 1 is c; the one of system in Fig. 9 is c'. The calculation values of them are shown in Fig. 11.

It is known from Fig. 11 that the higher t_3 (= t_w) is, the less the cost is. For the system in Fig. 9, when t_3 increases from 40°C to 80°, the c' decreases from 66 Yuan/t to 12 Yuan/t. Therefore, it is concluded that the air and water should be heated by collectors as hot as possible to reduce the cost of freshwater.

4. Conclusion

The studies in the paper are focused on air humidifying experiments. The results show that bubbling hu-

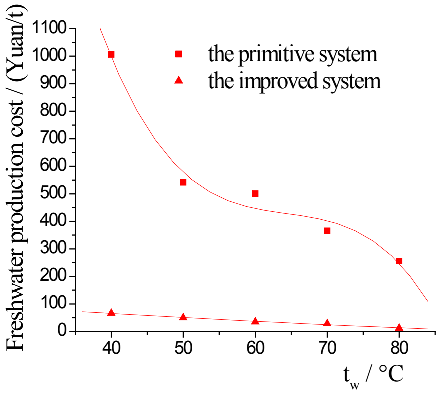

Fig. 11. Cost of fresh water production changed with temperature.

midification has higher efficiency and a simple structure of equipment. In the range of experiments, the relative humidity of air achieved is 100%. During the humidifying process, the pressure drop and the power consumption of the blower are increased with increasing the air flow rate; when enough humidifying capacity is assured, the lower the water level is, the smaller the pressure drop and blower power consumption are; when the temperature of air and water in the humidifier are risen, the humidification quantity and GOR is increased, meanwhile, the cost of freshwater production is decreased. After the way of air cooling and seawater pre-heating improved, the GOR′ of the system increased and the *c*′ decreased significantly. Therefore, improving the performance of the heat collectors or using high temperature collectors to heat air and water, and selecting suitable air flow rate and water level height, the freshwater production and the cost could be reduced greatly.

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