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Study on variation laws of parameters in air bubbling humidification process

Lixi Zhang*, Wenbin Chen, Hefei Zhang

School of Engine and Energy, Northwestern Polytechnical University, No. 127 West Youyi Road, Xi'an 710072, China
Tel. +86 029 88492440; Fax: +86 029 88495911; email: zhanglixi@nwpu.edu.cn

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ABSTRACT

In this paper, the variation laws of parameters in air bubbling humidification of solar desalination process are studied. The experimental system and experimental phenomenon are introduced. The parameters of remaining water quantity, humidifying capacity, and water temperature at any instantaneous time in humidifier are calculated and analyzed under different conditions by differential equations of energy balance and mass balance. The results show that the water temperature and the humidifying capacity are changed significantly with time increased in the initial humidifying stage. The change of these parameters depends on heat supplied to the water in the humidifier, whether the heat is higher or lower than the one absorbed by the water evaporating. If the supplied heat is higher, the water temperature and the humidifying capacity will increase in the initial humidifying stage; otherwise they will decrease or remain unchanged. After a certain time of humidifying, these parameters tend to be stable. The remaining water quantity in the humidifier is almost decreased in straight line with time increased in the heating states. The greater the heat provided to the humidifier, the faster the amount of water in it reduced, or the greater the humidifying capacity. These results are important to be used to predict the variation of parameters in bubbling humidifier, and benefit to guide the operation of air bubbling humidification process.

Keywords: Bubbling; Humidification; Solar desalination; Water temperature; Humidifying capacity

1. Introduction

Humidification–dehumidification desalination has many advantages over other methods, such as the simple structure of equipments, working at normal pressure, the flexible scale, available use of low-grade energy, and so on.

Now, the main methods to humidify air are single stage seawater spraying humidification and multistage one. To enhance the efficiency of spraying humidification, Dai and Zhang [1] used honeycombs made of paper as mass transfer mediums. EI-Agouz and Abugderah [2] firstly put a porous air pipe in seawater to humidify air by bubbling; its humidification efficiency was nearly 95%, corresponding to a multistage humidification [3,4].

A new solar desalination process with bubbling humidification was designed and studied by authors of this paper [5,6]. The experiments show that by

*Corresponding author.

single stage bubbling humidifier, the relative humidity of air can be rapidly reached 100% in about 30 s.

2. Solar desalination process

The flow chart of solar desalination process with bubbling humidification designed by authors is shown in Fig. 1, and the main working process of it is that: after the air and seawater are heated separately by solar collectors, they all enter the single stage bubbling humidifier. Air enters the sieve hole from the bottom of sieve plate, and is humidified by water on the plate in the bubbling process. Then the wet air flows into dehumidifier to be cooled, and a part of vapor in it is condensed into freshwater. Finally, the dry air flows into solar air heater to be heated again.

The main advantages of this process are that: the humidifier is operated at normal pressure; the structure of humidifier is simple, and it could be produced by nontoxic plastic material to resist the corrosion of seawater; the cost of humidifier is lower; the electric consumptions of the process are less; the efficiency of humidifying is higher, etc. This process is particularly suitable to be used in the small- or middle-scale desalination unit.

The main equipments in the process are as follows: the glass of evacuated tubular solar seawater collectors with inorganic heat pipe, double channels plate solar air heater, bubbling humidifier, dehumidifier, etc. The assistant equipments are blower, seawater pump, valves and pipes, and so on.

In experiments, it is found that the remaining water quantity, the humidifying capacity, and the water temperature in humidifier are all obviously changed in the initial humidifying stage. It needs to calculate their transient values to grasp the variation laws of these parameters in the humidifying process, and use the laws to guide the humidifying operation.

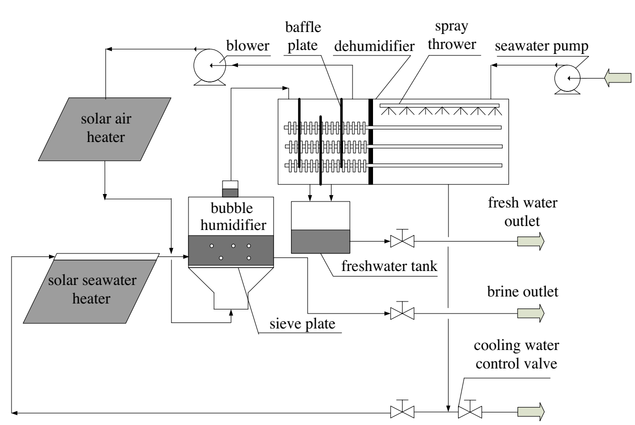

Fig. 1. Solar desalination process by bubbling humidification.

3. Experimental system and phenomenon

3.1. Experimental system

The test bed of bubbling humidification is shown in Fig. 2. It consists of single stage sieve plate bubbling humidifier, blower, air heater, and measuring instruments, such as pressure meters, flow meter, thermometers, and moisture meter.

3.2. Experimental phenomenon

The experiments of air bubbling humidification carried out at atmospheric pressure. The initial water temperature and the water level height in humidifier were $T_1 = 333\,\text{K}$ and $H = 1\,\text{cm}$. The temperature of air entering humidifier maintained in 333 K and the heat supplied to water in humidifier was $Q_s = 600\,\text{W}$, which provided by the electric heater instead of the solar collector. The experiments show that: when the humidifying starts about 60 s later, the water temperature rapidly decreased from 60 to 48℃. The experimental water temperatures, t_E, are changed with time. The data of t_E in different times are shown in Table 1.

4. Relations of water temperature and water quantity

To study the variation laws of parameters in bubbling humidification process, some calculations and analysis are carried out as follows.

Taking water in the humidifier as the research object, the states of air in the inlet and outlet of humidifier are expressed separately as node 1 and node 2, and they are shown in Fig. 3.

Here, M_0—air mass flow rate, kg/s; M_s—water quantity in humidifier, kg; m—humidifying capacity, kg/s; Q_s—heat supplied to water in humidifier by solar collector in unit time, W; T—node's temperature, K; and P—node's pressure, kPa.

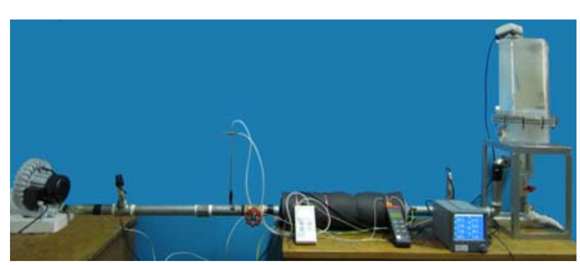

Fig. 2. Test bed of bubbling humidification.

Table 1
t_E changed with time

Time/s	30	60	90	120
t_E/℃	49.5	48.0	47.4	47.1

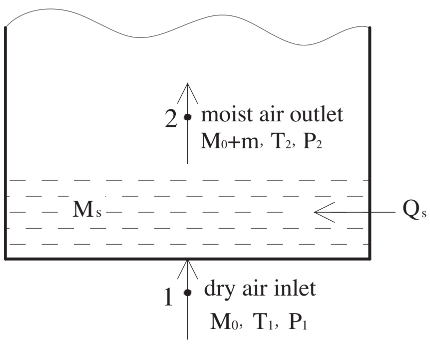

Fig. 3. Schematic diagram of energy balance in humidifier.

Supposing that the differences of kinetic energy and potential energy of air in the inlet and outlet of humidifier are ignored; the change of kinetic energy, the water potential energy, and the heat loss of the system are all neglected; the change of constant-volume specific heat with temperature is ignored; the heat supplied to water in humidifier by solar collectors in unit time is a constant.

Based on the above simplified hypothesis, the energy balance equation for the opened system of humidifier in infinitesimal time $d\theta$ can be expressed as [7]:

$$M_0 h_{1,a} d\theta - (M_0 + m_i) h^s_{2,i} d\theta + Q_s d\theta = d(\mathrm{MU})_{s,i} \tag{1}$$

Here, $h_{1,a}$—air specific enthalpy in the inlet of humidifier, kJ/kg; m_i—the humidifying capacity in infinitesimal time i, kg; $h^s_{2,i}$—specific enthalpy of saturated moist air in the outlet of humidifier in micro time section i, kJ/kg; $M_{s,i}$—remaining water quality in humidifier in the end of micro time section i, kJ/kg; and θ—time, s.

Taking 0 K as calculated standard, the air specific enthalpy in this state is considered as 0 kJ/kg, therefore Eq. (1) can be expressed as follows:

$$\begin{aligned} M_0 h_{1,a} d\theta - (M_0 + m_i) h^s_{2,i} d\theta + Q_s d\theta \\ = M_{s,i} dU_i + U_i dM_{s,i} \end{aligned} \tag{2}$$

Under the experimental conditions, the atmospheric pressure p_0 is 97.8 kPa, the range of humidifying temperature is 30–60℃. The air saturated moisture content d_s and specific enthalpy can be looked up in psychrometric chart under the different state of air dry-bulb temperatures T and p_0. The relations of d_s and $h^s_{2,i}$ changed with T can be, respectively, fitted into quadratic functions as follows:

$$d_s = 10542.6 - 70.172T + 0.11707T^2 \tag{3}$$

Here, d_s—saturated moisture content of air, g/kg (dry air) and T—absolute temperature of air, K.

$$h^s_{2,i} = 20977.5 - 143.1T_2 + 0.24465T_2^2 \tag{4}$$

In micro time section i, $M_{s,i\text{-}1}$ subtracting the evaporated water quantity equals $M_{s,i}$, so $M_{s,i}$ can be expressed by mass balance equation as follows:

$$M_{s,i} = M_{s,i-1} - \int_{\theta_{i-1}}^{\theta_i} m_i d\theta \tag{5}$$

In Eq. (5), as $M_{s,i-1}$ is a constant, so $dM_{s,i-1} = 0$, the differential form of Eq. (6) is simplified as:

$$dM_{s,i} = -m_i \cdot d\theta \tag{6}$$

During micro time section i, the evaporated water quantity in bubbling humidification process can be calculated by $m_i = M_0(d_{2,i} - d_0)$ Here $d_{2,i}$ is moisture content of air in the end of micro time section i, g/kg(dry). For $(d_{2,i} - d_0)$ can be regarded as a constant, and M_0 is not changed, so m_i can be regarded as a constant too. In the bubbling humidification experiments, the relative humidity of air can be reached to 100% quickly. In fact, $d_{2,i}$ is equal to the saturate moisture content d_s, and it can be calculated by Eq. (3). Taking Eqs. (5) and (6) into Eq. (2), then Eq. (2) can be expressed as:

$$\begin{aligned} [M_0 h_{1,a} - (M_0 + m_i) h^s_{2,i} + Q_s + m_i c_{v,w} T_2] d\theta \\ = (M_{s,i-1} - m_i \delta\theta) c_{v,w} dT_2 \end{aligned} \tag{7}$$

here, $\delta\theta = \theta_i - \theta_{i-1}$.

In the above equation, $c_{v,w}$—constant-volume specific heat of water, kJ/(kg·K) and θ_i—the end moment of micro time section i.

In Eq. (7), the second-order differential term $(-m_i c_{v,w} \delta\theta dT_2)$ is smaller than the other items, so it can be ignored. Making definite integration for this equation from time $\theta_{i\text{-}1}$ to θ_i, the water temperatures are correspondingly changed from $T_{2,i\text{-}1}$ to $T_{2,i}$. Thus, the integrated equation is expressed as:

$$\theta_i - \theta_{i-1} = \frac{M_{s,i-1} C_{v,w}}{m_i C_{v,w}} \ln \frac{M_0 h_{i,a} - (M_0 + m_i) h^s_{2,i} + m_i C_{v,w} T_{2,i}}{M_0 h_{1,a} - (M_0 + m_i) h^s_{2,i} + m_i C_{v,w} T_{2,i-1}} \tag{8}$$

Order:

$$J = \frac{M_0 h_{1,a} - (M_0 + m_i)h^s_{2,i} + Q_s}{m_i c_{v,w}} \tag{9}$$

$$G = \frac{M_{s,i-1} c_{v,w}}{m_i c_{v,w}} = \frac{M_{s,i-1}}{m_i} \tag{10}$$

Substituting J and G into Eq. (8), then it can be arranged as follows:

$$T_{2,i} = (J + T_{2,i-1})e^{\frac{\theta_i - \theta_{i-1}}{G}} - J \tag{11}$$

Here, $T_{2,i-1}$, $T_{2,i}$—water temperature in the end of micro time section $(i-1)$ and i, K and m_i—humidifying capacity in the time θ_i, kg.

According to above derivation relation, in any micro time section i, from its initial to final humidifying time, m_i, $T_{2,i}$, and $M_{s,i}$ can be calculated according to the process, as shown in Fig. 4.

In the calculations, there are assumed that:

(1) In any micro time section i, the temperature of air entering the humidifier T_1 remains constant, only $T_{2,i}$ is changed during humidifying process.
(2) In every micro time section, the temperature of humidified air is equal to the temperature of water in humidifier, they are both expressed as $T_{2,i}$.
(3) Humidity $d_{2,i}$ and enthalpy h_2,is of humidified air in the micro time section i are calculated by its initial temperature $T_{2,i\text{-}1}$.
(4) The initial water temperature $T_{2,0}$ is equal to T_1.
(5) The water temperature in the end of micro time section i is the initial one of micro time section $(i+1)$.

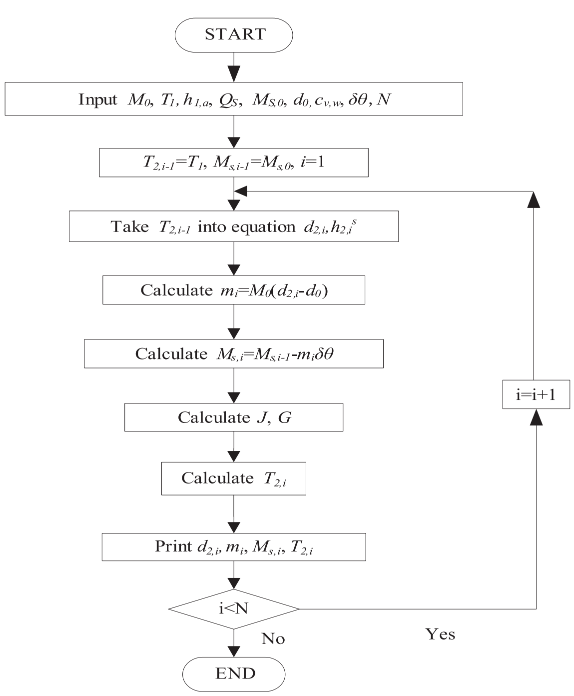

Fig. 4. Calculation flow chart of humidifying process.

5. Results and analysis under different conditions

According to the procedure in Fig. 4, m_i, $T_{2,i}$, and $M_{s,i}$ in different conditions are calculated and analyzed as follows.

5.1. Change of supplied heat

Supposing $T_1 = T_{2,0} = 60\,^\circ\mathrm{C} = 333\,\mathrm{K}$, the temperature of air entering the humidifier maintains constant. Taking the experimental data $M_0 = 5.834 \times 10^{-3}\,\mathrm{kg/s}$, $h_{1,a} = 68.2\,\mathrm{kJ/kg}$, $M_{s,0} = 0.307\,\mathrm{kg}$, $d_0 = 3.127 \times 10^{-3}\,\mathrm{kg/kg}$, $c_{v,w} = 3.9736\,\mathrm{kJ/(kg{\cdot}K)}$, $H = 1\,\mathrm{cm}$, then taking $Q_s = 400$, 600, 800, and 1000 W separately, the calculated relationships of $M_{s,i}$, $T_{2,i}$, and m_i that changed with time are shown in Figs. 5–7.

In Fig. 5, the curves in it are similar to that in Fig. 6. If the heat supplied to water is less than the heat absorbed by water evaporating, $T_{2,i}$ would be rapidly reduced at the beginning of humidifying; meanwhile, m_i would be reduced as $T_{2,i}$ decreased. The larger the Q_s is, the slower the m_i and the $T_{2,i}$ decrease, the less time they needed to reach their stable states, and the larger the values of m_i and the $T_{2,i}$ at their stable states.

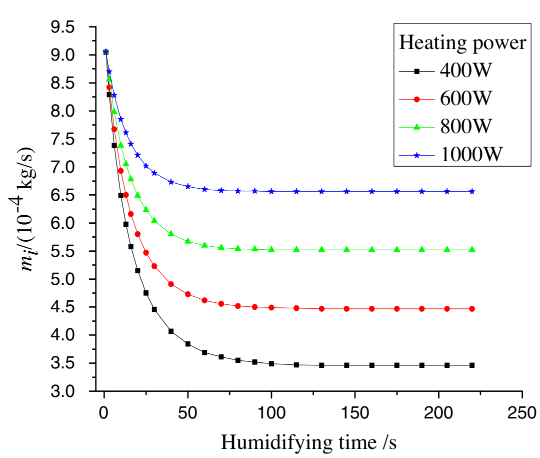

Fig. 5. m_i changed with time ($T_1 = 60\,^\circ\mathrm{C}$).

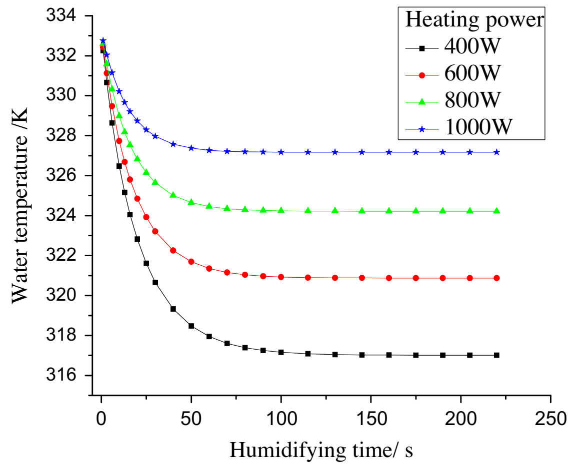

Fig. 6. Water temperature changed with time ($T_1 = 60$℃).

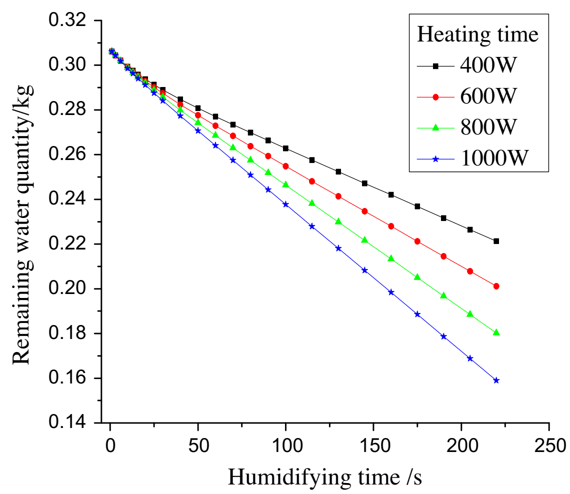

Fig. 7. Water quantity changed with time ($T_1 = 60$℃).

Fig. 7 shows that the values of $M_{s,i}$ are decreased nearly by linear as humidifying time increased under different values of Q_s; the larger the Q_s is, the faster the M_s decreases, it means that the more quantity of freshwater would be produced.

5.2. Change of initial humidifying temperature

As above conditions remain constant ($H = 1$ cm, $M_{s,0} = 0.307$ kg), and the initial humidifying temperature T_1 is taken 50 and 40℃ separately, the relationships of m_i, $T_{2,i}$, and $M_{s,i}$ changed with time are shown in Figs. 8–12.

As $T_1 = T_{2,0} = 323$ K $= 50$℃, the relationships of m_i and $T_{2,i}$ changed with time are shown in Figs. 8 and 9, and the curve shapes in Figs. 8 and 9 are different from the ones in Figs. 5 and 6. When Q_s is 1000 W,

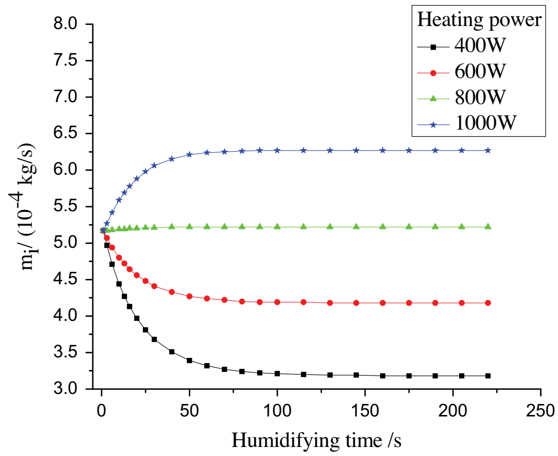

Fig. 8. m_i changed with time ($T_1 = 50$℃).

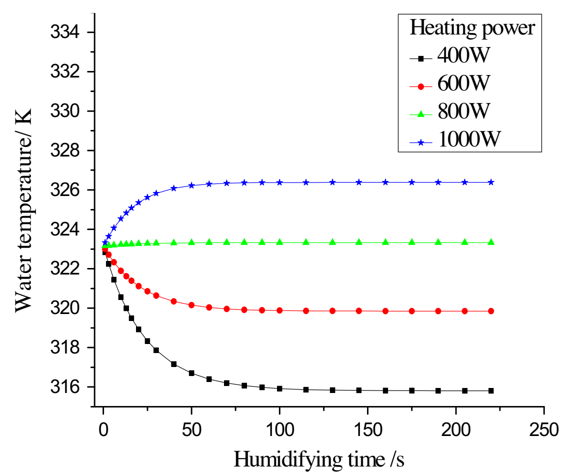

Fig. 9. Water temperature changed with time ($T_1 = 50$℃).

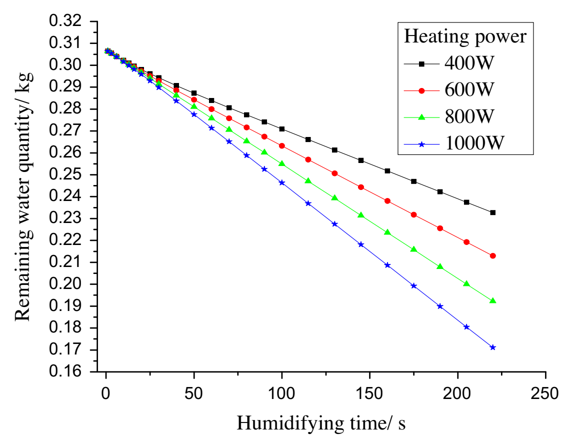

Fig. 10. Water quantity changed with time ($T_1 = 50$℃).

which is larger than the heat absorbed by water evaporating, $T_{2,i}$ and m_i would be rapidly increased in the initial stage of humidifying, after more than 60 s, $T_{2,i}$ and m_i tend to be stable; when Q_s is 800 W, which is almost equal to the heat absorbed by water evaporating, T_2 and m_i are almost unchanged; and when Q_s is less than 800 W, which is less than the heat absorbed by water evaporating, $T_{2,i}$ and m_i would be rapidly decreased in the initial stage of humidifying. The lower the Q_s is, the faster the $T_{2,i}$ and the m_i decrease, the more time the $T_{2,i}$ and the m_i need to reach the stable states, and the lower values of $T_{2,i}$ and m_i in the stable state. The curves of $M_{s,i}$ changed with time in above different conditions are shown in Fig. 10. They are similar to the ones shown in Fig. 7.

As $T_1 = 40$℃, and Q_s is more than the heat absorbed by water evaporating, the water temperature $T_{2,i}$ changing with humidifying time is shown in Fig. 11, these curve shapes are similar to the ones shown in Fig. 9 as Q_s equals to 1000 W. The regulation of $M_{s,i}$ changed with time in Fig. 12 is also similar to that in Fig. 7.

In humidifying process, under the different T_1 and the different supplied heat Q_s, the calculation results of $T_{2,i}$ and m_i in stable states are shown separately in Tables 2 and 3.

They indicate that the higher the T_1 and the Q_s, the higher the $T_{2,i}$ and the m_i at stable states, that means the more the water output.

When $T_1 = T_{2,0} = 333$ K, and $Q_s = 1000$ W, m_i in stable state reaches maximum.

When Q_s is 1000 W, $T_1 = T_{2,0} = 60$ $= 333$ K, and the initial water quantity in humidifier is 0.307 kg ($H = 1$ cm), the calculation results show that the water in humidifier would be completely vaporized in the time of 458 s.

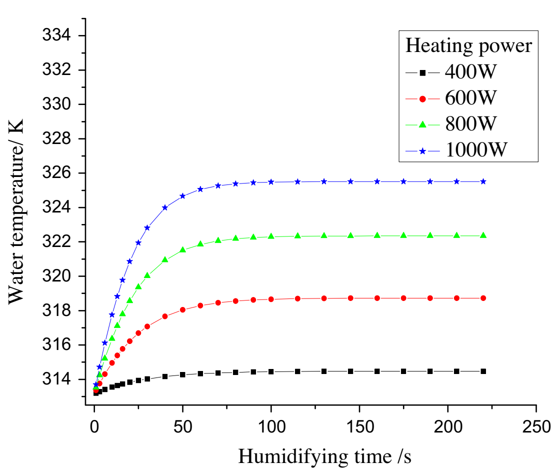

Fig. 11. Water temperature changed with time ($T_1 = 40$℃).

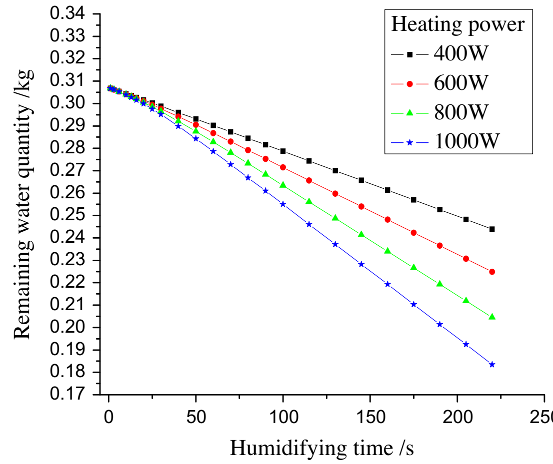

Fig. 12. Water quantity changed with time ($T_1 = 40$℃).

Table 2
Water temperature in stable state/K

T_1/K	333	323	313	303
1000 W	327.17	326.38	325.51	324.61
800 W	324.22	323.33	322.35	321.33
600 W	320.88	319.85	318.72	317.54
400 W	317.01	315.82	314.47	313.05

Table 3
Humidifying capacity in stable state/($\times 10^{-4}$ kg/s)

T_1/K	333	323	313	303
1000 W	6.65	6.27	5.96	5.65
800 W	5.52	5.22	4.91	4.60
600 W	4.47	4.18	3.87	3.58
400 W	3.46	3.18	2.90	2.63

Table 4
Time needed for all water vaporized

T_1/K	303	313	323	333	343
Time/s	563	526	490	458	429

As the other conditions same as above, only changing the different initial humidifying temperatures ($T_1 = T_{2,0}$), the time needed for all water (0.307 kg) vaporized in humidifier are calculated and shown in Table 4. It indicates that the lower the T_1, the more the time needed for the same quantity water to evaporate.

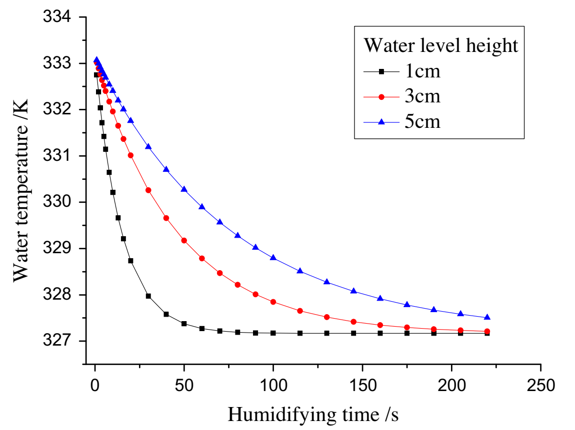

Fig. 13. Water temperature changed with time ($T_1 = 50$℃).

5.3. Change of initial water quantity in humidifier

As $T_1 = T_{2,0} = 323\,K = 50$℃, $Q_s = 1000\,W$ and other conditions unchanged, the initial water quantity in humidifier is taken as $M_{s,0} = 0.921\,kg$ and $1.535\,kg$ separately (equivalent to $H = 3\,cm$, $5\,cm$), $T_{2,i}$ and $M_{s,i}$ are calculated correspondingly, the results of them are shown in Figs. 13 and 14.

From Fig. 13, it is known that the less the Q_s than the heat absorbed by water evaporating, the more the $M_{s,0}$, and the longer the time it needs for water in humidifier to achieve the stable state. If the humidifying time is long enough, the water temperature in different $M_{s,0}$ would tend to be steady and uniform, no matter how much the $M_{s,0}$ is. Fig. 14 shows that the remaining water quantity $M_{s,i}$ would be decreased with humidifying time increased by linear.

Above conclusions are obtained under the hypothesis that there are no heat loss in humidifier. Actually, there are some heat loss in humidifying process, the actual values of $T_{2,i}$ and m_i are smaller than the theoretical ones, and the water quantity would be decreased more slowly than the theoretical one.

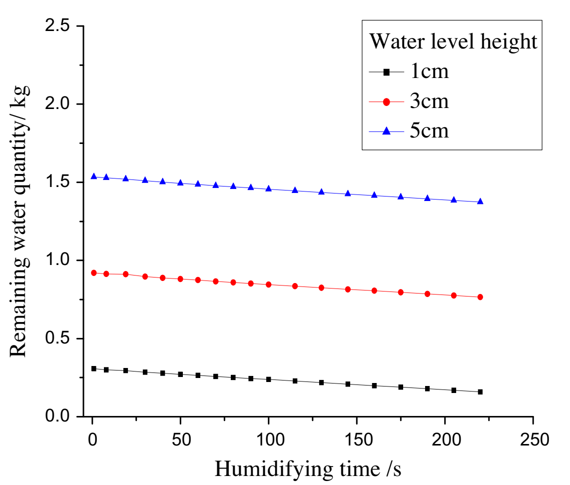

Fig. 14. Water quantity changed with time ($T_1 = 50$℃).

Table 5
t_E and t_C changed with time

Time/s	30	60	90	120
t_E/℃	49.5	48.0	47.4	47.1
t_C/℃	50.0	48.3	47.7	47.6

5.4. Comparisons of experimental values with calculated ones

In the conditions of $T_1 = 333\,K$, $H = 1\,cm$, $Q_s = 600\,W$, and the temperature of air entering the humidifier maintained in 333 K, the experimental water temperatures t_E and the calculated ones t_C in humidifier are all shown in Table 5. It expresses that: after 60 s of humidifying, the water temperature rapidly decreases from 60 to 48℃; the experimental results are less than the calculated ones, for the heat loss are real existed in the experiments, but they are not taken into account in the calculations.

6. Conclusion

In this paper, the parameters of remaining water quantity, the instantaneous humidifying capacity and the water temperature in humidifier in unsteady states are calculated and analyzed by differential equations of energy balance and mass balance. It concludes that:

(1) In the conditions of the heat supplied to water is less than the heat absorbed by water evaporating, $T_{2,i}$ and m_i would be rapidly reduced at the beginning of humidifying process; the more the Q_s is, the slower the m_i and the $T_{2,i}$ decrease, the shorter the time it needed for water to reach the stable state, and the larger of m_i and $T_{2,i}$ at the stable state. In different Q_s, the remaining water quantity is decreased by linear as humidifying time increased.

(2) The higher the T_1 and Q_s, the higher the $T_{2,i}$ and the m_i, and the greater the water output. When $T_1 = T_{2,0} = 333\,K$, $H = 1\,cm$, and $Q_s = 1000\,W$, the humidifying capacity in stable state is $6.65 \times 10^{-4}\,kg/s$.

(3) When the supplied heat is less than the heat absorbed by water evaporating, the more the initial water quantity ($M_{s,0}$) in humidifier is, the more the time needed for water to achieve stable state.

Nomenclature

$c_{v,w}$ – constant-volume specific heat of water, kJ/(kg·K)
d_s – saturated moisture content of air, g/kg (dry air)
G – algebraic expression
$h_{1,a}$ – air specific enthalpy in the inlet of humidifier, kJ/kg
$h^s_{2,i}$ – specific enthalpy of saturated air in the outlet; of humidifier in infinitesimal time i, kJ/kg
H – water level on the sieve plate, m
J – algebraic expression
m_i – humidifying capacity in the micro time section i, kg
M_0 – air mass flow rate, kg/s
M_s – water quantity in humidifier, kg
$M_{s,i}$ – the remaining water quality in humidifier in the end of infinitesimal time i, kg
P_0 – the atmospheric pressure, kPa
P_1 – initial air pressure, kPa
P_2 – moist air pressure in the outlet of humidifier, kPa
Q_s – heat supplied to water by solar collector in unit time, kJ/s
t_C – calculated temperature, K
t_E – experimental water temperature, K
T – absolute temperature of air, K
T_1 – initial water temperature in humidifier, K
T_2 – moist air temperature in the outlet of humidifier, K
$T_{2,i}$ – water temperature in the end of micro time section i, K
I – the number of micro time section
θ – time, s
θ_i – the end moment of micro time section, s

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