Study on the Effect of Porosity on Countercurrent Hollow Fiber Membrane Humidification System

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Research Article

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Abstract

The effect of porosity on the humidification efficiency of countercurrent hollow fiber membrane humidification system was investigated by using numerical simulation method to study polypropylene (PP) porous fiber membrane material. Firstly, the correctness of the numerical model was verified by experiments, and then the influence of porous fiber membrane material on humidification efficiency was further explored by changing the porosity of the model. The simulation results show that the humidification capacity and efficiency of the humidification component increase with the increase of porosity. When the porosity is between 0.35-0.8, the humidification capacity and efficiency increase significantly. However, when the porosity is between 0.8-0.9, although the humidification amount and humidification efficiency value are high, the increment is not obvious, and the porosity of the fiber film is inversely proportional to the support strength of the film, and the larger the porosity is, the shorter the service life of the film material is. Therefore, it is suggested to design the porosity of polypropylene (PP) film material between 0.65 and 0.8. It can not only ensure the high humidification capacity and efficiency of the fiber membrane, but also prolong the service life of the membrane.

1. Introduction

Indoor air humidity is not only directly related to human comfort but also closely related to human body health. When the humidity is too low or too high, it will lead to the reduction of human comfort, and even cause dry mouth, eye dryness, respiratory tract infection and other diseases. In an industrial production environment, the scientific regulation of humidity control in a reasonable range of humidity also has a very important position. In electronic components, food processing, wood furniture, agricultural production and other industries. If the humidity is not regulated, the product quality will be seriously affected, so that the product can not be used normally and cause unnecessary economic losses. Accordingly, it is very important to adjust indoor humidity reasonably.

There are cooling dehumidification, liquid absorption dehumidification, solid adsorption dehumidification, membrane dehumidification, membrane liquid dehumidification and so on[1], Membrane liquid dehumidification is a new indirect contact dehumidification technology. The combination of membrane separation technology and liquid dehumidification technology can effectively prevent direct contact between high humidity air and desiccant. This eliminates the possibility of the desiccant contaminating the air with each other. Water vapor is dehumidified through the membrane driven by the partial pressure of water vapor on both sides of the membrane[2].

Dehumidifying separation membrane material is an important part of determining dehumidifying efficiency. The selectivity, permeability and structure of the membrane are the key factors affecting the performance of the membrane material. It is of practical significance to study the characteristics of membrane materials for promoting the development of membrane liquid dehumidification technology. The selectivity of membrane is that compared with other substances, membrane has a higher transmittance to water vapor, and other substances have a smaller transmittance. Membrane permeability refers to the heat and mass transfer process of water vapor through the ability of the film, can be reflected in the amount of water vapor through the film in unit time unit area. Su[3] et al. studied the influence of permeability on the flux of the gas-liquid contactor membrane, and the results showed that the separation membrane with higher permeability had less resistance in the process of water vapor transfer, and higher water vapor transmembrane flux, which could carry out effective and high-quality mass transfer.

In addition, porosity is the determining factor affecting the permeability of membrane materials. Porosity refers to the ratio of the volume of pores in the dehumidifying film material to the total volume of the film material. The porosity is proportional to the diffusion flux and inversely proportional to the mechanical strength that the film material can withstand. Therefore, the service life of the film material should be considered when considering increasing the porosity. The dehumidification efficiency of the membrane liquid dehumidifier used by Liu[4] et al is significantly increased when the porosity of the fiber membrane changes from 0.1-0.5. To sum up, this paper established a hollow fiber membrane materials humidification component physical model, then the correctness of the numerical model was validated by experiment. To add wet film under different porosity components are simulated, and puts forward the porous polypropylene (PP) fiber membrane materials and reasonable range of porosity, for the development of fiber membrane material after lay the theory foundation.

2. Numerical Simulation

2.1 Theoretical basis

When the countercurrent hollow fiber membrane humidification, water vapor molecules through the gap between the fibers from the solution side to the gas measurement. Is a particularly complex heat and mass transfer process. After years of research, the process of heat and mass transfer is simplified to the heat and water vapor exchange in three areas: air-membrane, membrane-membrane and membrane-solution. The heat on both sides of the gas and liquid is mainly transferred by thermal convection, and the heat transfer coefficient is determined by nusselt number, thermal conductivity and characteristic length[5−7], As shown in Eq. (1); The heat transfer form in the film consists of two parts: heat conduction and latent heat of vaporization[8]. The calculation formula of heat transfer coefficient as written in Eq. (2).

$$h_i = \frac{N_{ui} k_i}{d_i} \quad (1)$$

$$h_{\mathrm{m}} = h_a + \frac{N \Delta h}{\Delta T_m} \quad (2)$$

To sum up, the total heat transfer coefficient can be expressed as:

$$\frac{1}{h} = \frac{1}{h_1} + \frac{1}{h_m} + \frac{1}{h_2} \quad (3)$$

During humidification, mass transfer and heat transfer occur simultaneously in three regions, The mass transfer coefficient on both sides of the gas and liquid is determined by Sherwood number, mass diffusion coefficient and characteristic length[6−7], as written in Eq. (4). In the fiber membrane, the pore size is generally on the order of μm, and the free motion range of water vapor molecules is generally less than the pore size.The value transfer coefficient in the membrane is obtained by Fick's law[9], and the calculation formula is shown in Eq. (5).

$$g_i = \frac{S_{hi} Ds_i}{di} \tag{4}$$

$$g_m = \frac{D_m \varepsilon}{\delta_\tau} \tag{5}$$

In conclusion, the total mass transfer coefficient can be expressed as:

$$\frac{1}{g} = \frac{1}{g_1} + \frac{1}{g_m} + \frac{1}{g_2 H} \tag{6}$$

2.2 Assumptions

In the countercurrent hollow fiber membrane humidifier, the heat and mass transfer process is complex and easily affected by the external environment. In order to ensure the accuracy of the experiment and simulation, the following assumptions are made in this paper:

(1) All flows are laminar flows;
(2) Air is an ideal gaseous mixture of water vapor and dry air;
(3) The capacitive effect of heat and mass transfer is ignored in the process of humidification because the porous fiber membrane is homogeneous and homogeneous;
(4) Air and solution are evenly distributed in their respective channels, and the fluid is at the full development stage;
(5) The whole humidifier component is adiabatic with the surrounding environment, and heat transfer only occurs inside;
(6) Ignore the heat and mass transfer generated along the direction of flow;
(7) The fiber membrane is a porous medium;
(8) The liquid is Newtonian fluid;
(9) Heat and mass transfer are steady-state.

2.3 Physical model

In order to further discuss the influence of porosity on humidification efficiency, a physical model of countercurrent hollow fiber membrane humidification component was established according to Table 1 parameters, as shown in Fig. 1. It is mainly composed of shell and hollow fiber tube. During the humidification process, air enters through the lower entrance of shell and flows out through the upper exit, and the solution enters from the right side of the fiber tube and exits from the left side, thus forming a reverse flow with air to complete humidification.

Table 1 parameters of the membrane module

Component parameters	symbol	data	unit
Membrane assembly diameter	D	56	mm
Length of membrane assembly	L	265	mm
Inner diameter of hollow fiber membrane tube	di	0.25	mm
Outer diameter of hollow fiber membrane tube	do	0.4	mm
Pore size	s	0.2	μm
Wall thickness	σ	50	μm
Hollow fiber membrane tube porosity		0.45	
Effective length	Lm	225	mm
Length of shell inlet and outlet pipe	Ls	20	mm
Shell inlet and outlet diameter	dw	13	mm
Component fill rate	χ	0.5	-

Porosity directly affects the flux of the membrane material in the humidification process and the support strength of the membrane material. The greater the porosity, the greater the membrane flux and the increase of the appropriate amount, but the porosity is inversely proportional to the support strength of the membrane, too large porosity will make the support of the fiber membrane smaller and shorten the service life. Generally, the porosity of porous fiber membrane is between 0.35 and 0.9[10]. Therefore, this paper selects 6 common fiber membrane materials for simulation under 5 working conditions as shown in Table 2, and sets the porosity values as 0.35, 0.45, 0.65, 0.8, 0.85 and 0.9respectively, for further discussion.

Table 2
air condition

Air condition	**Condition 1**	**Condition 2**	**Condition 3**	**Condition 4**	**Condition 5**
Air flow rate(kg/h)	2.96	5.92	8.88	11.84	14.80
Liquid flow rate(kg/h)	7.00	7.00	7.00	7.00	7.00
temperature at the air inlet(K)	298	298	298	298	298
temperature at the inlet of the liquid(K)	290	290	290	290	290
Moisture content at the air inlet(g/kg)	4.9	4.9	4.9	4.9	4.9

2.4 Boundary conditions

The solution is completed in Fluent16.0, and the related parameters are set as follows:

Table 3

Parameter Settings of the numerical simulation[8]

parameter	set
Flowing model	Laminar
Fluid	Air, water, water vapor
Solid	Porous membrane material, porosity 0.45
Inlet of air	Veloctiy-inlet Relative humidity 25% Inlet temperature 25°C Moisture content 4.9g/kg
Outlet of air	Pressure-out
Inlet of liquid	Veloctiy-inlet
Out of liquid	Pressure-out

3. Results And Discussion

3.1 Experimental verification

In order to ensure the correctness of the numerical model, five types of counter-current hollow fiber membrane humidifier compone

nts were firstly simulated using the numerical model, and the temperature and humidity of the air outlet side under simulated conditions were obtained as shown in Table 4 Then, an experimental platform was established according to the relevant data shown in Table 1 Repeat the five working conditions shown in Table 2 to obtain the temperature and humidity data at the air outlet side under the experimental working conditions, as shown in Table 4.

Table 4 Data statistics

Air condition	Working condition of simulated		Experimental condition	
	Temperature at the air inlet K	Humidity at the air inlet g/kg	Temperature at the air outlet K	Humidity at the air outlet g/kg
Condition 1	294.8	11.4	295.1	11.1
Condition 2	295.5	10.9	295.8	10.8
Condition 3	296.2	10.4	296.1	10.6
Condition 4	296.5	10.3	296.3	10.5
Condition 5	297.0	10.2	296.5	10.1

By comparing the experimental and simulated values in Fig. 2 and Fig. 3, it can be seen that there is little difference between the numerical simulation results and the experimental test results. After calculation, it is found that the error of the two results is within 10%. And when the air flow gradually increases, the temperature at the air outlet side increases and the moisture content decreases, and the variation trend of the two results is consistent. This verifies the correctness of the numerical simulation and indicates that the model can be used for further discussion.

3.2 Results and analysis

Fig. 4 shows the variation of air outlet temperature with air flow under five working conditions with different porosity. It can be seen in 6 porosity conditions, the air outlet temperature increases with the increase of air flow. This is because the increase of air flow reduces the contact time with the fiber film, which leads to shorter heat transfer time. Under the condition of a certain air inlet flow rate of 2.96kg/h, the air outlet temperature distribution cloud diagram of the porosity of 6 fiber films is shown in Fig. 5. It can be seen from the figure that with the increase of porosity, the temperature at the air outlet gradually decreases. This is because the increase of porosity enhances the heat transfer efficiency on both sides of the film and transfers more heat from the air to the solution, leading to lower and lower temperature at the air outlet.

In addition, it can also be seen in Fig. 4 that under each constant flow condition, when the porosity changes from 0.35-0.8 an obvious temperature difference of about 2K at the air outlet side. However, when the porosity changes from 0.8-0.9 the temperature difference at the air outlet side is only about 0.2K with no significant temperature change. This phenomenon indicates that when the porosity is between 0.35-0.8, the heat transfer effect of hollow fiber membrane humidifier module is significantly enhanced. However, when the porosity is between 0.8-0.9, the increase of porosity has no obvious effect on the heat transfer enhancement of humidifier components.

Fig. 6 shows the variation of air outlet moisture content with air flow under five working conditions with different porosity. It can be seen that under the conditions of six porosity, the moisture content at the air outlet decreases with the increase of air flow rate. On the one hand, the increase of air flow rate reduces the driving force of mass transfer on both sides of the film. On the other hand, the porosity controls the water vapor flux across the membrane to a certain extent, and the moisture content decreases with the increase of air flow. Under the condition that the air inlet flow rate is 2.96 kg/h at a certain working condition, the cloud diagram of water vapor mass fraction distribution at the air outlet of 6 kinds of fiber membrane porosity is shown in Fig. 7. It can be seen that with the gradual increase of porosity, more and more water vapor molecules are found at the air outlet, which also indicates that the air moisture content is getting higher and higher. This is because the increase of porosity enhances the mass transfer process and increases the transmembrane flux, so the moisture content at the air outlet is increased.

In addition, as shown in Fig. 6, under each constant air flow condition, when the porosity changes from 0.35-0.8, the moisture content at the air outlet side increases significantly by about 1.5g/kg, while when the porosity changes from 0.8-0.9, the moisture content at the air outlet side does not increase significantly. Even when the porosity of working conditions 1 and 5 changes from 0.8-0.85, the moisture content does not increase.

Fig. 8 shows the variation of humidification capacity and humidification efficiency with porosity under constant air flow condition. It can be seen that when the porosity increases from 0.35 to 0.8, the humidification capacity of the fiber membrane module increases from 0.0193 to 0.0242kg/h, and the humidification efficiency increases from 53.3–66.7%. The humidification capacity and humidification efficiency increase obviously with the increase of porosity. When the porosity increases from 0.8 to 0.85, the addition amount of the fiber membrane humidifier and the humidification efficiency have little change under the first working condition, which indicates that the increase of the porosity has no obvious effect on the improvement of the addition amount and the humidification efficiency. When the porosity is greater than 0.8 and less than 0.9, the humidification capacity and humidification efficiency of the fiber membrane module increase from 0.0242 to 0.0248kg/h and from 66.7–67.6% respectively. Although the increase of porosity also increases the humidification capacity and driving efficiency, the increase of porosity has no significant effect on the increase of humidification capacity and humidification efficiency compared with the increase of porosity from 0.35 to 0.8. This result is obtained by analyzing the addition amount and humidification efficiency under all working conditions, so it is not described here too much. In conclusion, when the porosity is between 0.35-0.8, the heat and mass transfer effect of porous fiber membrane material is the best. Although when the porosity is greater than 0.8, there are also high adding amount and humidification efficiency, but too much porosity will affect the supporting strength of the membrane material and further affect the service life of the membrane material. Therefore, it is suggested that the porosity of PP porous fiber membrane material should be controlled between 0.65 and 0.8, which can guarantee the humidification efficiency of the membrane material and prolong the service life of the membrane material, which is the best porosity range.

4. Conclusion

Through the study of the performance of hollow fiber membrane humidification system made of porous polypropylene (PP) material, the following conclusions are drawn:

(1)Under the condition of constant porosity, the increase of air flow shortensthe contact time between air and solution per unit volume, leading to the decrease of heat transfer effect, and the air outlet side temperature increases with the increase of air flow; Similarly, the increase of air flow leads to the decrease of moisture content at the air outlet side, which reduces the humidification efficiency.

(2)Under constant flow condition, the air outlet temperature decreases with the increase of porosity, indicating that porosity strengthens the heat transfer effect of hollow fiber membrane humidifier. The moisture content at the air outlet side increases with the increase of porosity, indicating that the greater the porosity, the greater the membrane flux and the greater the humidification.

(3)When the porosity of the fiber membrane material increases from 0.35 to 0.8, the humidification capacity and efficiency of the membrane component increase with the increase of porosity, and the increment is significant; However, when the porosity of the fiber film material increases from 0.8 to 0.9, the enhancement effect on the humidification capacity and efficiency is not obvious. Although the humidification capacity and efficiency are relatively high at this time, the high porosity reduces the support strength of the fiber film material. To sum up, the higher the porosity, the greater the humidification efficiency. However, considering that the porosity is inversely proportional to the support strength of the fiber membrane material, this paper suggests that the porosity of porous fiber membrane polypropylene (PP) membrane material used for membrane liquid dehumidification should be controlled between 0.65 and 0.8.

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Figures

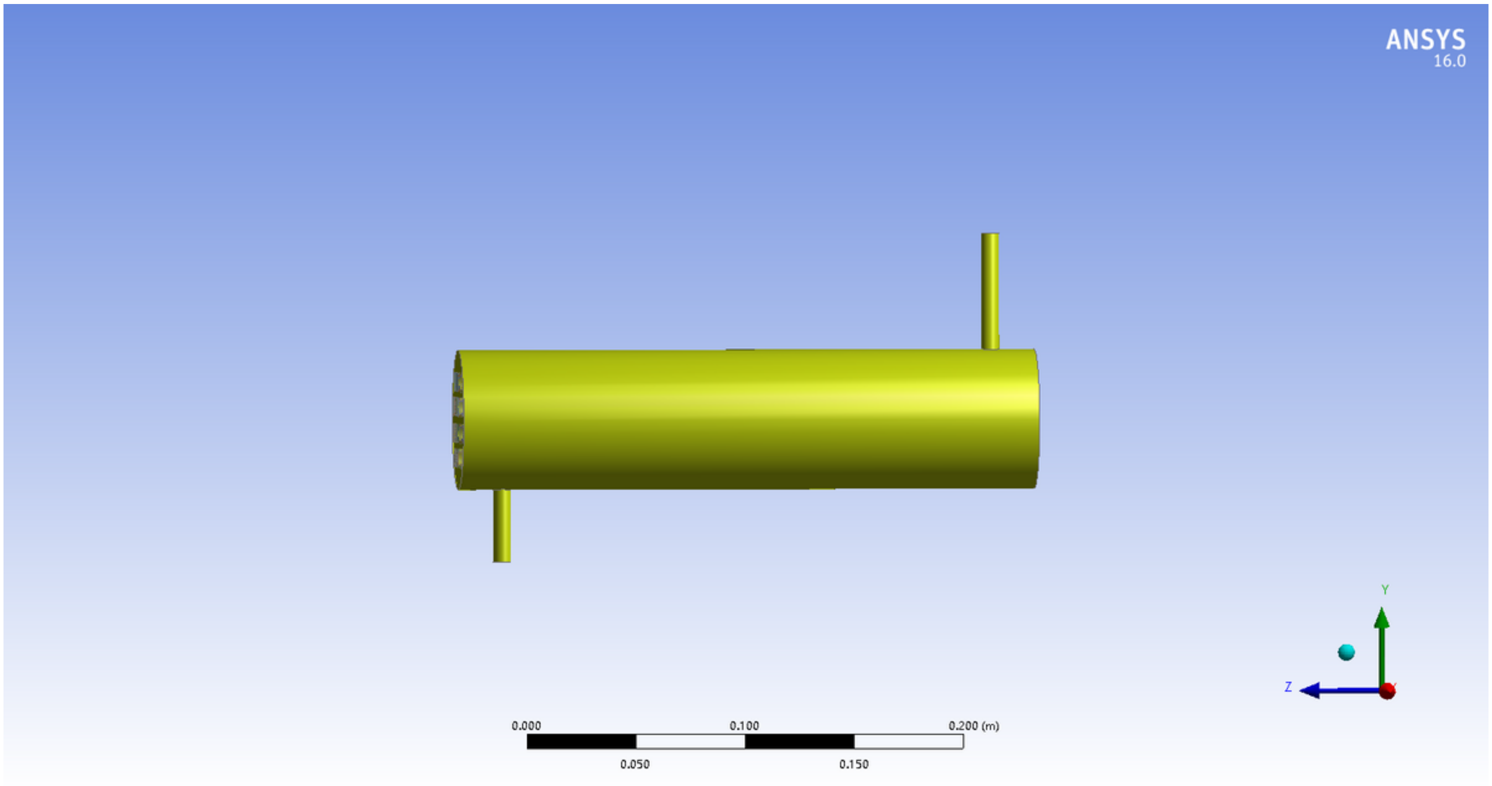

Figure 1

physical model of counter-flow hollow fiber membrane humidification module

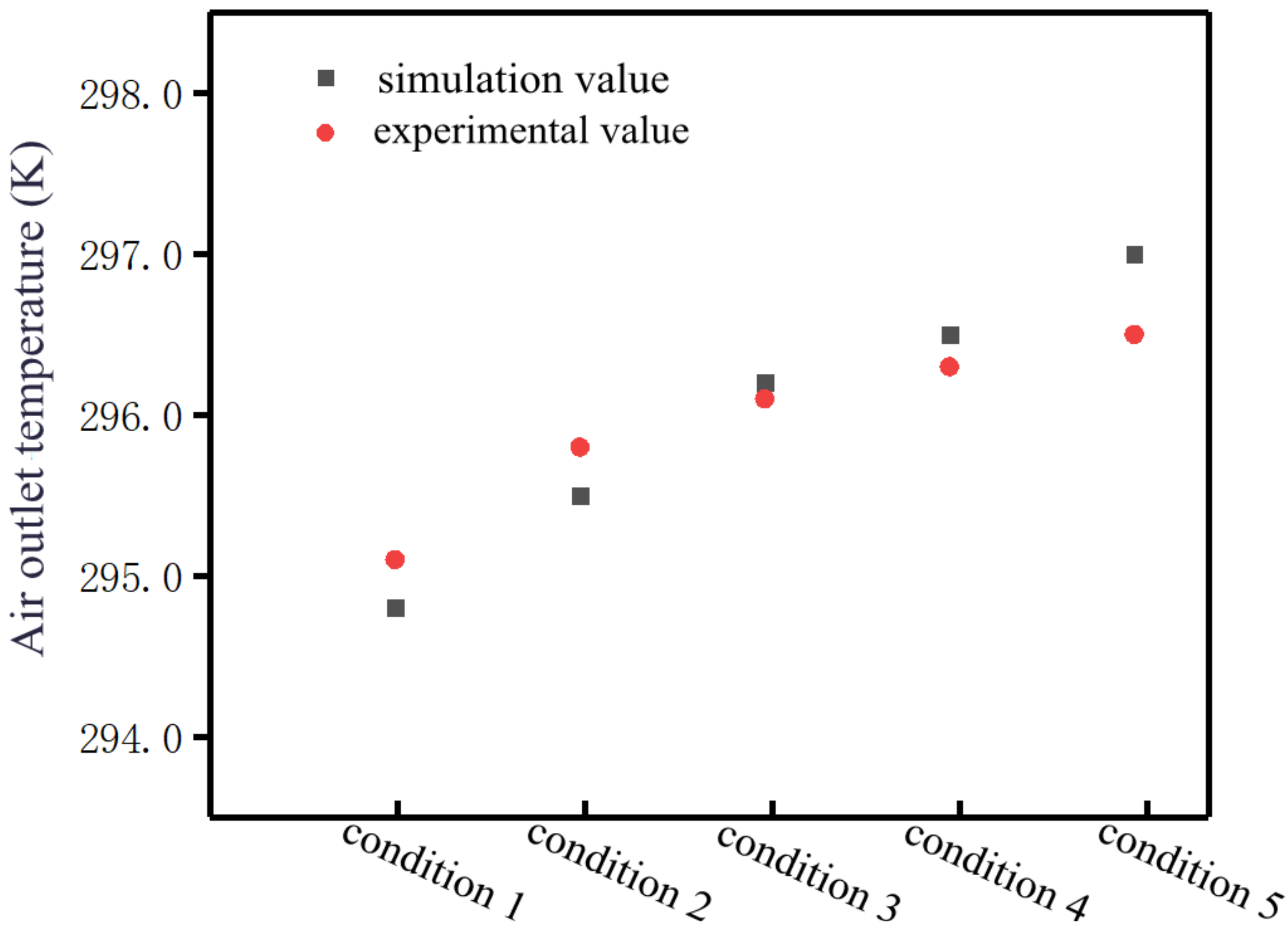

Figure 2

comparison of experimental and simulated air outlet temperature under different working conditions

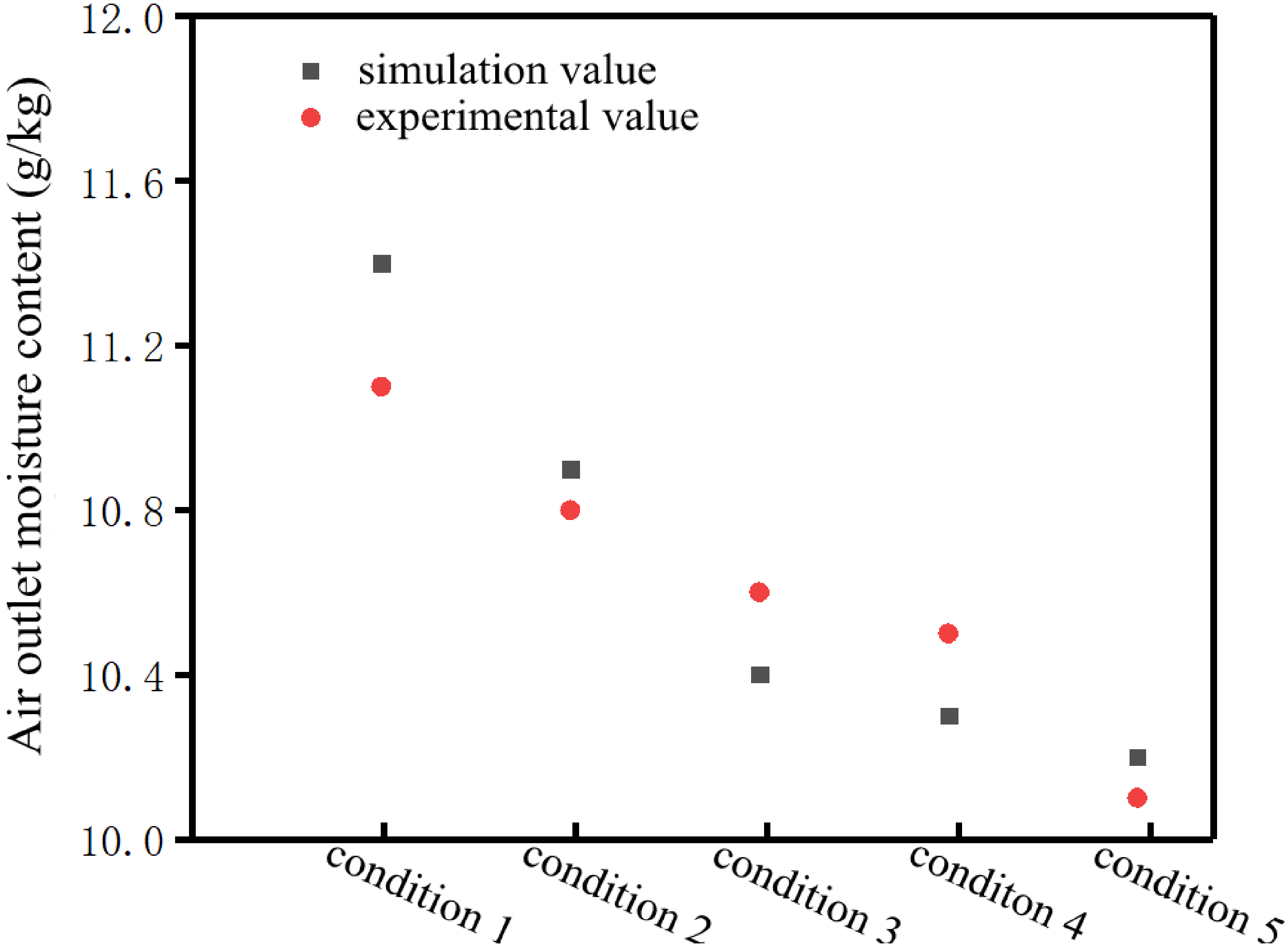

Figure 3

comparison between experimental value and simulation value of air outlet moisture content under different working conditions

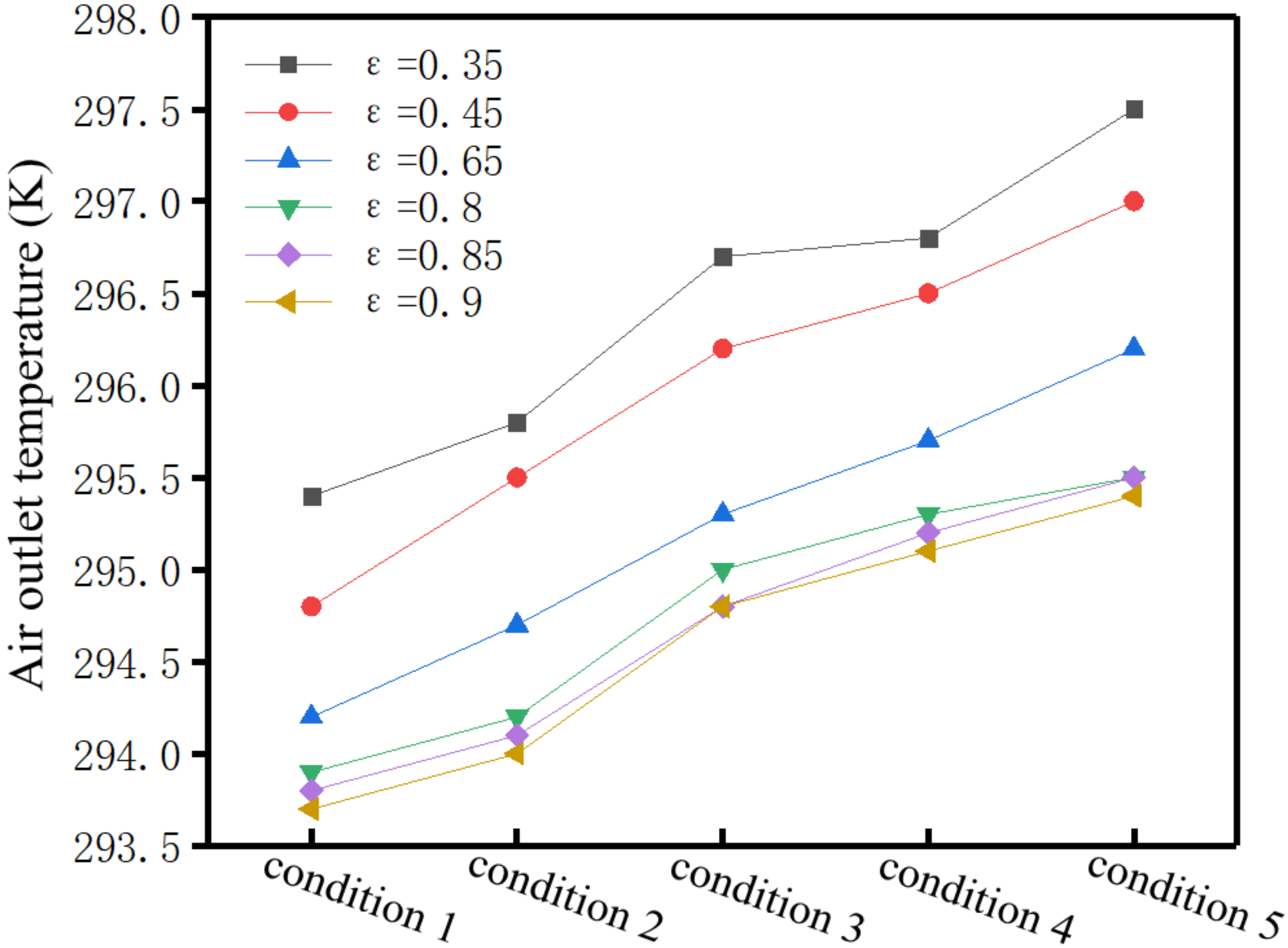

Figure 4

change of air outlet temperature with air flow rate under different porosity

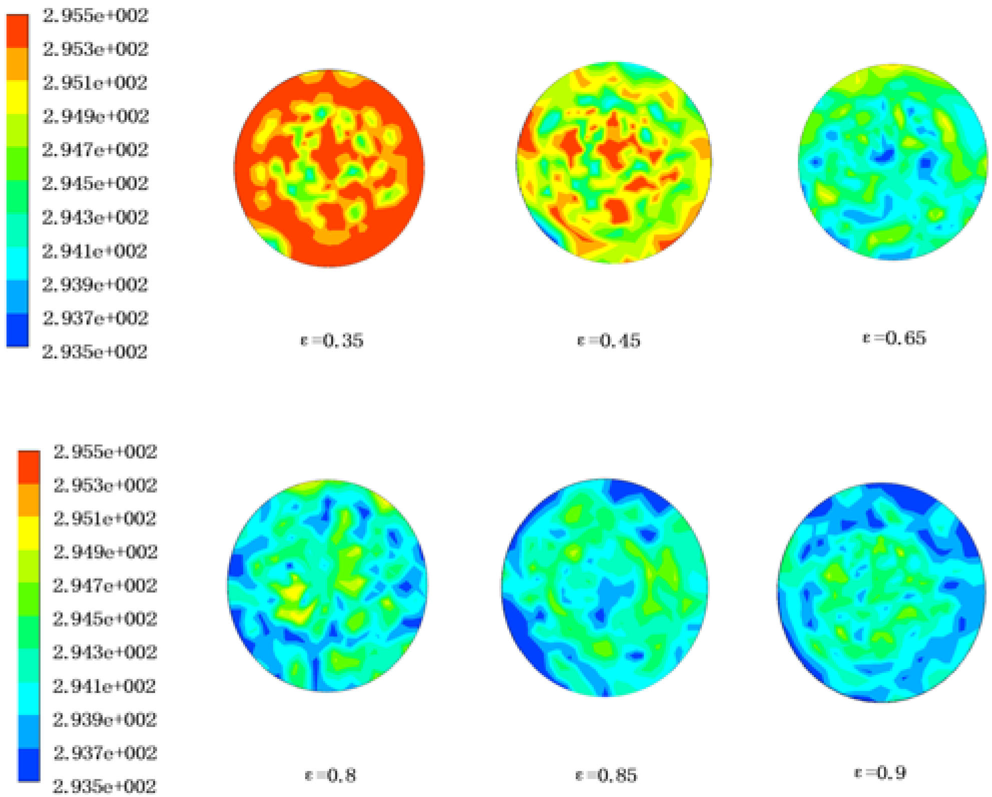

Fig.5 air outlet temperature distribution under different membrane porosity

Figure 5

air outlet temperature distribution under different membrane porosity

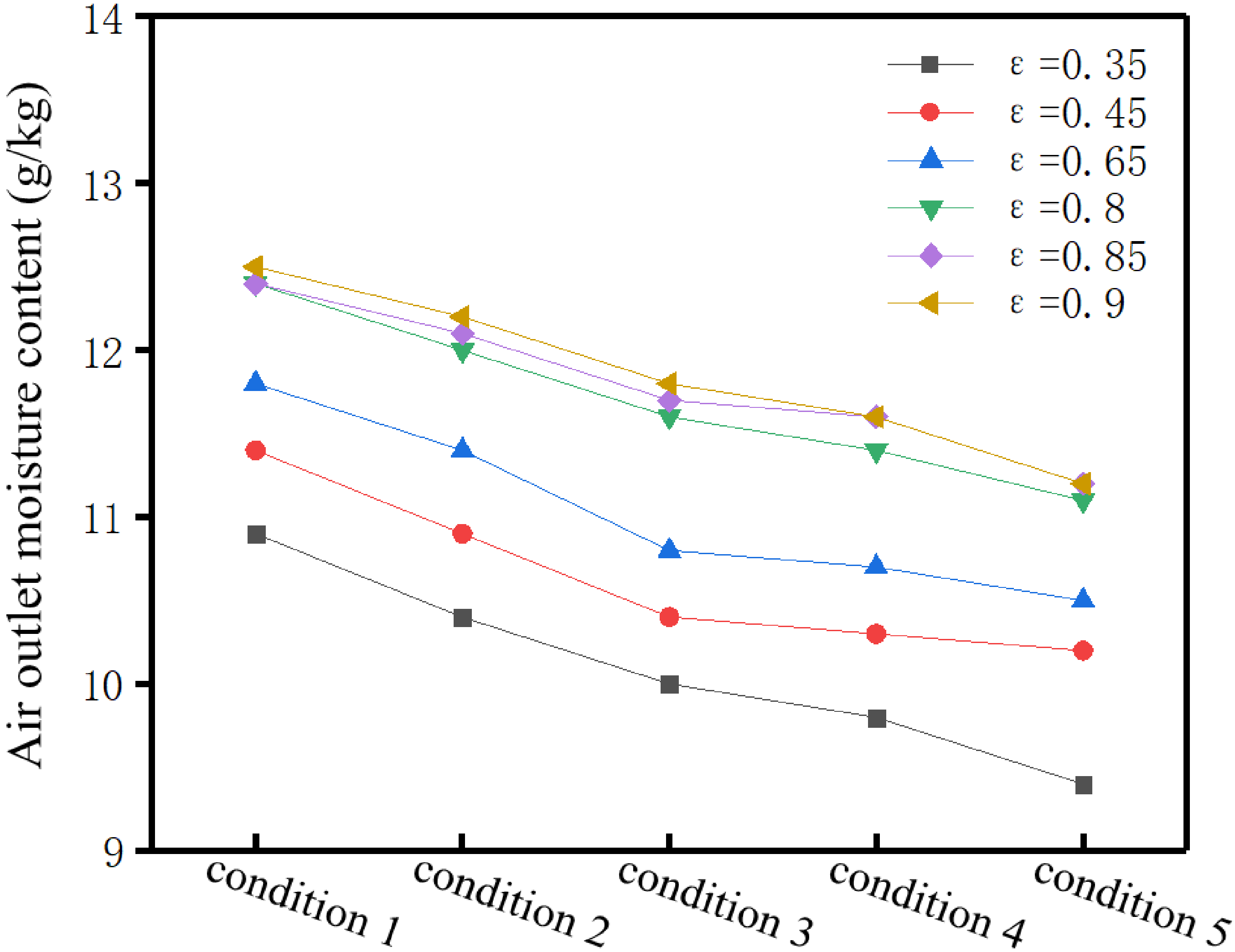

Figure 6

change of air outlet moisture content with air flow rate under different porosity

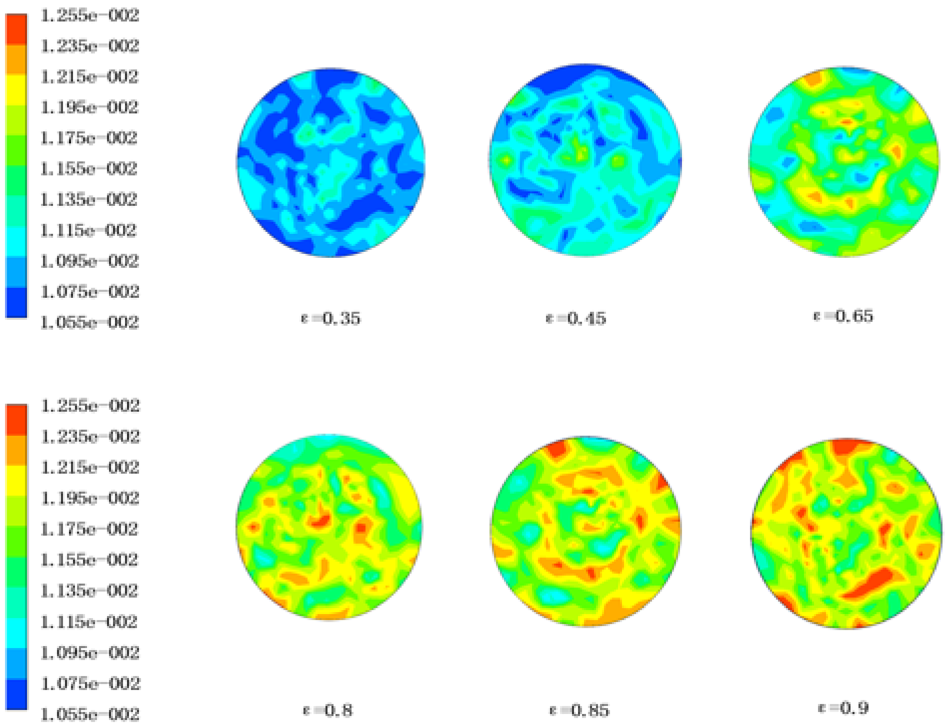

Fig.7 distribution of water vapor mass fraction at air outlet with different

Figure 7

distribution of water vapor mass fraction at air outlet with different membrane porosity

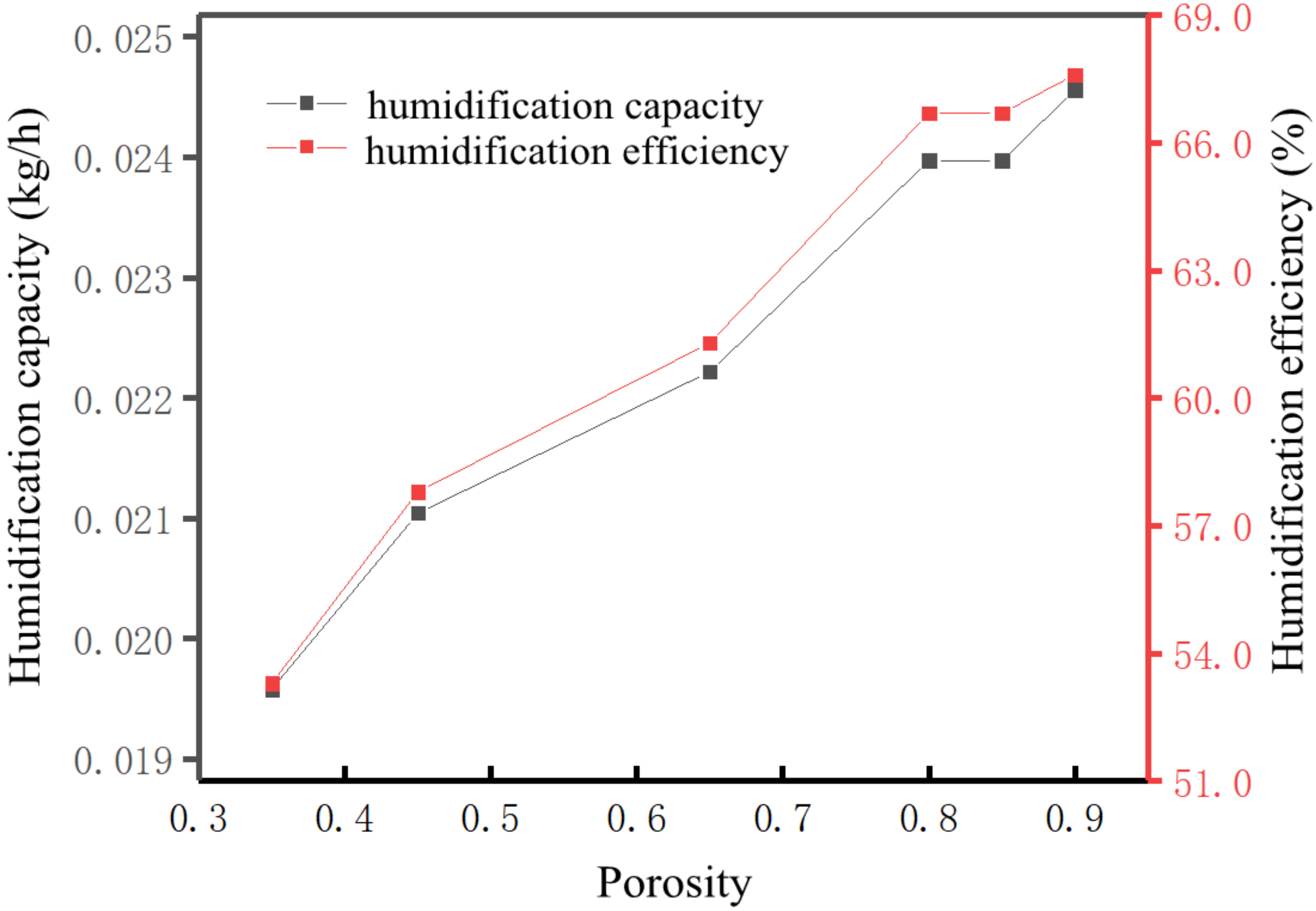

Figure 8

humidification capacity and humidification efficiency under different porosity under working condition one