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Experimental Investigation of a Vertical Tubular Desalination Unit Using Humidification-Dehumidification Process*

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Abstract A vertical tubular desalination unit with shell and tube structure was built to perform humidification and dehumidification simultaneously on the tube and shell side of the column, respectively. The effects of several operating conditions on the productivity and thermal efficiency of the column were investigated. The results show that both the productivity and thermal efficiency of the column enhance with the elevation of the inlet water temperature. The flow rates of water and carrier gas both have optimal operating ranges, which are 10—30 $kg \cdot h^{-1}$ and 4—7 $kg \cdot h^{-1}$ for the present column, respectively. Meanwhile, the increase of external steam flow rate will promote the productivity of the column but reduce its thermal efficiency.

Keywords desalination, humidification, dehumidification

1 INTRODUCTION

The global limited and unevenly distributed fresh water resources have resulted in water shortage in many countries, including China, where fresh water is highly scarce in its north and northwest territory. Seawater and brackish water desalination have been proved to be able to provide reliable unconventional water sources, with a cumulative contracted capacity of 36000000 $m^3 \cdot d^{-1}$ by the end of year 2003[1]. As well known, conventional desalination processes such as multistage flash (MSF), multi-effect distillation (MED) and reverse osmosis (RO) have made big successes in the half past century. However, their requirements of high initial capital costs and permanent qualified maintenance limit their access to many developing countries. Further, it is not economical to employ them when the capacity is small, especially when there is a need to utilize solar energy or other renewable energy. As a result, small or medium scale water desalination units with good flexibility in capacity, moderate capital cost and possibility of using renewable energy are of great interest in regions like the northwest region and many islands of China as well as many other remote arid area across the world where the infrastructure is fairly low and the water demand is decentralized.

The humidification-dehumidification process is an interesting technique adapted for water desalination, in which air is used as a carrier gas to evaporate water from saline feed and to form fresh water by later condensation. It is thought to be the most promising process of solar desalination[2]. Most researchers[3—11] performed the humidification-dehumidification process in two separate columns, one for humidification and another for dehumidification, while the columns can be made in different structure with different materials. However, the separate structure increases the complexity of the system as well as the capital cost. Furthermore, in a separate humidification column the latent heat of evaporation for humidification can only come from the sensible heat of saline water fed to humidify the carrier gas, which limits the amount of the water vaporized resulting in a limited humidification effects. At the same time, large amounts of condensation latent heat in another column is lost or reused to preheat the feed saline water with low efficiency due to a large temperature difference in such a heat transfer process.

In recent years, Hamieh *et al.*[12,13] proposed an interesting desalination process known as dewvaporation, in which the humidification and dehumidification processes were simultaneously performed in one continuous contact tower. The tower was made up of multiple flat vertical chambers, in which the humidification and dehumidification processes were performed alternately.

In this work, the equipment with shell and tube structure is built to carry out desalination process by

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humidification-dehumidification cycle. And the preliminary experimental results will be presented.

2 EXPERIMENTAL

2.1 Equipment

To simultaneously implement the humidification and dehumidification process in unique equipment, a tubular experimental column with shell and tube structure was designed and constructed to evaluate the performance of the process. The tube bundle of the column is made up of 240 copper tubes by triangular pitch arrangement. The outside diameter, wall thickness and length of the copper tubes are 6 mm, 0.25 mm and 2.4 m, respectively. The tube bundle is put in a polypropylene (PP) shell with inner diameter of about 150 mm. The total effective heat transfer area of the column is about 9.6 m^2.

2.2 Process description

The experimental flow diagram is shown in Fig. 1. As the carrier gas, air at room temperature, is brought into the tube side of the column from the bottom by a wind blower and then flows upward on the tube side. The inside wall of the tube is wetted by preheated saline feed water, which is fed into each tube at the top of the column through overfall holes in the wall of the tube. As the air moves from the bottom to the top in the tubes, heat is transferred from the shell side to the tube side through the tube wall allowing the air to rise in temperature and evaporate water from the wetting saline water coating the inside tube wall. Concentrated brine leaves from the bottom of the column, while hot and nearly saturated humid air leaves the column from the top. Atmospheric pressure steam, generated by an electric steam generator, is added to the exit hot and humid air increasing its humidity and temperature a little. This hotter saturated air is sent back into the shell side of the column from the top

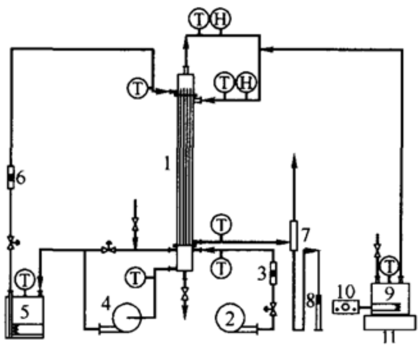

Figure 1 Schematic diagram of experimental set-up
1—desalination column; 2—wind blower;
3—gas flow meter; 4—water recycling pump;
5—water heating tank; 6—liquid flow meter;
7—gas/liquid separator; 8—measuring cylinder;
9—steam generator; 10—voltage regulator;
11—electronic balance

inlet. The shell side of the column, being slightly hotter than the tube side, allows the humid air to cool and get condensate, while the condensation latent heat is transferred to the tube side. Finally, water condensate and the dehumidified air leave the shell side of the column.

2.3 Instrumentation

The flow rates of air and saline water are measured by several rotameters. The flow rate of the fresh water is measured by hand with measuring cylinders. The temperature of the preheated saline water is controlled by a thermocontroller. Seven thermal resistances (Pt100) are placed at different locations to measure the temperature of air and saline water. The flow rate of the steam is recorded by an electronic balance (Sartorius, BL12) under the steam generator. Further, a data acquisition software is developed to collect all the temperatures and the balance readings in real time using a computer.

2.4 Parameters of performance

The water productivity and thermal efficiency are usually two important indexes to evaluate the equipment performance. In this paper, production density (PD), the water production per unit heat transfer area per unit time, is used to present the water productivity of the desalination unit. At the same time, the thermal efficiency is roughly evaluated by gained output ratio (GOR), which is here defined as, very similar to Hamieh *et al.*[13], the flow rate ratio of the fresh water and the atmospheric pressure steam added to the humid air.

However, it is worthy to note that the above definition of GOR can only partially evaluate the thermal efficiency of the desalination unit itself. As for the thermal efficiency of the whole system, it should be evaluated after the implementation of due heat recovery measures, but it will not be discussed in this paper.

3 RESULTS AND DISCUSSION

The effects of operating parameters on the performance of the desalination unit were studied, including water flow rate (L, kg·h^{-1}), inlet water temperature (T_w, ℃), carrier gas flow rate (G, kg·h^{-1}) and the flow rate of external steam added into the humid air (S, kg·h^{-1}).

3.1 Effect of water flow rate

Typical results to highlight the significant effect of feed water flow rate on the performance of the desalination column are shown in Fig. 2. Actually, water flow rate does have two opposite effects on the desalination process. On one hand, as the water flow rate increases, the wetting condition of inside tube wall is improved resulting in the enhancement of humidification effect of the carrier gas, especially at low flow rates, shown in Fig. 3. Here, the parameter *HD* (humidification degree), defined as the ratio of the humidity of the air exiting from the tube side to the saturated humidity of air at the same temperature as the inlet water, is used to quantitatively evaluate the humidification effect of the carrier gas by the water coating on the inside wall of the tubes. The improvement of humidification effect is the precondition of a good productivity.

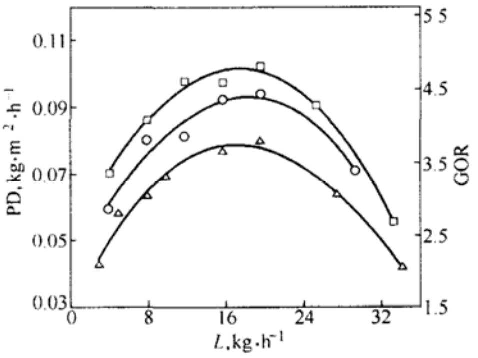

Figure 2 The effect of water flow rate on the column performance ($S = 0.18\,kg{\cdot}h^{-1}$)
□ $T_w = 78.5$℃, $G = 3.95\,kg{\cdot}h^{-1}$
○ $T_w = 83.7$℃, $G = 3.32\,kg{\cdot}h^{-1}$
△ $T_w = 83.1$℃, $G = 2.50\,kg{\cdot}h^{-1}$

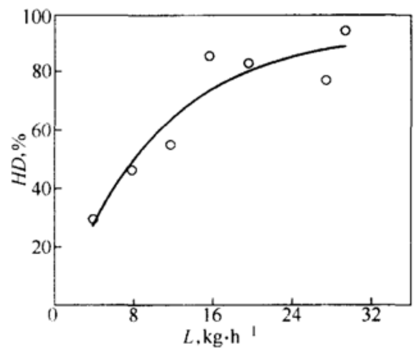

Figure 3 The effect of gas humidification as a function of water flow rate
($T_w = 83.7$℃, $G = 3.32\,kg{\cdot}h^{-1}$, $S = 0.18\,kg{\cdot}h^{-1}$)

On the other hand, the increasing water flow rate linearly increases the sensible heat the water carried, which leads to a smaller water temperature difference between the top and the bottom of the tube ($T_w - T_{w,out}$), as is clearly shown in Fig. 4. The reduction of the water temperature difference naturally means the decrease of the heat transfer driving force between the shell and the tube side of the column, and the reduction of the fresh water productivity.

The best performance shown in Fig. 2 is the result of the above two opposite effects. Such maximum values have also been observed experimentally by Nawayseh *et al.*[5]. The optimal range of the water flow rate is 10—30 $kg{\cdot}h^{-1}$ under our experimental conditions.

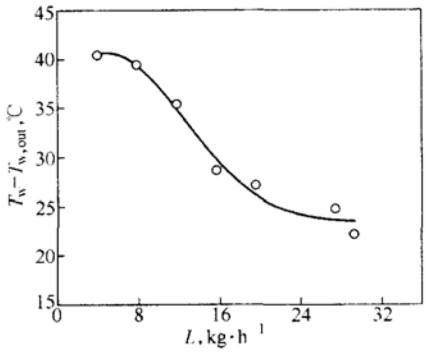

Figure 4 The difference of water temperature as a function of water flow rate
($T_w = 83.7$℃, $G = 3.32\,kg{\cdot}h^{-1}$, $S = 0.18\,kg{\cdot}h^{-1}$)

3.2 Effect of inlet water temperature

The humidification-dehumidification based desalination process is usually dependent on the operating temperature due to the high dependence of the saturated humidity of air on the temperature. In this work, the operating temperature of the process is mainly controlled by the inlet water temperature. Naturally, the elevation of the inlet water temperature increases the temperature and humidity of the carrier gas on the tube side and results in the enhancement of both PD and GOR of the column, as demonstrated in Fig. 5.

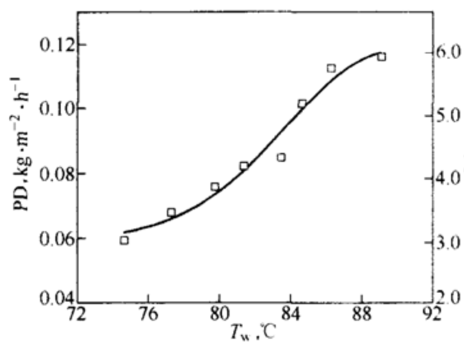

Figure 5 The effect of inlet water temperature on the column performance
($L = 19.6\,kg{\cdot}h^{-1}$, $G = 3.20\,kg{\cdot}h^{-1}$, $S = 0.18\,kg{\cdot}h^{-1}$)

However, the improvement of the column performance by inlet water temperature is not as much as the super linear temperature dependence of the saturated air humidity, because the humidification effect of carrier gas is not only determined by the inlet water temperature but also the heat transfer rate from the shell side to the tube side. As shown in Fig. 6, in the experiments *HD* actually decreases with the elevation of inlet water temperature, which weakened the improvement of performance of the column due to the increase of operating temperature.

Such temperature dependence implies that in an industrial desalination unit an operating temperature in the range of 70—90℃ is preferred, provided that the heat source is available and the materials are durable. However, improvement of the heat transfer efficiency is also a key factor for the enhancement of the process.

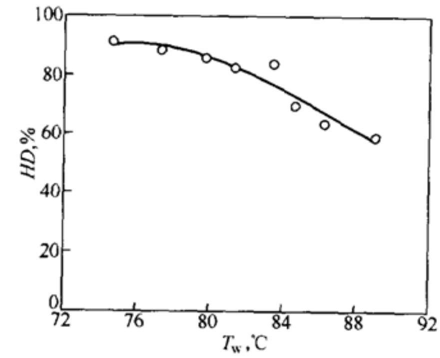

Figure 6 The effect of gas humidification as a function of inlet water temperature
($L = 19.6\,kg{\cdot}h^{-1}$, $G = 3.20\,kg{\cdot}h^{-1}$, $S = 0.18\,kg{\cdot}h^{-1}$)

3.3 Effect of air flow rate

In the humidification-dehumidification desalination process, the flowing air is the carrier of water vapor. Fig. 7 shows the effect of the air flow rate on the column performance. The tendency is similar to that of the water flow rate, with optimal values of PD and GOR.

Obviously, as the air flow rate increases, the amount of possible carrier of water vapor increases, and so do the gas velocity and heat transfer coefficient. Further, with the increase of the air flow rate, the water temperature difference increases, as shown in Fig. 8. These above factors favor the increase of the column productivity.

However, as shown in Fig. 9, the increase in carrier gas flow rate decreases the relative humidification effect, which naturally reduces the productivity and thermal efficiency of the column. The optimal range of the air flow rate is 4—7$kg{\cdot}h^{-1}$ for the present column.

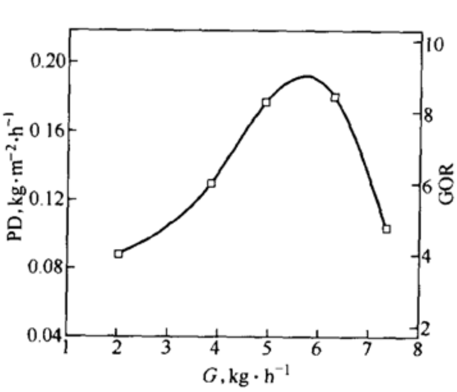

Figure 7 The effect of air flow rate on the column performance
($T_w = 86.1$℃, $L = 19.6\,kg{\cdot}h^{-1}$, $S = 0.21\,kg{\cdot}h^{-1}$)

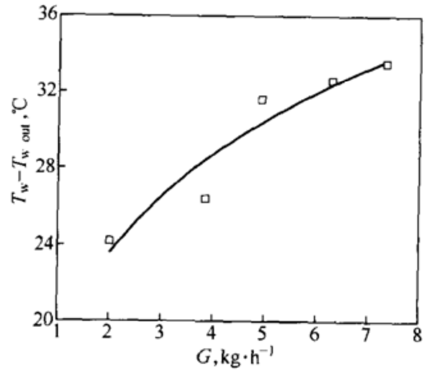

Figure 8 The difference of water temperature as a function of air flow rate
($T_w = 86.1$℃, $L = 19.6\,kg{\cdot}h^{-1}$, $S = 0.21\,kg{\cdot}h^{-1}$)

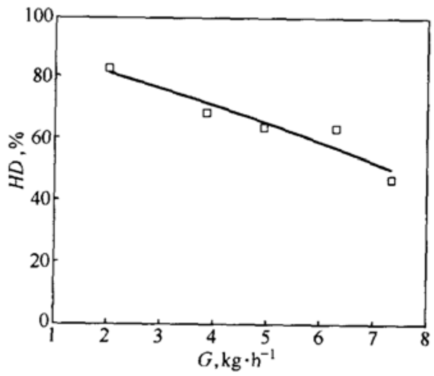

Figure 9 The effect of gas humidification as a function of air flow rate
($T_w = 86.1$℃, $L = 19.6\,kg{\cdot}h^{-1}$, $S = 0.21kg{\cdot}h^{-1}$)

3.4 Effect of external steam flow rate

Since the humidification and dehumidification were simultaneously performed in the tube and shell side of column, a temperature difference should be built between the shell and tube side. This can be implemented by adding a certain amount of external steam to the humid air exiting from the tube side. Obviously, the increase of the external steam flow rate leads to a rise in the temperature of the shell side as well as the heat transfer driving force between the shell and the tube side of the column. The productivity of the column increases consequently with the increase of external steam flow rate, as demonstrated in Fig. 10.

However, the GOR of the column decreases with the increase of flow rate of external steam added to the humid air, shown in Fig. 10. In view of a balance between the productivity and thermal efficiency, a steam flow rate in the range of 0.1—0.3$\,kg{\cdot}h^{-1}$ is suitable for the present column.

4 CONCLUSIONS

A vertical tubular unit with shell and tube structure was built to carry out the desalination process by simultaneous humidification and dehumidification.

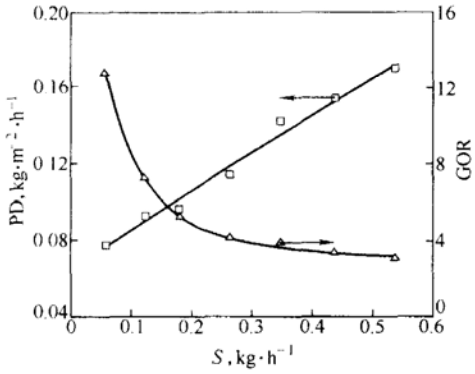

Figure 10 The effect of external steam flow rate on the column performance
(T_w = 86.5°C, L = 29.3 kg·h^{-1}, S = 4.04 kg·h^{-1})

The effects of several operational parameters on the performance of the desalination unit were experimentally investigated. The results show that it is preferred for the built column to operate with an inlet water temperature in the range of 70—90°C, while the flow rates of the water, the carrier gas and the external steam added to the humid air are in the ranges of 10—30 kg·h^{-1}, 4—7 kg·h^{-1} and 0.1—0.3 kg·h^{-1}, respectively. Furthermore, the wetting property of the inside tube wall and the heat transfer efficiency of the condensation process are the controlling factors for further improvement of the process, which are the next objectives of further investigation.

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