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A new method for determining coupled heat and mass transfer coefficients between air and liquid desiccant

Yonggao Yin *, Xiaosong Zhang

School of Energy and Environment, Southeast University, 2# Sipailou Road, Nanjing 210096, China

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Abstract

This paper presented the characteristic of liquid desiccant dehumidification based on *NTU–Le* model. The results showed that the Lewis number *Le* had little effect on air outlet humidity ratio during desiccant solution dehumidification process. A new method called h_D–*Le* separative evaluation method was developed for determining coupled heat and mass transfer coefficients between air and liquid desiccant, through which the heat and mass transfer coefficients between air and liquid desiccant were calculated to obtain from experimental inlet and outlet parameters of air and desiccant solution. The effects of the air volume flow rate, temperature, humidity ratio and the solution concentration, temperature on the Lewis number, heat and mass transfer coefficient were analyzed according to experimental data and the h_D–*Le* separative evaluation method. Based on the computation results, it was concluded that the Lewis number greatly depended on the operation parameters and conditions of the air and desiccant. In addition, the correlations of the heat and mass transfer coefficients were developed. The additional 74 groups of experiments validated the developed correlations by comparison of air/solution parameters change with the calculation data.

Keywords: Mass transfer coefficient; Lewis number; Heat transfer coefficient; Liquid desiccant; Air dehumidification

1. Introduction

Traditional refrigeration and air conditioning equipments are using more and more widely and energy consumption by them is very high. The environment problems caused by CFCs and HCFCs refrigerants become very serious. The application of liquid desiccant to air conditioning can improve indoor air quality, reduce energy consumption and bring environmentally friendly products. Therefore liquid desiccant air conditioning systems are drawing more and more attention in recent years. Gommed et al. [1] studied a liquid desiccant cooling system experimentally under varying operation conditions. Realistic data about operating parameters and heat and mass transfer coefficients were provided. Kinsara et al. [2] proposed an energy-efficient air conditioning system using $CaCl_2$ solution. A simulation study was carried out to find that the system was more energy-efficient than a conventional air conditioning system. Oliveira et al. [3] modeled a new air conditioning system using LiBr solution and needle impeller rotors. Zhang et al. [4] and Yin et al. [5] established a LiCl-H_2O solution desiccant evaporative cooling experimental system with energy storage and studied the thermal performance of the system with packed tower dehumidifier and regenerator experimentally. Dehumidification process using liquid desiccants in a packed tower showed energy saving potential when it was combined with traditional vapor compression refrigeration systems [6]. New types of air conditioning systems based on liquid desiccants cooling could utilize solar energy well, and the air conditioning technology was very promising [7,8].

Liquid desiccant dehumidification is a very important process in these systems. The aim of dehumidification process is to remove the water vapor of the processed air to liquid desiccants. The falling film absorption is a conventional dehumidification model. Grossman [9] developed a

* Corresponding author. Tel./fax: +86 25 83792722.
E-mail address: minigao_79@hotmail.com (Y. Yin).

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Nomenclature

a_w	wetted surface area of packing (m^2/m^3)
Cp	specific heat (kJ/(kg °C))
G	flow rate of control volume (kg/s)
h_C	heat transfer coefficient (W/(m^2 °C))
h_D	mass transfer coefficient based on air humidity ratio difference (kg/(m^2 s))
H	height of the packing (m)
L	length of the packing (m)
Le	Lewis number, dimensionless
M_a	mass flow rate of the air (kg/s)
NTU	transfer unit number, dimensionless
r	latent heat of vaporization (kJ/kg)
Re	Reynolds number, dimensionless
T	temperature (°C)
U	uncertainty, dimensionless
W	width of the packing (m)
X	mass concentration of desiccant solution in salt (%)
Greek symbol	
ω	humidity ratio of the air (kg/kg)
Subscripts	
a	air
deh	dehumidification
out	outlet
s	desiccant solution
T_{sat}	saturation status under temperature of T

theoretical analysis model of heat and mass transfer process taking place in the laminar liquid film absorption and gave the temperature and concentration variations at the liquid–gas interface and at the wall. Ali and Vafai [10] investigated the heat and mass transfer between air and falling desiccant film for inclined parallel and counter flow configurations and discussed that the inclined angles had significant effect on the dehumidification, cooling and regeneration processes.

Packed towers can bring more mass transfer by providing a large contacting area in a relatively small volume, which have been studied by many investigators [11–13]. Khan [14] conducted detailed sensitivities analysis of heat and mass transfer performance of a packed-type liquid desiccant system. Al-Farayedhi et al. [15] conducted the theoretical analysis of heat and mass transfer coefficients in an air desiccant contact equipment. A cost effective liquid desiccant CELD was used as the liquid desiccant. The air phase transfer coefficients correlations were developed based on the dimensionless numbers. The effects of temperature and concentration of the solution on the heat and mass transfer coefficients were considered. Chung et al. [16] carried out the experiments with random and structured packing in the dehumidifier using lithium chloride solution. The overall gas phase heat and mass transfer coefficients correlations were developed [17]. Ren et al. [18] provided a way to obtain the average overall heat and mass transfer coefficients from experimental data presented by Chung et al. [16], and results showed that the Lewis number varied from 0.7 to 1.3. Chen et al. [19] presented an integrated analytical solution of adiabatic heat and mass transfer in packed-type liquid desiccant equipment under the assumption of constant concentration of solution at inlet and outlet of the absorber based on the logarithmic mean humidity difference and pointed out that the Lewis number should not be unity value. Stevens et al. [20] also indicated that a disparity of experimental data and modeled results and gave the explanation of either experimental error or the use of a unity value for the Lewis number, which provided more precise results with the Lewis number value of 1.2 under the referenced experimental data.

The earlier studies showed that there were some doubts and suspicions about the Lewis number. In addition, heat and mass transfer coefficients of packed tower dehumidifiers are very limited in the open literature, especially for structured packing towers. Considering the heat and mass transfer coefficients are affected not only by packing material, but also by operation conditions, such as air inlet parameters and liquid desiccants parameters, traditional correlations by dimensionless *Sh* number and *Nu* number are not comprehensive enough, as it cannot indicate the effects of the temperature, humidity, and concentration of liquid desiccant on heat and mass transfer coefficients. Heat and mass transfer coefficients correlations developed by many studies were calculated by the logarithmic mean temperature difference or arithmetical mean temperature difference. Little study is concerned on the method of measuring coupled heat and mass transfer coefficients during liquid desiccant dehumidification process.

This study developed a new method to determine the coupled heat and mass transfer coefficients between air and liquid desiccant. Based on the new method and experimental results, the coupled heat and mass transfer coefficients were obtained.

2. Methodology

2.1. Dehumidification model: NTU–Le model

Liquid desiccant solution is brought into packing tower and contacts directly with the process air. The thick solution absorbs the water vapor from the air because the vapor partial pressure of the air is higher than that on the solution surface. Temperature of the solution increases because of the water vaporization heat released. Therefore the surface vapor partial pressure of the desiccant solution increases, which depresses the solution absorption. Hence coupled heat and mass transfer happen during the dehumidification process. In order to study the characteristic of the liquid desiccant dehumidification, the computation model for the cross flow dehumidification (shown in Fig. 1) was developed as an extension of the earlier study by Stevens et al. [20]. To simplify the mathematical analysis, assumptions are made as follows: (1) The desiccant solution can be distributed to the packing equably, and wet the packing material completely. (2) The resistance of desiccant solution film is ignored because of very thin film thickness. (3) In the control volume, parameters of the desiccant solution and air are uniform.

Mass transfer occurs because the vapor partial pressure of the air is higher than the desiccant solution's surface. The mass transfer coefficient h_D is driven by air humidity ratio difference. So mass transfer equation in the control volume is defined as

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

The airside heat transfer equation between liquid desiccant and air can be defined as

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

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

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

Substitute Eqs. (1) and (2) into (3) to yield:

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

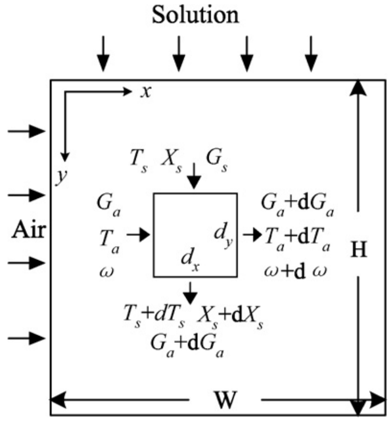


Fig. 1. Sketch of cross flow dehumidification.

Here Lewis number Le and NTU are defined:

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

$$NTU = \frac{h_D a_w HWL}{M_a} \tag{6}$$

Combine Eqs. (4)–(6) to yield:

$$dh_a = NTU \cdot Le\left[(h_{T_{s,sat}} - h_a) + \left(\frac{1}{Le} - 1\right) r(\omega_{T_{s,sat}} - \omega_a)\right]\frac{dx}{W} \tag{7}$$

where $h_{T_{s,sat}}$ is the air enthalpy in equilibrium with the desiccant solution (kJ/kg).

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

$$G_a dh_a = G_s Cp_s dT_s + Cp_s T_s G_a d\omega_a \tag{8}$$

Substitute Eq. (7) into (8) and simplify to give:

$$dT_s = \frac{G_a\left\{NTU \cdot Le\left[(h_{T_{s,sat}} - h_a) + \left(\frac{1}{Le} - 1\right) r(\omega_{T_{s,sat}} - \omega_a)\right]\frac{dx}{W}\right\} - Cp_s T_s G_a d\omega_a}{G_s Cp_s} \tag{9}$$

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

$$dX_s = \frac{G_a d\omega_a}{G_s - G_a d\omega_a} X_s \tag{10}$$

The above equations describe the air dehumidification process in the packing using liquid desiccant solution. Eqs. (1) and (2) indicate the air temperature and humidity ratio change, and so the air outlet temperature and humidity ratio of the control volume can be resolved. Combined the air outlet parameters of the control value, the desiccant solution outlet parameters can be easily calculated. For the expression convenience, the solution model is named as *NTU–Le* model.

2.2. h_D–Le separative evaluation method

The *NTU–Le* model shows that the outlet parameters of the air and desiccant solution are determined by many factors, such as air and desiccant solution inlet status parameters, nominal dimension of the packing, Lewis number Le and mass transfer units number NTU. So outlet parameters of dehumidification processes can be described simply as follows:

$$\omega_{deh,out} = f_1(L_{deh}, G_a, T_a, \omega_a, G_s, X_s, T_s, h_D, Le) \tag{11}$$

$$T_{a,out} = f_2(L_{deh}, G_a, T_a, \omega_a, G_s, X_s, T_s, h_D, Le) \tag{12}$$

$$T_{s,out} = f_3(L_{deh}, G_a, T_a, \omega_a, G_s, X_s, T_s, h_D, Le) \tag{13}$$

where L_{deh} is the nominal dimension of the packing.

The mass transfer coefficient h_D and Lewis number Le determine the outlet parameters of the air and the desiccant solution according to the NTU–Le model. The key parameters h_D and Le are affected not only by the mass flow rates of the air, but also by status parameters of air and desiccant solution, such as temperatures of the air and the desiccant solution, the humidity ratio of the air, the mass concentration of the desiccant solution. So traditional mass transfer coefficients correlations of Sh as the function of Nu and Sc are not comprehensive enough since they could not present effect of the temperature of the air and desiccant solution, the humidity ratio of air, the mass concentration of desiccant solution on mass transfer coefficient h_D. On the other hand, Lewis number Le is usually assumed to be equal to one. But the fact is not exactly like the assumption [18–20].

In order to study the characteristic of the coupled heat and mass transfer during liquid desiccant dehumidification process, effects of mass transfer unit NTU and Lewis number Le on the air outlet humidity ratio has been studied based on the NTU–Le model. The simulation operation conditions of the dehumidification process are shown in Table 1.

The effects of NTU and Le on the air outlet humidity ratio are shown in Fig. 2. In Fig. 2 Lewis numbers are varied from 0.6 to 2 under different NTUs, and the computation results show that air outlet humidity ratio changes very slightly from 6.691 to 6.502 g/kg under the NTU of 2.0, and the air outlet humidity ratio almost keeps the value of 10.752 g/kg under the NTU of 0.1. The results suggest that air outlet humidity ratio changes little with the same NTU under different Lewis numbers (0.8–1.5), so to speak, it can conclude that Lewis number Le has hardly effect on air outlet humidity ratio, and especially with the NTU of less than 0.2, it may be considered that Lewis number has no effect on air outlet humidity ratio. In addition, the same result is found under other operation conditions. The result is very crucial to develop the new method for determining the coupled heat and mass transfer coefficients. According to the above results, the Eq. (11) can be simplified to the following function under small NTUs:

$$\omega_{\mathrm{deh,out}} = f_1(L_{\mathrm{deh}}, G_{\mathrm{deh,air}}, T_{\mathrm{deh,air}}, \omega_{\mathrm{deh}}, G_{\mathrm{deh,sol}}, X_{\mathrm{deh}}, T_{\mathrm{deh,sol}}, h_D) \tag{14}$$

So it is feasible to presume the Lewis number as an appropriate value, and then according to Eq. (14) and experimental data (parameters of inlet air and solution and outlet air humidity ratio) the mass transfer coefficient can be worked out. With that, substitute the mass transfer coefficient h_D to the Eqs. (12) or (13) to obtain the practical

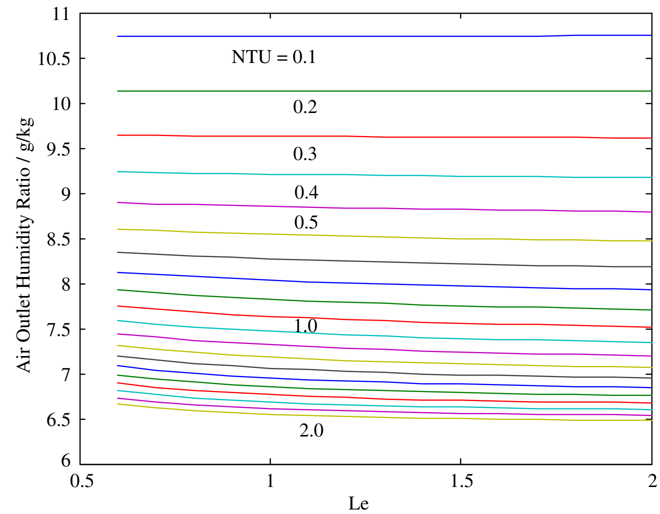


Fig. 2. Effect of Le on air outlet humidity ratio under different NTU.

Lewis number Le. Finally, the heat transfer coefficient h_C can be evaluated by following equation according the h_D and Le:

$$h_C = Le \cdot h_D \cdot Cp_a \tag{15}$$

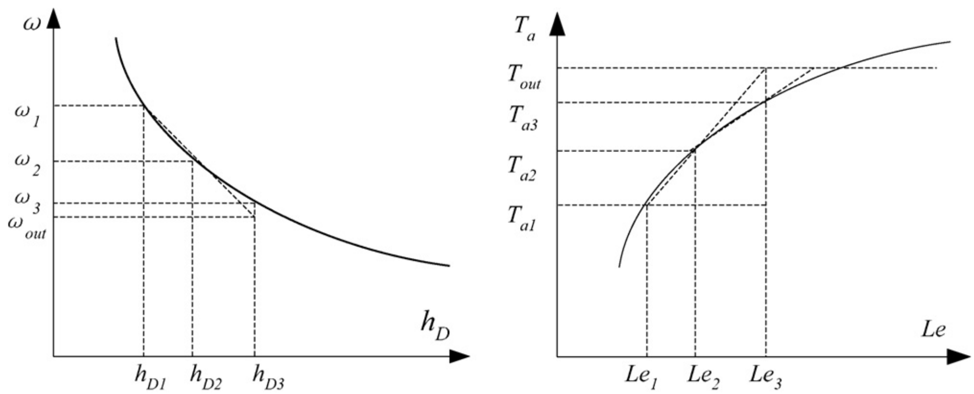
The above method is called h_D–Le separative evaluation method.

The steps for solving for the coupled heat and mass transfer coefficients h_C, h_D using the h_D–Le separative evaluation method are:

(1) According to liquid desiccant dehumidification experiments, the following parameters are obtained, which are humidity ratio of the outlet air ω_{out}, the status parameters of the inlet air and the inlet desiccant solution and parameters of the packing. Assume that Lewis number Le is equal to 1.5. Give the initialization of h_{D1}.
(2) Based on the NTU–Le model, the outlet air humidity ratio ω_1 is obtained according to the inlet parameters and assumed h_{D1}, shown in Fig. 3a; if $\omega_1 > \Delta\omega + \omega_{out}$ ($\Delta\omega$ is the permission error bound), the mass transfer coefficient h_{D2} is modified to $h_{D2} = 1.1h_{D1}$; otherwise $h_{D2} = 0.8h_{D1}$; then according to the h_{D2}, the outlet air humidity ratio ω_2 is obtained.
(3) If $\omega_2 > \Delta\omega + \omega_{out}$, the new mass transfer coefficient h_{D3} is obtained using Newton iterating method, just shown in Fig. 3a.
(4) Based on the NTU–Le model, the outlet air humidity ratio ω_3 is obtained according to the inlet parameters and the new mass transfer coefficient h_{D3}; if $\omega_3 >$

Table 1
Operation conditions

Packing				Desiccant solution			Air		
H (m)	L (m)	W (m)	a_w (m^2/m^3)	G_s (kg/s)	T_s (°C)	X_s	G_a (kg/s)	T_a (°C)	ω_a (g/kg)
0.8	0.8	0.8	360	0.09	27	40.0%	0.6	25	10.5



(a) Iterative illustration for solving h_D (b) Iterative illustration for solving *Le*

Fig. 3. Iterative illustrations for the h_D–*Le* separative evaluation method.

$\Delta\omega + \omega_{out}$, substitute h_{D2} to h_{D1}, and substitute h_{D3} to h_{D2}, repeat step (3) until $\omega_3 - \omega_{out} \leqslant \Delta\omega$; the final mass transfer coefficient h_D is obtained.

(5) Since the mass transfer coefficient h_D is known, use the same iteration processes (shown in Fig. 3b) to obtain the real Lewis number according to Eqs. (12) or (13).

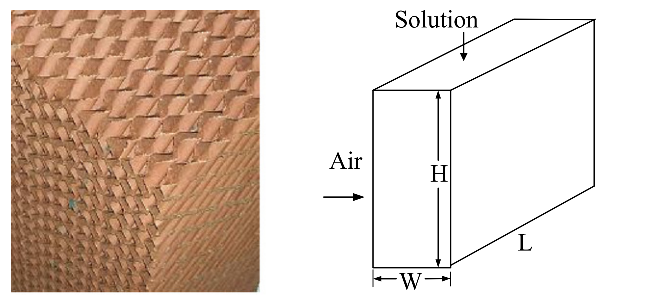
(6) Substituting the obtained mass transfer coefficient h_D and Lewis number *Le* to Eq. (15), the heat transfer coefficient is achieved.

The simultaneous heat and mass transfer happen in the liquid desiccant dehumidification of the air. The process is so strongly coupled. The capability of mass transfer is revealed by the parameter h_D according to the *NTU–Le* model. The Lewis number *Le* reveals not only the capability of heat transfer, but also the coupled characteristic between heat and mass transfer. The above method of determining the heat and mass transfer coefficients solves the h_D by the humidity ratio of the outlet air firstly, and then the *Le* is solved by the temperature of the outlet air or desiccant solution. The solution process achieves the decoupling of the heat and mass transfer, which makes it possible to evaluate the heat and mass transfer coefficients separately.

3. Results and analysis

In order to provide some required experimental data for evaluation of the heat and mass transfer coefficients, a structured corrugated packing with inorganic material (Munters Celdek) was used as the dehumidifier shown in Fig. 4. The specific area of the packing is 396 m^2/m^3. Fig. 4a shows the shape viewed from the upside. The definition of the packing dimensions is shown in Fig. 4b. The dehumidifier is with the dimensions of height $H = 0.5$ m, width $W = 0.2$ m, length $L = 0.5$ m. An aqueous lithium chloride is used as the liquid desiccant in the experiments. During the experiments, the packing was wetted well.

The schematic diagram of the liquid desiccant dehumidification setup is shown in Fig. 5. It is made up of a dehumidifier, a pump, a concentrated solution tank, a diluted solution tank, a rotameter, etc. Two liquid desiccant tanks (Tank 1 and Tank 2) are cylinders with the same dimensions, 70 cm in height and 55 cm in diameter. Before experiments, valve 5, 6 used for drainage were close and liquid desiccant solution with the weight concentration of about 39% was confected by 59 kg of lithium chloride granular dissolved into 92 kg pure water and poured into the Tank 1. After closing the valve 1, 4 and opening the valve 2, 3, dehumidification experiments started, and the liquid desiccant solution was transported from the Tank 1 to the dehumidifier by the pump and collected in the Tank 2. Until the Tank 1 was emptied out, the desiccant solution was pumped again via the dehumidifier from the Tank 2 to the Tank 1 by opening the valve 1, 4 and closing the valve 2, 3, and so repeated. The inlet temperature of the solution entering into the dehumidifier was controlled by the cooler and the electric heater which was controlled by a temperature controller. The flow rate of the solution was adjusted by the valve 3 or 4. An environmental chamber was used for providing the air with different temperature and humidity. The environmental chamber provided the measuring instruments for the flow rate, dry-bulb temperature and wet-bulb temperature of the air, respectively. The dry-bulb and wet-bulb temperature at outlet point were measured by T_4 and T_{s2}. Temperatures of the desiccant solution at inlet point and outlet point were measured by T_1 and T_2. The



(a) Packing (b) Definition of the packing dimensions

Fig. 4. Shape and structure of the packing in the dehumidifier.

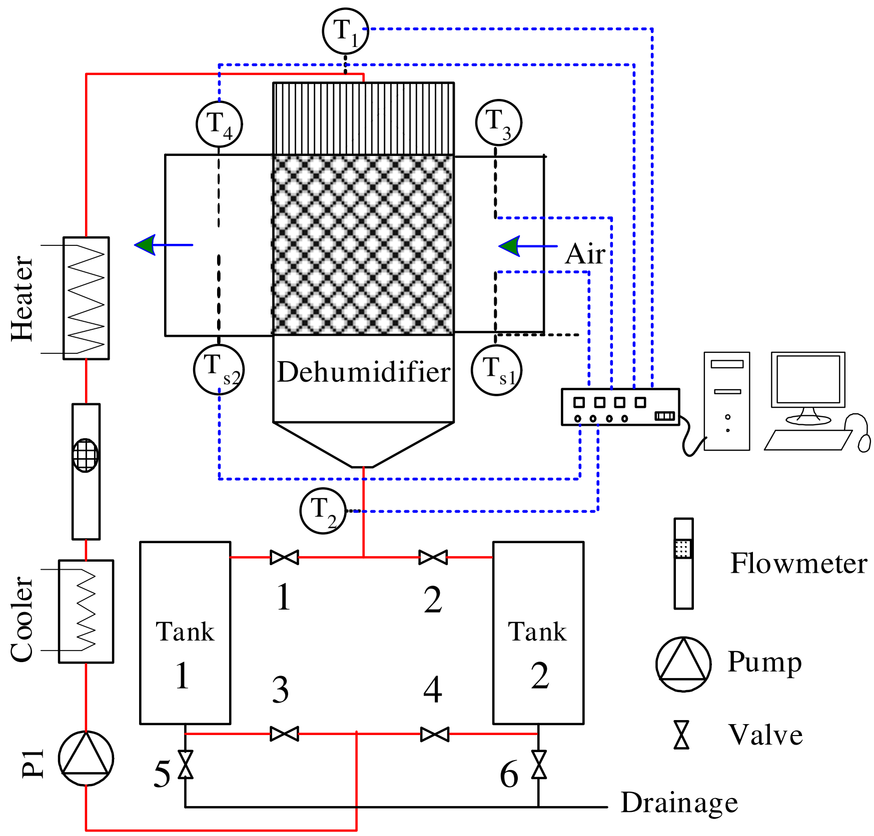


Fig. 5. Schematic diagram of desiccant dehumidification setup.

objective of the experimental apparatus is to obtain the inlet and outlet parameters of the air and desiccant solution. The inlet and outlet parameters of the air and desiccant solution include the dry-bulb and wet-bulb temperature, flow rate of the air and the temperature, mass concentration and flow rate of the desiccant solution. Temperature was measured by some Pt100 RTDs (resistance temperature detectors) with the accuracy of 0.1 °C. Flow rate of the desiccant solution was measured by an anticorrosive rotameter with the measure range from 40 to 400 l/h with the accuracy of 10 l/h. All the experiments were carried out under the steady state of the air and desiccant. The air flow rate was measured by three standard nozzles with the accuracy of 1%, whose diameters were 70, 80 and 110 mm, respectively, corresponding measure range from 208 to 485 m^3/h, from 424 to 990 m^3/h and from 513 to 1197 m^3/h. The mass concentration of the aqueous lithium chloride was indirectly tested by measuring the density and temperature of the solution. According to the density and temperature of the solution, its mass concentration could be worked out. The solution density was measured by three different specific gravity hydrometers with the accuracy of 1 kg/m^3, whose measure ranges were, respectively, from 1000 to 1100 kg/m^3, from 1100 to 1200 kg/m^3 and from 1200 to 1300 kg/m^3.

Experiments were carried out to study the effects of the parameters on the heat transfer coefficient and Lewis number under different experimental conditions.

3.1. Effects of the air flow rate on the heat and mass transfer coefficient

Some experiments were carried out under the conditions shown in Table 2. According to the experimental data and the h_D–Le separative evaluation method, the Lewis number and mass transfer coefficient could be calculated. Fig. 6 presents the effects of the air flow rate on the mass transfer coefficient and Lewis number. The results show that the mass transfer coefficient rises with the increase of the air flow rate. As the air flow rate was varied from 0.055 to 0.178 m^3/s, the mass transfer coefficients changed greatly from 3.1 to 9 g/(m^2 s), and Lewis numbers changed from 1.3 to 1.9. The average value of the Lewis number was about 1.6.

According to the Eq. (15), the heat transfer coefficients were easy to obtain since the mass transfer coefficients and the corresponding Lewis numbers were known. Fig. 7 presents the effects of the air flow rate on the heat transfer coefficient h_C. The heat transfer coefficients

Table 2
Experimental conditions (1)

Air			Desiccant solution		
G_a (m^3/s)	T_a (°C)	ω_a (g/kg)	G_s (kg/s)	T_s (°C)	X_s
0.055–0.178	28.1–28.3	8.38–8.4	0.06	30.5–30.8	35–35.07%

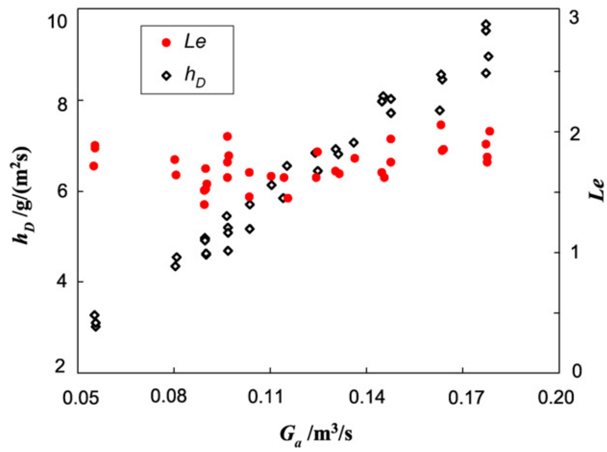


Fig. 6. Effects of air flow rate on mass transfer coefficient and Lewis number.

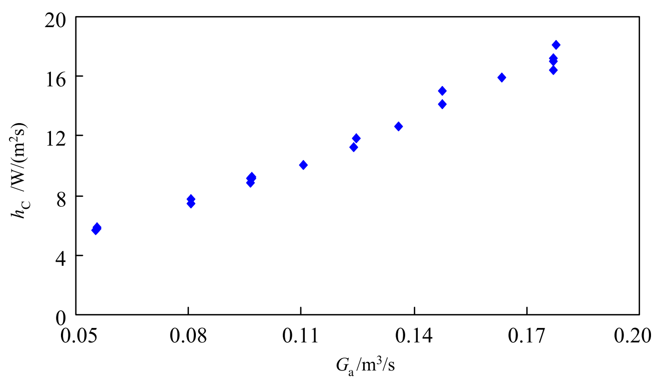


Fig. 7. Effects of air flow rate on heat transfer coefficient.

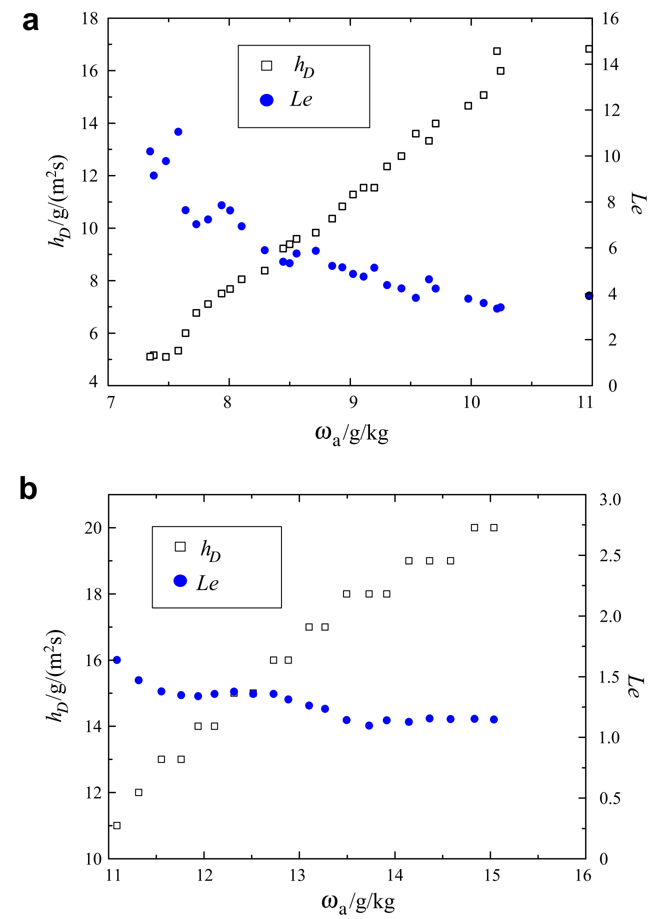


Fig. 8. Effects of air humidity ratio on mass transfer coefficient and Lewis number.

reduced with the decrease of the air flow rate. When the air flow rate changed from 0.055 to 0.178 m^3/s, the heat transfer coefficient changed from 5.45 to 17.9 $W/(m^2\ s)$.

3.2. Effects of air humidity ratio on mass transfer coefficient and Lewis number

Liquid desiccant dehumidification is a nonlinear process because of two reasons: one is coupled heat and mass transfer during the process and the other is that the important properties of the air and desiccant solution – h_C, h_D are changing because of different parameters of inlet air and solution. Two sets of experiments were carried out with different air humidity ratio, shown in Table 3. Fig. 8a presents the effects of the air humidity ratio on the mass transfer coefficient and Lewis number. The mass transfer coefficients are greatly dependent on the air humidity ratio. The mass transfer coefficients increased twice as faster as the increase of the humidity ratio from 7.3 to 10.97 g/kg at the air flow rate of 0.255 m^3/s. The Lewis numbers reduced rapidly from 10 to 4. Fig. 8b shows the effects of the higher humidity ratio on the mass transfer coefficients with the humidity ratio from 10 to 16 g/kg and an air flow rate of 0.118 m^3/s. Whereas, the Lewis number was nearly constant and kept around 1.3. From the results of Fig. 8, it is concluded that the mass transfer coefficients increase rapidly with the increase of the air humidity ratio, but the Lewis number reduce at different rates.

3.3. Effects of air temperature on mass transfer coefficient and Lewis number

To study the effects of air temperature on the mass transfer coefficient, the experimental conditions were shown in Table 4. In this experiment, the aqueous lithium

Table 3
Experimental conditions (2)

Group	T_a (°C)	ω (g/kg)	G_a (m^3/s)	G_s (kg/s)	T_s (°C)	X_s (%)
(a)	25.5	7.3–11	0.255	0.08475	30	35.7
(b)	24.7	10–16	0.118	0.08475	30	36.5

Table 4
Experimental conditions (3)

T_a (°C)	ω_a (g/kg)	G_a (m^3/s)	G_s (kg/s)	T_s (°C)	X_s (%)
25.6–26.7	10.6	0.151	0.1017	31.2	37.3

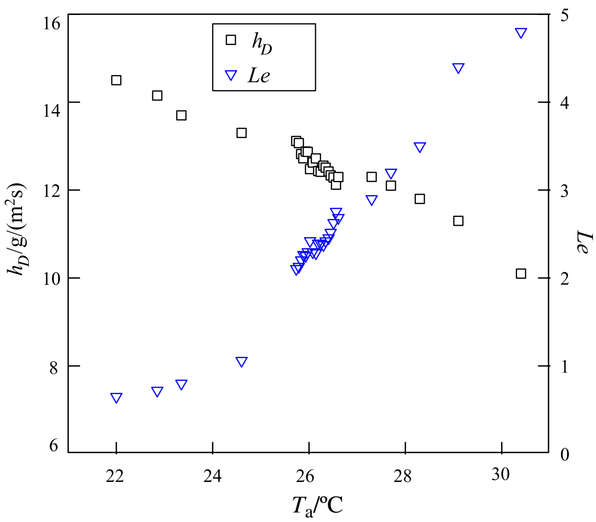


Fig. 9. Effects of air temperature on mass transfer coefficient and Lewis number.

chloride of 37.3% weight concentration was used. Fig. 9 indicates the effects of the air temperature on the mass transfer coefficient and Lewis number. The air inlet temperature changed from 22 to 30 °C, which resulted in mass transfer coefficients decreasing from 14.2 to 10.1 g/(m^2 s), and the Lewis number increased greatly from 0.6 to 4.7.

3.4. Effects of solution temperature on mass transfer coefficient and Lewis number

Three sets of experiments shown in Table 5 were conducted, respectively, under different solution temperatures. The solution flow rate was at 0.0847 kg/s. The experimental results were shown in Fig. 10. As was described in the figure, mass transfer coefficients decreased rapidly with the increase of the desiccant temperature at three sets of experiments. In the first set of experiment, the desiccant solution temperature changed from 20.5 to 29.3 °C, which resulted in the heat transfer coefficients decreased from 12.3 to 6.5 g/(m^2 s) rapidly. The change was rather notable. In addition, the Lewis number increased distinctly with the increase of the desiccant temperature. During the first set of experiment, the Lewis number increased from 1.7 to 5.8. During the second and third set of experiment, the Lewis number increased from 1.5 to 2.6 and from 4.2 to 6.8, respectively. So it is concluded that the Lewis number would change much greatly depending on the operation parameters. So during the heat and mass transfer process of air dehumidification, the Lewis number should not be assumed to be constant or unity, especially in the processes parameters of air and desiccant change very much.

Table 5
Experimental conditions (4)

Group	T_a (°C)	ω (g/kg)	G_a (m^3/s)	G_s (kg/s)	T_s (°C)	X_s (%)
1	25.9	7.9	0.23	0.0847	20.5–29.3	35.0
2	25.1	10.6	0.15	0.0847	28–32.36	37.2
3	25.5	10	0.25	0.0847	29–31.2	36.6

3.5. Effects of desiccant concentration on mass transfer coefficient and Lewis number

The experiment conditions were shown in Table 6. In this set of experiment, the thick solution with the solution concentration of 40.2% was confected by 30 kg LiCl dissolved into 44.6 kg pure water. The solution absorbed the water from the air and became diluted, and the diluted solution was pumped into the dehumidifier again till the solution concentration was less than 35%. Therefore, the solution with some different concentrations could be tested. Fig. 11 presents the effects of the desiccant concentration on the mass transfer coefficient and Lewis number. The figure indicates that the mass transfer coefficients increased obviously by increasing the mass concentration of the solution. The mass transfer coefficient was about only 2 g/(m^2 s) at the solution concentration of 34.7%, whereas the h_D was about 21 g/(m^2 s) at the solution concentration of 40.2%, which was more than 10 times of the former. This is just the reason of desiccant solution with high concentration yielding good dehumidification performance. Also, the results showed the Lewis number increased rapidly with the increase of solution concentration. When the concentration of desiccant solution was nearly 40%, the Lewis number was about 1.7.

3.6. Uncertainty analysis and development of experimental correlations of h_D and Le

The mass transfer coefficient h_D and Lewis number Le were derivate from the experimental data and the h_D–Le separative evaluation method. So the uncertainties of h_D *and* Le were from the uncertainty of experimental data U_d and calculated model U_m. The uncertainty of h_D and Le is defined as following equation:

$$U_E = \sqrt{U_d^2 + U_m^2} \tag{16}$$

The input experimental parameters include temperature, flow rate and humidity of the air, temperature, flow rate and concentration of the solution. The uncertainties of these parameters were given in above experiment setup description section. The uncertainty of the calculated method was determined using the uncertainty propagation equation [21]:

$$U_m = \sqrt{\left(\frac{Y_1}{m}\frac{\partial m}{\partial Y_1}\right)^2\left(\frac{U_{Y1}}{Y_1}\right)^2 + \left(\frac{Y_2}{m}\frac{\partial m}{\partial Y_2}\right)^2\left(\frac{U_{Y2}}{Y_2}\right)^2 + \cdots + \left(\frac{Y_n}{m}\frac{\partial m}{\partial Y_n}\right)^2\left(\frac{U_{Yn}}{Y_n}\right)^2} \tag{17}$$

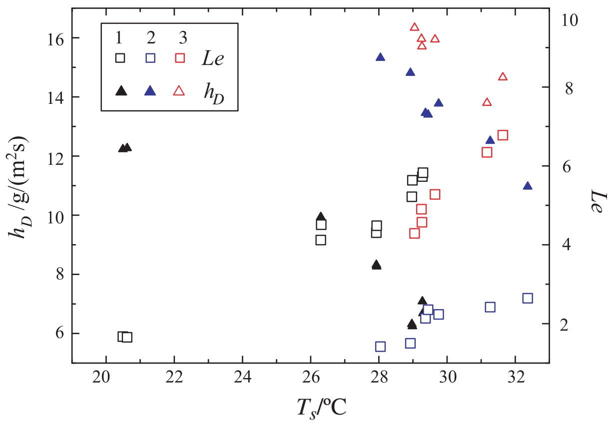


Fig. 10. Effects of solution temperature on mass transfer coefficient and Lewis number.

Table 6
Experimental conditions (5)

T_a (°C)	ω_a (g/kg)	G_a (m^3/s)	G_s (kg/s)	T_s (°C)	X_s (%)
24.9	8.3	0.254	0.0861	29.5	34.0–40.2

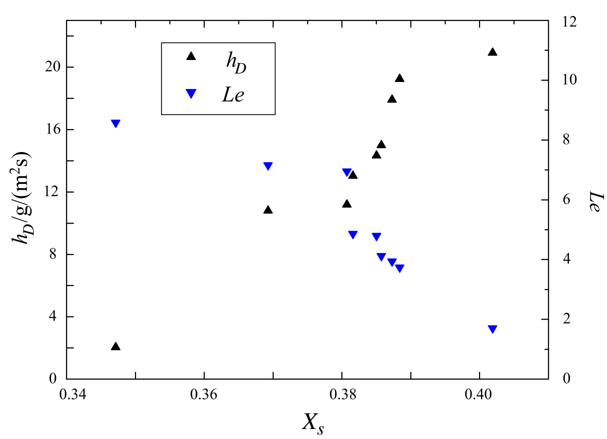


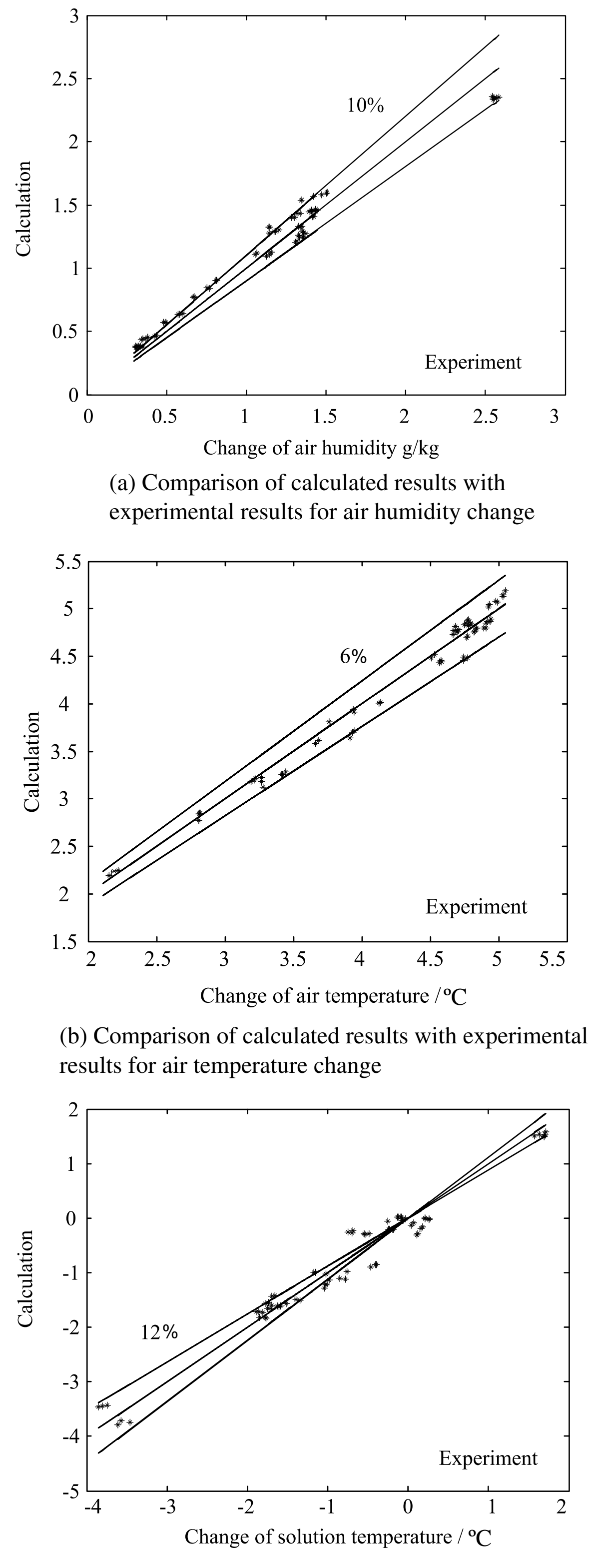
Fig. 11. Effects of solution concentration on mass transfer coefficient and Lewis number.

Here the Y_i terms represent the input variables to the h_D–Le separative evaluation method. The derivatives were determined numerically using a finite difference method. The uncertainty of the mass transfer coefficient h_D from the experimental data was 5.72%, and the uncertainty of the Lewis number was 8.25%.

The mass transfer coefficients of the dehumidification process in the packing were function of the air and solution inlet parameters. Combined with the experimental data and the heat and mass transfer coefficients deduced by the h_D–Le separative evaluation method, the correlations of the

Table 7
Experimental conditions for precision validation

T_a (°C)	ω_a (g/kg)	G_a (m^3/s)	G_s (kg/s)	T_s (°C)	X_s (%)
25.1–28.6	7.4–9.8	0.150–0.308	0.08472–0.1017	28–33.5	34.7–40.2



(a) Comparison of calculated results with experimental results for air humidity change

(b) Comparison of calculated results with experimental results for air temperature change

(c) Comparison of calculated results with experimental results for solution temperature change

Fig. 12. Validated comparison between the calculated value and experimental findings.

heat and mass transfer coefficients h_C, h_D were developed as following by regression method:

$$h_D = 3.0223 \times 10^{-4} U_a^{0.7407} \omega_a^{2.1505} \exp(-0.0011294 T_s) \times \exp(-0.057101 T_a) \exp(19.377 X_s) \quad (18)$$

$$h_C = 6.834 \times 10^6 U_a^{1.3} T_a^{-3.9} T_s^{-1.2} \omega_a^{2.2} \times \exp(6.68 X_s) \exp(-5.71 \times 10^{-2} T_a) \times \exp(-1.13 \times 10^{-3} T_s) \exp(-9.28 \times 10^{-2} \omega_a) \quad (19)$$

where U_a is the velocity of the air entering the packing, m/s. In the correlations the flow rate of the solution is permitted to ignore considering that it is very little but enough to wet the packing.

3.7. Precision validation of the correlations based on h_D–Le separative evaluation method

In order to check the precision of the correlations based on the h_D–Le separative evaluation method, additional 74 groups of experiments were carried out under different operating conditions shown in Table 7. The calculated parameters changes of the air and solution (the flow rate G_a, temperature T_a and humidity ratio ω_a of the air, the temperature T_s and concentration X_s of the solution) were computed based on the regressive correlations applied into *NTU–Le* model. The comparison results were shown in Fig. 12. Fig. 12a showed the discrepancy of the air humidity ratio change between experimental results and the calculated results, and in the figure the discrepancy was within 10%. The discrepancy of the air temperature change between experimental results and the calculated results was within 6%, shown in Fig. 12b. And Fig. 12c indicated the discrepancy of the solution temperature change was less than 12%. Also the results illustrate that the h_D–Le separative evaluation method is acceptable and the correlations of mass transfer coefficients is available for designing or simulating the thermodynamic performance of packing tower.

4. Conclusions

The study presented in the paper led to the following conclusions:

1. Based on the *NTU–Le* model for structured cross flow dehumidification using liquid desiccant, this investigation developed a new method – h_D–Le separative evaluation method for evaluating the coupled heat and mass transfer coefficients between air and liquid desiccant. The new method emphases to the local heat and mass transfer coefficients, which is different from conventional overall average transport coefficients.
2. Inlet parameters such as air temperature, humidity ratio, and flow rate as well as solution temperature and concentration had significant effect on the coupled heat and mass transfer coefficients. Many experiments under different conditions were carried out for providing valid and important data for dehumidifier using the liquid desiccant – aqueous lithium chloride.
3. According to the h_D–Le separative evaluation method, the heat and mass transfer coefficients and Lewis number were solved easily from the experimental data. Effects of the different operating parameters on the heat and mass transfer coefficients and the Lewis number were studied. The results would provide valid data for optimum design of dehumidifiers using for liquid desiccant air conditioning systems and make it possible to study the nonlinear characteristic of liquid desiccant dehumidification process, which will be conducted in our future research based on the new method and its application.
4. Finally, the correlations of the coupled heat and mass transfer coefficients were developed. Additional 74 groups of experiments validated the correlations. The calculated value were compared with the experimental value and it was found that the difference of air humidity change, temperature change and solution temperature change between the calculated and experimental results were, respectively, less than 10%, 6%, 12%. The results illustrated that the h_D–Le separative evaluation method was acceptable and the correlations of mass transfer coefficients were available for designing or simulating the thermodynamic performance of the liquid desiccant air conditioning systems using aqueous lithium chloride.

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