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Study on An Air-Side Heating Source Liquid Desiccant Regeneration Model

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ABSTRACT

An air-side heating regeneration model was achieved by heating air, which was aiming to utilize the waste air with high temperature. The coupled heat and mass transfer model for the desiccant solution regeneration process with cross flow type was established, and the parameters distribution characteristic of the desiccant solution and air was discussed numerically, which indicated that the regeneration model using waste heated air was feasible. Regeneration efficiency was defined to describe the thermal performance of the process. The results suggested that the regeneration efficiency increased first and then decreased with the increase of the air flow rate, and the same behavior happened to the desiccant solution. As a result, for the air-side heating source regeneration model there was the optimal flow rate of the air and desiccant which completely depended on the operation conditions and dimensions of the packing.
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1. INTRODUCTION

Liquid desiccant cooling systems show great energy-saving potential by using low-grade heat, such as solar energy, industrial waste heat etc, and can be combined with traditional vapor compression refrigeration systems to promote thermal performance obviously (Dai et al., 2001; Mago and Goswami, 2003). In dehumidifiers, concentrated liquid desiccant solution absorbs moisture from the processed air in packed towers, and the solution becomes diluted gradually. In order to recycle the desiccant solution, a liquid desiccant regeneration process is required.

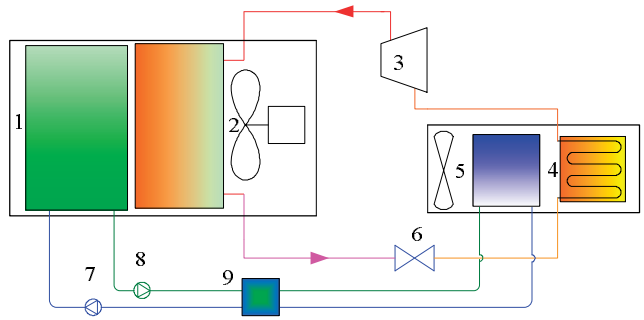
Traditional regeneration is achieved by heating desiccant solution contacting directly with the air in packing (Peng and Howell, 1984). In the regeneration mode, the heat required for the regeneration process is brought in by the heated desiccant solution, and hereafter the regeneration mode is named as desiccant-side heating source desiccant solution regeneration model. Whereas in the other regeneration mode, the heat required for the regeneration process can be introduced by heated air, which accordingly is named as air-side heating source desiccant solution regeneration model. Plenty of studies (Factor and Grossman, 1980; Khan and Ball, 1992; Elsayed et al., 2003; Gandhidasan, 2005) on the former regeneration mode have been carried out and the heat and mass transfer behavior had been investigated theoretically and experimentally (Patnaik et al., 1990; Fumo and Goswami, 2002; Liu et al, 2007; Yin et al., 2007).

Although the regeneration process by using directly the desiccant solution as the heated fluid was more effective, sometimes some hot air with high temperature is available in some situations, and it is possible to recycle the heat of the air to regenerate the desiccant solution. Leboeuf and Lof (1980) put forward a desiccant cooling system applied to more humid climates, and in the system the diluted glycol was regenerated by solar heated air. The temperature of the air could be heated to 70-90ºC by a plate solar collector theoretically. Sultan *et al.* (2002) conducted experimental study on the operation of packed tower for the regeneration of the desiccant solution with the air temperature varying from 62.8ºC to 112.6ºC, and the temperature of the solution was very low, about 28.2-39.9ºC. It was found that the air inlet temperature and flow rate had great important effect on the exit parameters of the regenerator. However, comparing the two regeneration models, previous study on the air-side heating source regeneration model was not sufficient. Especially it was required to demonstrate the heat and mass transfer behavior of the regeneration mode under different conditions and thermal performance of the regeneration model. This study would present a simulation study on the parameters distribution characteristic and parameters sensitivity analysis of the air-side heating source regeneration model to discuss its heat and mass transfer behavior.

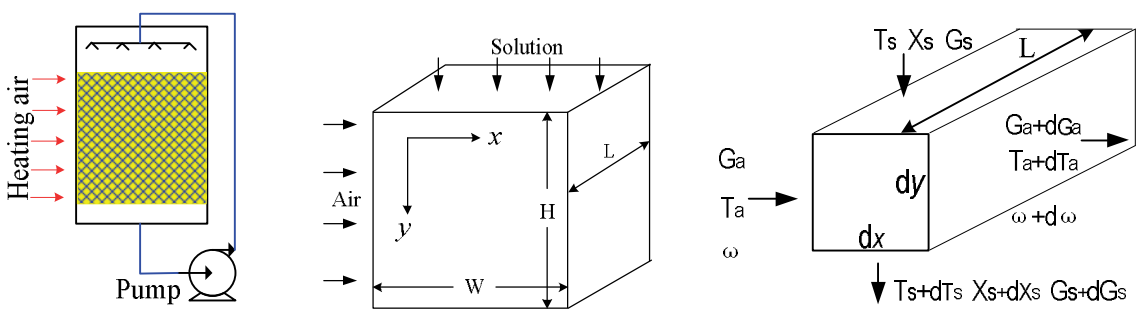
2. AIR-SIDE HEATING SOURCE LIQUID DESICCANT REGENERATION MODEL

2.1 Problem description

Often there is useless hot air as the exhaust gas in some industrial processes or equipments. For instance, the condensers of traditional vapor compression refrigeration systems produce the air with high temperature, which actually is not reused. Steel mills often give out a great deal of air with high temperature. In addition, the air dehumidification process is necessary in these industrial scenes. Here taking account of the refrigeration systems, air dehumidification is required and it's possible to use the exhaust heating air for dehumidification, shown in Fig.1. In the steel mills, during the blast roasting the air is firstly required to be dehumidified to enter into the roaster. Therefore, maybe it should be a good idea to use the exhaust hot air for regeneration to recycle the exhaust heat.



1-air-side heating source desiccant regenerator 2-conderser 3-compressor 4-evaporator
5-desiccant dehumidifier 6-valve 7, 8-pumps 9-heat exchanger
Fig.1. Energy-saving air conditioner using the air-side heating source desiccant regenerator



(a) Configuration (b) Description of the regenerator (c) Control volume
Fig.2. Air-side heating source desiccant regeneration model

In above systems, air-side heating source desiccant regenerator using directly the exhaust air with high temperature for desiccant solution regeneration is very effective to promote the thermal performance of the systems. In order to investigate the performance and characteristic of the air-side heating source desiccant solution regenerator model, the simulation study on a packed bed regenerator with cross flow type was carried out. The physical model schematic of the regenerator was shown in Fig. 2(a). The hot air with high temperature can flow horizontally cross with the desiccant solution falling down on the packing. Heat and mass transfer take place between the air and desiccant, which make temperature of the air decrease and water of the desiccant solution transfer to the air, and then the concentration of the desiccant solution and the absolute humidity of the air increase.

2.2 Mathematical model

The dimension description of the air-side heating source desiccant regenerator is shown in Fig. 2(b). Before establishing the mathematical model of the regenerator, some hypotheses should be made as follows: the desiccant solution is distributed to the packing equably and wetted the packing completely, and in the control volume shown in Fig.2(c), the parameters of desiccant solution and air are uniform.

Mass transfer occurs because of the vapor partial pressure difference between the air and the desiccant solution's surface. So mass transfer equation in the control volume is defined as:

$$G_a d\omega_a = h_D(\omega_{T_s,sat} - \omega_a) a_t L dx dy \tag{1}$$

Heat transfer happens between the air and the desiccant. Therefore, heat transfer equation can be defined as:

$$G_a Cp_a dT_a = h_C (T_s - T_a) a_t L dx dy \tag{2}$$

Considering the enthalpy equation of the moist air, enthalpy change of the air is defined as:

$$dh_a = Cp_a dT_a + r d\omega_a \tag{3}$$

Substitute eqns (1) and (2) into (3) to yield:

$$G_a dh_a = h_D (\omega_{T_s,sat} - \omega_a) a_t L r dx dy + h_C (T_s - T_a) a_t L dx dy \tag{4}$$

The Lewis number *Le* is defined as:

$$Le = \frac{h_C}{h_D Cp_a} \tag{5}$$

Combine eqns (4), (5) and (6) to yield:

$$dh_a = \frac{h_D H L a_t Le}{G_a}\left[\left(h_{T_s,sat} - h_a\right) + \left(\frac{1}{Le} - 1\right) r \left(\omega_{T_s,sat} - \omega_a\right)\right] dx \tag{6}$$

The energy balance equation of the control volume between the air and desiccant solution is described as:

$$G_a dh_a = G_s Cp_s dT_s + Cp_s T_s G_a d\omega_a \tag{7}$$

Substitute eqns (6) into (7) and simplify to give:

$$dT_s = \frac{Le \cdot h_D \cdot H \cdot L \cdot a_t \left[\left(h_{T_s,sat} - h_a\right) + \left(\frac{1}{Le} - 1\right) r \left(\omega_{T_s,sat} - \omega_a\right)\right] dx - Cp_s T_s G_a d\omega_a}{G_s Cp_s} \tag{8}$$

The mass balance equation of the control volume between the air and desiccant solution is considered and simplified to give:

$$dX_s = \frac{G_a d\omega_a}{G_s - G_a d\omega_a} X_s \tag{9}$$

The heat and mass transfer coefficients between the air and desiccant solution are very important and necessary during the simulation. Here the *k*-type mass transfer coefficients are determined using the empirical correlations by *Onda et al.* (1968):

$$k_G = 5.23 \times \frac{a_t \cdot D_{air}}{R \cdot T_a}\left(\frac{G_{air}}{a_t \cdot \mu_{air}}\right)\left(\frac{\mu_{air}}{\rho_{air} \cdot D_{air}}\right)\left(a_t \cdot D_P\right)^{-2} \tag{10}$$

$$k_L = 0.0051\left(\frac{\mu_{sol} g}{\rho_{sol}}\right)^{1/3}\left(\frac{G_{sol}}{a_t \cdot \mu_{sol}}\right)^{2/3}\left(\frac{\mu_{sol}}{\rho_{sol} \cdot D_{sol}}\right)^{-0.5}\left(a_t \cdot D_P\right)^{-2} \tag{11}$$

Here an aqueous lithium chloride is chosen as the desiccant solution. The desiccant solution properties concerned in above equations can be calculated according to the paper by *Conde* (2004).

3. RESULTS AND DISCUSSION

3.1 Parameters distribution characteristic

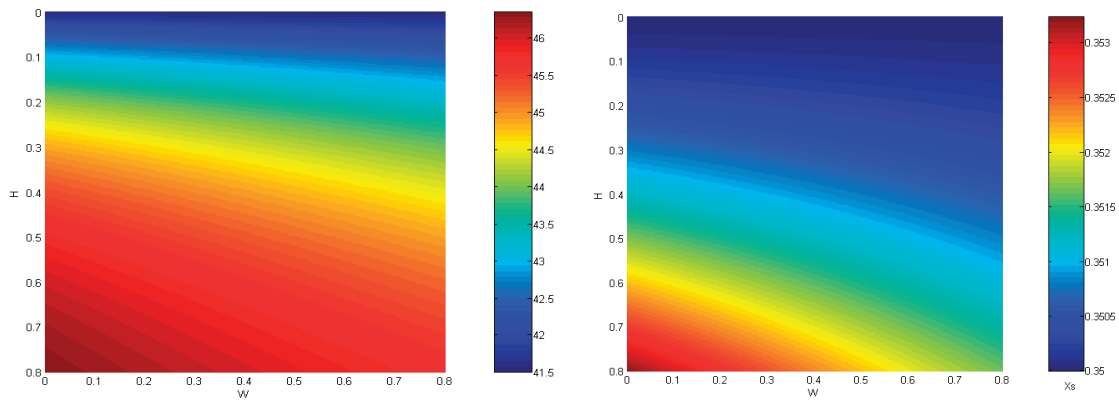
In order to discuss the feasibility of the air-side heating source regenerator model, the parameters distribution characteristic of the regenerator with a cross flow configuration were investigated numerically. The simulation parameters of the packing, the air and desiccant solution ($LiCl$-H_2O) are shown in *Table 1*. Steven *et al.* (1989) suggested that a Lewis number of 1.2 was valid by comparing with the data from the Science Museum of Virginia and here the *Le* was supposed as 1.2. A finite differential method was used to solute the problem of heat and mass transfer between the air and desiccant solution. Parameters distribution characteristic of the air and desiccant could be greatly helpful to discover and analyze the heat and mass transfer behavior and thermal performance of the regenerator.

Fig.3 (a) and (b) show the parameters distribution of temperature and concentration of the desiccant solution at the section of the regenerator. It is seen from Fig.3 (a) that the temperature of the desiccant increased obviously, and at

the bottom of the regenerator the temperature of the control volume is 46.36ºC at the maximum value and 45.69ºCat the minimum value. Fig.3 (b) demonstrates that the concentration of the desiccant solution changes very little. The outlet average concentration is about 35.24% and is only 0.24% higher than the inlet concentration.

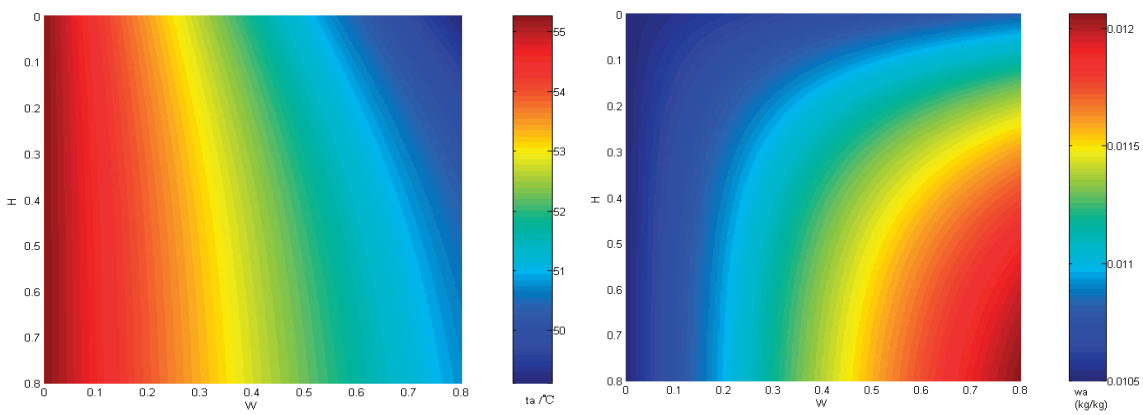
Table 1 Simulation parameters of the packing, the air and desiccant solution

Packing				*Desiccant Solution*			*Air*		
H /m	L /m	W /m	a_t /m^2/m^3	G_s /kg/s	T_s /ºC	X_s	G_a /kg/s	T_a /ºC	ω_a /g/kg
0.8	0.8	0.4	360	0.09	41.5	35%	0.6	55	10.5



(a) Temperature (b) Concentration

Fig.3. Parameters distribution of the desiccant solution



(a) Temperature (b) Absolute humidity

Fig.4. Parameters distribution of the air

Fig.4 (a) and (b) depict the parameters distribution of temperature and absolute humidity of the air. The outlet average temperature of the air was about 50.18ºC, which was too high and indicates that the heat exchanging was not enough and, more heat and mass transfer area was necessary. So in Fig.4 (b) the absolute humidity of the air increased very little, only from 10.5g/kg to 11.7g/kg. The heat and mass transfer behavior suggests that for the air-side heating source desiccant regeneration model enough area for air and desiccant should be provided to recycle efficiently the thermal energy from the exhaust air.

3.2 Parameters sensitivity analysis

The objective of the desiccant regeneration is to remove the water vapor from the desiccant solution by the scavenging air. So the amount of removed water from the solution can be calculated as follows:

$$\dot{m}_{reg} = M_{air,reg} \cdot (\omega_{reg,out} - \omega_{reg,in}) \tag{12}$$

Here in order to evaluate the thermal performance of the regeneration, the regeneration efficiency is defined as:

$$\eta_{reg} = \frac{\dot{m}_{reg} \cdot r}{Q_h} \tag{13}$$

For the air-side heating source regeneration model, the amount of input heat providing for the regeneration can be determined by change of air enthalpy, and therefore the equation (13) can be calculated as follows:

$$\eta_{reg} = \frac{\left(\omega_{reg,out} - \omega_{reg,in}\right) \cdot r}{C_p \cdot \Delta t_{air}} \tag{15}$$

Following parameters sensitivity study would be carried out to reveal how an individual parameter could influence the performance of the air-side heating source desiccant regeneration model. During the simulation, the temperature of the atmospheric environment was 38ºC in summer and the constant condition parameters are shown in *Table 2*.

3.2.1 Air Flow Rate

For the air-side heating source desiccant regeneration model, the air supplied the required thermal energy. The air flow rate had very important effect on the performance behavior of the regeneration process. Fig.5 displays the effects of the air flow rate on the regeneration process under the conditions shown in *Table 2*.

Table 2 Conditions under different air flow rate

Packing				*Desiccant Solution*			*Air*		
H /m	L /m	W /m	a_t /m^2/m^3	G_s /kg/s	T_s /ºC	X_s	V_s /m^3/s	T_a /ºC	ω_a /g/kg
0.8	0.4	0.8	360	0.10	41.5	35%	0.5	55	10.5

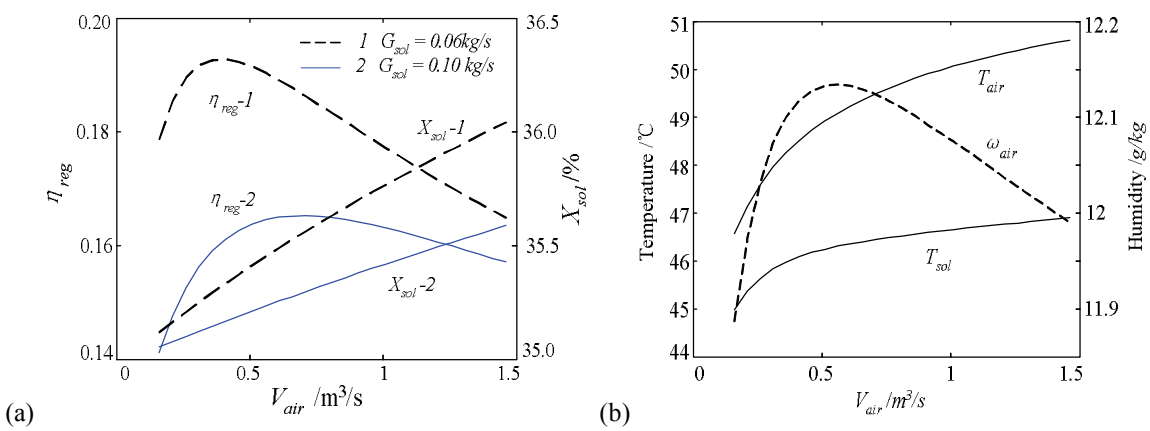


Fig.5. Effects of the air flow rate on the regeneration

Fig. 5(a) shows effects of the air flow rate on the regeneration efficiency and desiccant outlet concentration under two different desiccant flow rates respectively. From the figure it is easy to conclude that the outlet concentration of the desiccant solution increased with the increase of the air flow rate; such behavior is because higher flow rate of the air could provide more thermal energy and more heat and mass transfer coefficients. But according to eqn. (15), an optimal flow rate of the air ($V_{a,\,opt}$) exists to make the regeneration efficiency maximum ($\eta_{reg,\,max}$), the reason for which was that the maximum absolute humidity increase of the air was achieved under the optimal flow rate of the air, shown in Fig.5 (b). The effect of the air flow rate on the absolute humidity, as exposed in Fig.5 (b), was fairly noticeable and, with the increase of the air flow rate the desiccant temperature increased very slightly, but the air outlet temperature increased quickly.

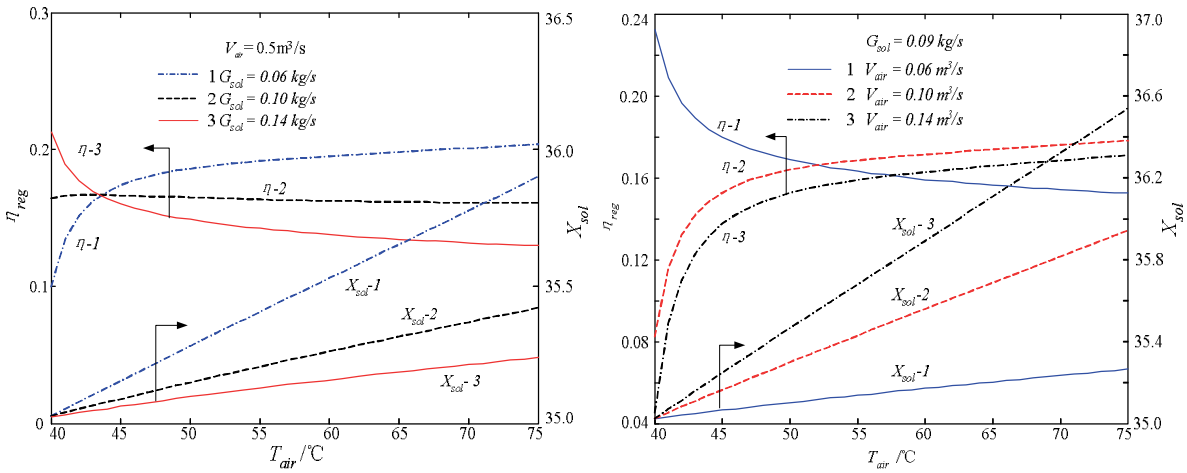
From the figure 5, it could draw following conclusions:

(1) Lower flow rate of the desiccant solution could make the maximum regeneration efficiency ($\eta_{reg,\,max}$) higher, shown in Fig.5 (a), the $\eta_{reg,\,max}$ at the desiccant flow rate of 0.06 kg/s is higher than that at 0.10 kg/s;

(2) Lower flow rate of the desiccant solution requires less flow rate of the air to achieve the maximum regeneration efficiency, but the flow rate ratio between the air and desiccant at the maximum regeneration efficiency is not constant and changed with the varying of the flow rate of the desiccant or air;
(3) To obtain higher outlet concentration of the desiccant, the lower flow rate of the desiccant solution is required.

3.2.2 Air Inlet Temperature

Fig.6 (a) and (b) show the effects of the air temperature on the regeneration under different flow rates of the desiccant solution and air. The outlet concentration of the desiccant solution increased with the increase of the inlet temperature of the air under different solution flow rates. The reason was explained that the air with higher inlet temperature would provide more heat for the regeneration. But at the same inlet temperature of the air, lower flow rate of the solution could bring higher outlet concentration of the desiccant solution.



(a) (b)

Fig.6. Effect of the air inlet temperature on the regeneration

From the figure 6(a), it is also seen that the effects of the air temperature on the regeneration efficiency was distinct and strongly depended on the solution flow rate. At very low inlet temperature of the air which was very close to the desiccant temperature, the regeneration efficiency was higher under more flow rate of the desiccant solution. However, at very high inlet temperature of the air which was obviously higher than the desiccant temperature, the regeneration efficiency was lower under more flow rate of the desiccant solution. The reason for the behavior could be explained as following: considering that regeneration process requires heat to make the water in the solution vaporize, heat would be provided by the air and the desiccant solution when the temperature of the air was very close to that of the desiccant, and with the progress of regeneration, both temperatures of the air and the desiccant solution would decrease, therefore at this case the more flow rate of the desiccant solution could offer more heat for the regeneration process, which meant higher regeneration efficiency and the regeneration process was dominated by the mass transfer behavior. Whereas, if the temperature of the air was obviously higher than that of the desiccant solution, the heat energy required by the regeneration was offered only by the air and after the regeneration, the temperature of the solution increased, and so at this case the more flow rate of the desiccant would consume more heat provided by the air, which meant less regeneration efficiency and this regeneration process was dominated by the heat transfer behavior.

Fig.6 (b) demonstrates that higher inlet temperature and more flow rate of the air could bring higher outlet concentration of the desiccant solution. But the effect of the inlet temperature of the air on the regeneration efficiency was very different under different air flow rate. But at very low inlet temperature of the air, the more flow rate of the air resulted in lower regeneration efficiency. The reason for the behavior maybe was that the heat and mass transfer was very feeble at the case and the absolute humidity change of air would be more at lower flow rate of the air, which meant higher regeneration efficiency. With the increase of the air inlet temperature, the heat and mass transfer was enhanced and the regeneration efficiency decreased at the air flow rate of 0.06 m^3/s, whereas the regeneration efficiency increased at the more flow rates of 0.10 and 0.14 m^3/s. But the regeneration efficiency at the air flow rate of 0.10 m^3/s was higher than that at the value of 0.14 m^3/s, which meant that there was an optimal value of the air flow rate just described in the *section 3.2.1*.

3.2.3 Desiccant solution flow rate

Fig.7 showed the effect of the flow rate of the desiccant solution on the regeneration under three different air flow rates. The flow rate of the desiccant solution had very important influence to the regeneration efficiency and outlet concentration of the solution. There was an optimal flow rate of the desiccant solution which made the highest regeneration efficiency. Moreover, the optimal value was different under different air flow rate. At the air flow rate of 0.5 m^3/s, the regeneration efficiency increased to the maximum value of 0.279 when the flow rate of the solution increased gradually to 0.03 kg/s, and with the continued increase of the solution flow rate, the regeneration efficiency would decrease. Besides, the maximum regeneration efficiency at lower flow rate of the air was higher. From the simulation data, it is concluded as follows:

(1) For air-side heating source regeneration models, there is an optimal solution flow rate to achieve maximum regeneration efficiency, which greatly depends on the air flow rate;
(2) The maximum regeneration efficiency decreases with the increase of the air flow rate;
(3) Usually, the maximum regeneration efficiency can achieve at very low flow rate of the desiccant solution.

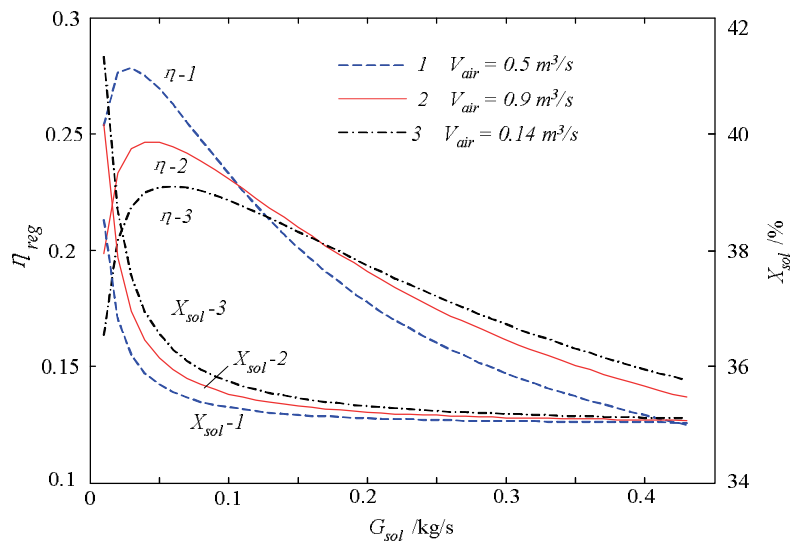


Fig.7. Effect of the desiccant flow rate on the regeneration

4. CONCLUSIONS

This paper presented an air-side heating source desiccant solution regeneration model. Both parameters distribution characteristic of the desiccant solution and air and parameters sensitivity analysis were investigated and discussed. The results suggested that in some special fields where sometimes some air with high temperature was available, it was feasible to use the exhaust hot air for dehumidification to achieve recycling the exhaust heat.

Also the simulation results showed that the flow rates of air and desiccant had very important effect on the desiccant outlet concentration and the regeneration thermal performance. Regeneration efficiency was defined to describe the thermal performance of the air-side heating source regenerator model, and there was the optimal flow rate of the air and desiccant to achieve the maximum regeneration efficiency, which was greatly determined by the operation conditions and dimensions of the packing. The results would provide theoretical foundation and optimization design and operation of this kind of regeneration model.

NOMENCLATURE

a_t	surface area of packing, m^2/m^3	G	mass flow rate, kg/s
Cp	specific heat, kJ/(kg°C)	g	acceleration of gravity, m/s^2
D	diffusivity, m^2/s	h_a	enthalpy of the air, kJ/kg
D_p	nominal size of the packing, m	h_C	heat transfer coefficient, kW/(m^2°C)

h_D mass transfer coefficient based on air humidity ratio difference, kg/(m^{2}s)
H height of the packing, m
k_G gas phase mass transfer coefficient, kmol/(m^{2}sPa)
k_L liquid phase mass transfer coefficient, m/s
L length of the packing, m
Le Lewis number, dimensionless
M_a mass flow rate of the air, kg/s
m regeneration rate, kg/s
Q_h heating capacity, kW
r latent heat of vaporization, kJ/kg
T temperature, ºC
V Volume flow rate, m^3/s
W width of the packing, m
X mass concentration of desiccant solution, %

Greek letters

η_{reg} regeneration efficiency, dimensionless
ρ density, kg/m^3
μ viscosity, N/m^2
ω humidity ratio of the air, kg/kg

Subscripts

a air
reg regeneration
out outlet
s, sol desiccant solution
T, sat saturation status under temperature of T

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