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Title: Investigation on the regeneration performance of liquid desiccant by adding surfactant PVP-K30

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Abstract: The liquid desiccant cooling system (LDCS) is a promising alternative for the conventional vapor compression system due to its high energy efficiency. To enhance the mass transfer between the regeneration air and liquid desiccant in the regenerator, the paper firstly introduced a kind of surfactant called polyvinyl pyrrolidone (PVP-K30) which was added into the LiCl solution for better desiccant regeneration performance. The falling film characteristics and regeneration performance were investigated and compared with and without surfactant. The results indicated that the contact angle of desiccant solution on plate decreased from 58.5^o to 28.0^o by adding surfactant with 0.4% of concentration. The average wetting area increased from 0.174m^2 to 0.209m^2 with a relative increment of 20.1% with the addition of surfactant. Correspondingly, the film thickness had a reduction of 0.103mm from 0.696mm to 0.593mm averagely. The regeneration rate had an average enhancement of 26.3% under the same working conditions, resulting from the decrement of solution contact angle with the addition of the surfactant. Finally, correlations to predict the mass transfer coefficient were proposed with and without surfactant and the mean absolute relative deviation between the results of correlations and the experiments were kept within 8%. The results and findings of present paper could be applied to guide the design of compact regenerator for higher regeneration performance.

Key words: surfactant, mass transfer enhancement, regeneration, falling film, correlation

Nomenclature			
A	Wetting area (m^2)	Greek symbols	
D	Diffusion coefficient (m^2/s)	φ	Relative humidity (%)
d	Absolute humidity (g / kg)	ρ	Density (kg / m^3)
G	Flow rate (kg / s)	μ	Dynamic viscosity ($Pa.s$)
h	Enthalpy (kJ / kg)	Δ	Change value
h_m	Mass transfer coefficient ($kg / (m^2.s)$)	$\sum v$	Diffusion volume of molecule (cm^2/mol)
l	Characteristics length (m)	Subscripts	
$LDCS$	Liquid desiccant cooling system	a	Air
M	Molar mass (g / mol)	dry	Dry bulb
Δm	Dehumidification rate (g/s)	e	Equilibrium
N	Data points	i	Inlet
Re	Reynolds number	o	Outlet
Sc	Schmidt number	s	Solution
Sh	Sherwood number	w	Cooling water or water vapor
T	Temperature (^oC)	pre	Predicted value
v	Velocity (m / s)	exp	Experimental valve
X	Concentration (%)		

1 Introduction

The energy consumption of buildings accounts for a heavy proportion in the whole energy consumption, such as more than 60% in Hong Kong, 30% in America and 40% in European countries [1]. Among the building energy consumption, about 30% to 50% is consumed by the air-conditioning system [2]. In the traditional air-conditioning system, the sensible heat load and latent heat load are handled together by cooling the processed air below the dew point temperature. However, in most situations, reheating is adopted subsequently to achieve suitable supply air temperature. As a result, the coefficient of performance of the system would reduce. Moreover, the condensation water due to the low temperature may provide a necessary condition for breeding bacteria [3]. Researchers try to find some alternatives for the conventional air conditioning system. By dealing with the sensible heat load and humidity load separately, the liquid desiccant cooling system (LDCS) is regarded as a prospective alternative among all the candidates.

Some previous investigation indicates that the LDCS has the potential to save up

40% energy compared with the traditional air conditioning system [4]. What is more, the regenerator in the LDCS can take advantage of solar thermal energy for regeneration so as to conserve energy and reduce CO_2 emission. Other merits, such as accurate humidity control ability and environmental friendly, are also possessed by the promising LDCS. Consequently, it draws more and more attention in recent years.

Dehumidifier and regenerator are two main components in a typical LDCS. In a dehumidifier, the concentrated liquid desiccant, such as lithium bromide (LiBr) and lithium chloride (LiCl) solution, absorbs water vapor from the processed air and becomes weak. The weak solution is then regenerated in a regenerator. The mass transfer driving force for both of the two processes are the partial water vapor difference between the air and the solution. In order to make the dehumidifier or regenerator more compact and efficient, various methods for heat and mass transfer enhancement have been proposed. The methods can be classified into two categories, namely structure improvement and solution modification. Researchers have put forward different structures for improvement, such as tube-fin [5], plate-fin [6, 7], constant curvature surface [8] and super-hydrophilic coating [9, 10]. The enhancement mechanisms can be summarized into two types, i.e., disturbance generation and wetting area increment. The solution modification includes adding nano-particle and surfactant to the desiccant. For the former one, certain kinds of nano-particles are dispersed into the desiccant solution with different physical and chemical ways. Nano-particles such like CNTs, Fe, and SiO_2 have been employed in the existing studies [11, 12]. Different degrees of heat and mass transfer improvement were observed from these studies. About adding the surfactant which is the research interest of present study, detailed review is conducted as follows.

Early in the 1960s, Beutler et al. [13] had found that the absorption rate of refrigeration vapor was enhanced by the adding of certain kinds of alcohols and other hydrocarbon chains compound with polar groups. Then in 1990s, Cosenza and Vliet [14] added 2-ethyl-1-hexanol into the desiccant solution to investigate the water vapor absorption characteristics. They found that the absorption rate was increased up to 4 times with the adding of surfactant. Different degrees of absorption enhancement were also observed by adding 2-ethyl-1-hexanol [15, 16]. The enhancement mechanism could be partly explained by the model proposed by Kashiwagi in 1988 [17]. The Kashiwagi model held the view of point that there were additive islands on the surface of solution. The surface tension gradient caused by the presence of additive islands triggered the Marangoni convection in the solution. However, other studies pointed out that the additive islands were not the prerequisites [18] for Marangoni convection. In 1991, Hozawa et al. [19] employed n-octanol and n-decanol as additives in lithium bromide (LiBr) solution to investigate the static absorption performance. They found that the initial absorption rate increased up to 2.5 times with the addition of n-octanol even under unsaturated additive concentration, which could not be explained by the Kashiwagi model. In order to explore the enhancement mechanism, Ziegler et al. [20] conducted a review based on the papers presentated in an academic conference in 1996. The commonly empolyed additives, such as n-octanol, n-heptanol, 2-ethyl-1-hexanol and 6-methyl-2-heptanol, were introduced and so were the influence of their addition amount on absorption enhancement. They also classified the related studies into four categories based on different applications, i.e., stagnant pool absorption, horizontal and vertical falling film absorber (both on tubes and plates) and filed test. Regrettably, they just summarized the research status rather than uncovered the mechanisms under the enhancement phenomenon. After that in 1997, Daiguji et al. [21] developed a new model called salting-out model to figure out the initial cause of Marangoni convection. They indicated that the hydration force between water molecules and electrolyte ions of Li^+ and Br^- was stronger than that between water molecules and additive molecules. The absorption of the water vapor at the surface of solution broke the balance of original status. The absorbed water molecules had to be combined with electrolyte ions in bulk solution rather than the additive molecules at the surface, which caused the segregation of additive molecules from bulk solution. Consequently, Marangoni convection occurred because of the surface tension imbalance. Nevertheless, the model did not work when the additive was over-saturated. For example, absorption enhancement was reported even at oversaturated solubility by Beulter et al. [13]. As a supplementary, Kang et al. [22] proposed the solubility model which could be applied to the situations of oversaturated solubility in 1999. When the concentration of surfactant exceeded the solubility, the inducement of Marangoni convection was the imbalance of surface tension and interfacial tension. All of the above models focused on the solution itself. Differently, Kulankara and Herold [23] focused on the additive vapor and proposed the vapor surfactant theory. But the theory has its limitation because certain kinds of surfactants, such as Triton X-100, have negligible volatility, while the absorption enhancement by adding Triton X-100 was detected by Kang et al. [24]. Accordingly, we can conclude that the mechanisms of the mass transfer enhancement of various surfactants are still not clear as each model has its limitations for the explanation of absorption enhancement regarding the variety of surfactants.

Previous researches of surfactant are mainly focused on absorption refrigeration. In the absorption cooling system, working pairs of refrigerant and absorbent were certain binary solvents that circulated in a closed loop. Therefore, it does not matter if the surfactants have odour, toxicity and volatility as they are in the closed type system. As a matter of fact, nearly all the adopted surfactants in existing studies are some kinds of alcohols or something similar, n-octanol, n-heptanol and 2-ethyl-1-hexanol and so on. They are more or less odorous, volatile or toxic. However, different from the absorption refrigeration system, the LDCS works in an open loop in which the processed air should contact directly with the desiccant solution. Therefore, the foregoing surfactants cannot be applied to the LDCS directly due to their odour, toxicity and volatility which might threat to the indoor air quality as the processed air can carry the droplets and pollutants into the indoor environment. Furthermore, all the previous studies were concentrated on the absorption performance in the absorber, but the regeneration process which is another indispensable part has drawn rare attention.

Considering the particular applications of LDCS, an odorless, non-volatile and nontoxic surfactant called polyvinyl pyrrolidone (PVP-K30) was firstly introduced in present study. As shown in Table 1 [26], PVP-K30 can easily dissolve in different kinds of solutions including LiCl desiccant solution and has steady physical and chemical properties under conventional working environment as well. It has been widely used in various industries, such as medicine, healthcare, food production, cosmetics and detergent [25]. Without polluting the processed air, PVP-K30 is very suitable for LDCS. In this study, a single channel plate regenerator made of stainless steel 316L with the size of 500mm*500mm (Length*Width) was employed for experiments. The detailed configuration of the regenerator was presented in Fig. 1. A cuboid distributor with a gap in the front was employed to uniformly distribute the liquid desiccant on the plate. An adjustable cover was employed to segregate the processing air from the ambient air and guarantee the processed air flow in the regenerator. The width between the regenerator plate and cover can be easily regulated according to experiment requirements. The contact angle, wetting area and film thickness of LiCl solution were firstly investigated with and without the addition of surfactant. Comparative investigations were carried out to identify the influences of different parameters on regeneration performance. Finally, correlations to predict the mass transfer performance were developed.

Table. 1. Specifications of the PVP-K30.

Name	Molecular formula	Molecular weight	Toxicity
polyvinyl pyrrolidone	$(C_6H_9NO)_n$	40000	non-toxic
Odour	Stability	Solubility	Manufacturer
odorless	stable	100mg/mL(water)	Aladdin

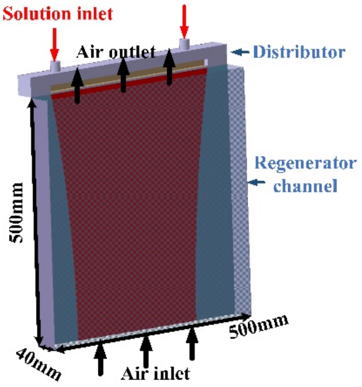


Fig. 1. Detailed configuration of the single channel regenerator.

2 Experimental method

2.1 Test bench description

An experimental system with the function of various parameters adjustment was purpose-built to identify the effects of different factors on regeneration performance. The detailed schematic diagram of the system is shown in Fig. 2. The whole test bench consisted of three loops distinguished by the color of the arrows, namely processed air loop, liquid desiccant loop and hot water loop. By regulating the instruments in each loop, six parameters, including air flow rate, temperature, inlet humidity and solution flow rate, temperature and concentration, can be adjusted to the set values. The test bench was installed in a laboratory with the ability to keep the temperature and moisture at a relatively steady level. All pipes or ducts in the system were wrapped by thermal insulation material to minimize the heat exchange with the ambient environment.

The air was pumped into the air duct by the help of an axial fan. By regulating the angle of a damper in the duct, the required air flow rate could be obtained. Then an electrical heater and a humidifier were employed to adjust the inlet air temperature and humidity. The heating power of electrical heater was controlled by a Proportion-Integration-Differentiation (PID) controller automatically through the feedback signal of air temperature. The air then flowed into the single channel regenerator for solution regeneration.

For the desiccant solution loop, the solution was stored in a plastic tank with an electrical heater inside. With another PID controller, the solution temperature was adjusted to a certain value. Then, the solution was driven by a pump to flow in the loop. The flow rate was controlled by a three-way valve by regulating the opening angle. After filling the distributor, the liquid desiccant overflowed the distributor through the gap and fell along the surface of the single channel stainless steel regenerator. A collector was installed under the regenerator to collect the solution after regeneration. Finally, the solution flowed back to another tank which was connected with the collector.

In the present study, internal heating was employed to improve the regeneration performance. In the process of regeneration, liquid water evaporates from the desiccant solution driven by the partial water vapor pressure difference between the solution and air. During the mass transfer process, vaporization latent heat is needed which was obtained mainly from the bulk solution. As a result, a temperature reduction of the solution would occur, resulting in the deterioration of regeneration performance if no measures are taken. The hot water provided by a controllable heat source complemented the heat for the solution during the regeneration process with a single channel heat exchanger as indicated in Fig. 2. Counter current configuration was arranged in the heat exchanger for higher efficiency.

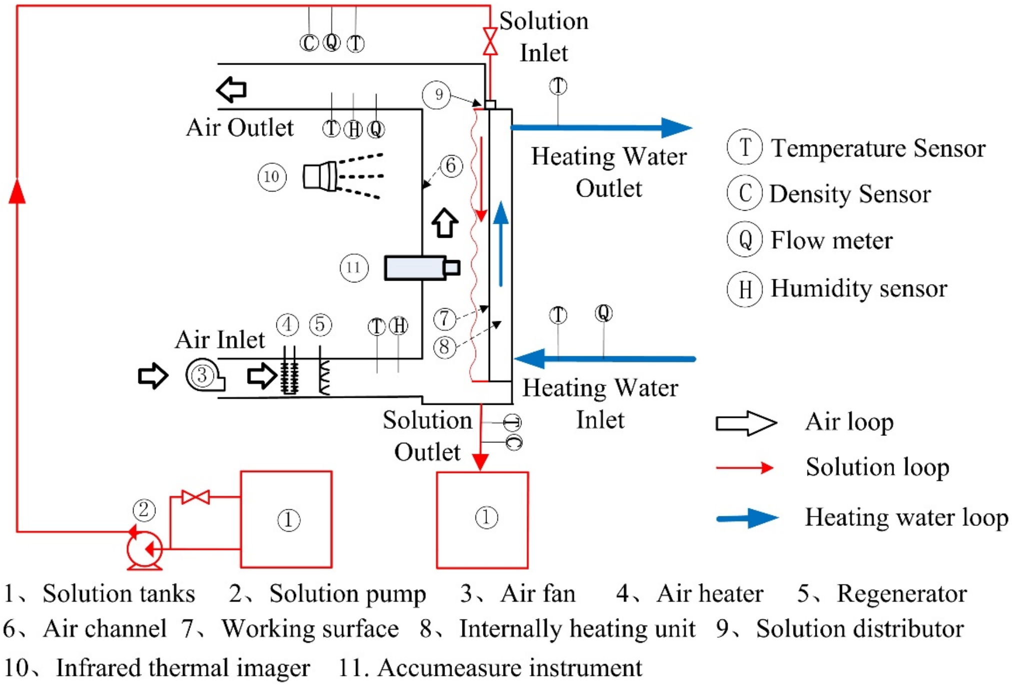


Fig. 2. Schematic diagram of the test bench.

2.2 Data measurement and reduction

The inlet and outlet air temperatures and humidity were measured by two sensors with the accuracy of 0.1K for temperature and 3% for humidity. A Pitot tube which was connected with a micro-manometer was installed at the outlet of air duct to measure the airflow rate. The accuracy of air flow rate measurement was 2.5%. Both the inlet and outlet temperatures of solution and hot water were got by four Pt-100 thermocouples with the accuracy of 0.1K. Two turbine flow rate sensors with the accuracy of 3% were employed to measure the flow rate of liquid solution and hot water respectively. For the measurement of solution concentration, a specific gravity hydrometer and a Pt-100 thermocouple were used. The solution density and temperature were obtained firstly. Then, with the conversion equations provided by Conde [27], the concentration was calculated with the uncertainty of 0.2%. All the experimental signals generated by thermocouple, flow meter and humidity sensor were collected, converted，displayed and stored by a data logger for subsequent processing. A standard contact angle goniometer produced by Rame-hart instrument Co. was employed to measure the contact angle on stainless steel plate. It has a high accuracy of 0.1^{o}. Before the measurment, the surface of the plate was cleaned by acetone and ultrasonic cleaning tank for credicle results. The wetting area was obtained by using a high resolution infrared thermal imager from FLUKE company with the error within 3%. For the measurment of falling film thickness, we empolyed the JDC-2008 accumeasure instrument developed by TianJin Univesity. It has the accuracy of $0.8\,\mu\mathrm{m}$. The working priciple of accumeasure instrument is shown in Fig. 3 [28]. The circuitry consists of a capacitor, a operational amplifier and two electrical condutors. The two conductors are seperated by a dielectric medium and when the permittivity of the medium changes, the capacitor voltage changes simultaneously. According to the measured capacitor voltage, initial value of height and other parameters, the thickness of falling film can be determined. The specifications of directly measured parameters are illustrated in Table 2.

Table 2. Specification of direct measured parameters.

Parameter	Instrument	Accuracy
Temperature (^{o}C)	Pt-100 thermocouple	$\pm 0.1K$
Air relative humidity ($\%$)	Humidity sensor	± 2.5%
Solution flow rate (kg/s)	Turbine flow rate sensor	± 3%
Water flow rate (kg/s)	Turbine flow rate sensor	± 3%
Air flow rate (kg/s)	Pitot tube	± 2.5%
Solution density (kg/m^3)	Specific gravity hydrometer	$\pm 1kg/m^3$
Contact angle (^{o})	Standard contact angle goniometer	$\pm 0.1^{o}$
Wetting area (m^2)	Infrared thermal imager	± 3%
Film thickness (mm)	JDC-2008 accumeasure instrument	$\pm 0.8\mu m$

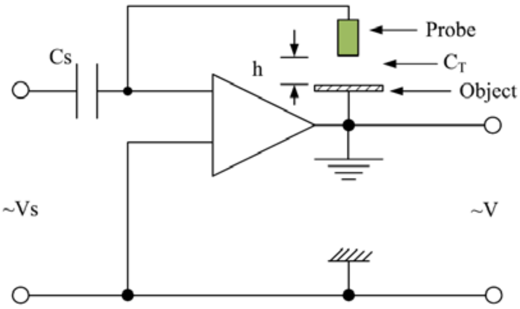


Fig. 3. Working principle of the JDC-2008 accumeasure instrument [28].

The regeneration rate which has been widely used by previous researchers was selected to evaluate the regeneration performance in present study.

The definition for regeneration rate is:

$$\Delta m = G_a.(d_{a,o} - d_{a,i}) \tag{1}$$

where G_a denotes the mass flow rate of air. The subscripts a, o, i correspond to air, inlet and outlet respectively. This index can reflect the amount of water evaporated from the solution directly.

d represents absolute humidity which is calculated by:

$$d = f(T_{dry}, \varphi) \tag{2}$$

where T_{dry} is the air dry bulb temperature and φ is the relative humidity measured by the humidity sensor.

The mass transfer coefficient is defined as:

$$h_m = \frac{G_a}{A} \frac{d_{a,o} - d_{a,i}}{d_e - d_{a,i}} \tag{3}$$

where A is the wetting area of falling film on plate. d_e represents the absolute moisture content of the processed air in the condition of equilibrium with desiccant solution at its concentration and temperature and is acquired by the equation in [27].

When regeneration occurs in the single channel regenerator, heat and mass transfer takes place simultaneously. According to the conservation theories, all such thermodynamics processes have to follow the energy and mass conservation theories, as presented in Equation 4 and 5 respectively.

$$G_s(h_{s,o} - h_{s,i}) = G_w(h_{w,i} - h_{w,o}) + G_a(h_{a,i} - h_{a,o}) \tag{4}$$

$$G_a(d_{a,i} - d_{a,o}) = G_s X_{s,i}\left(\frac{1}{X_{s,o}} - \frac{1}{X_{s,i}}\right) \tag{5}$$

In the above two equations, the mass flow rate, enthalpy and solution concentration are described by G, h and X respectively. The subscripts s, w denote the solution and cooling water correspondingly. Equation 4 indicates that the enthalpy change of water and air is equal to that of solution. The mass changes in air and solution due to the regeneration are equivalent, which is formulated by Equation 5.

2.3 Uncertainty analysis and experimental validation

Each parameter of measurement has its accuracy and it is determined by the precision of the sensor and data conversion module. Therefore, for the parameters that measured by sensors directly, their uncertainties are determined by the accuracies of sensors. In present study, the directly measured parameters and their accuracies have already been listed out in Table 2. Parameters, such as solution concentration, air absolute humidity and regeneration rate, are calculated through the formulas. Their uncertainties are obtained by employing the uncertainty propagation method and are summarized in Table 3.

Table 3. Uncertainties of indirect measured parameters.

Parameter	Uncertainty	Parameter	Uncertainty
Solution concentration/ X_s	0.2%	Regeneration rate/ Δm	4.1%
Air absolute humidity/ d	2.7%	Mass transfer coefficient/ h_m	6.2%

Before the systematic investigation on regeneration, the test bench was validated by the energy conservation equation. It is worth mentioning that the mass conservation was not checked in present study due to the negligible change of solution concentration on the right side of Equation 5. The validation results for solutions with and without surfactant are plotted in Fig. 4. It is found that most of the experimental points have the error less than 20%, which indicts the rationality of the subsequent experimental exploration.

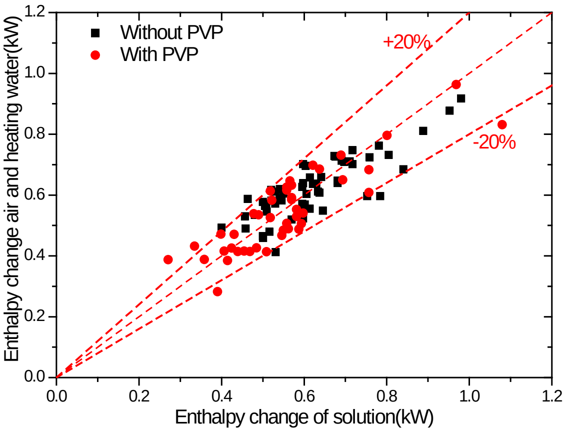


Fig. 4. Energy balance validation of the test rig.

3 The characteristics of falling film

3.1 Contact angles of solution under different surfactant concentrations

Using a standard contact angle goniometer, the contact angles of LiCl solution under various surfactant concentrations (ranging from 0% to 3%) were measured, as shown in Fig. 5. We can see a significant contact angle reduction of 16.5^{o} even when the concentration of surfactant is only 0.1%. With the increase of surfactant concentration, the contact angle presents a descending trend. However, the drop rate decreases gradually and reaches to a steady level. When the concentration of surfactant changes from 0% to 0.4%, the decrement of contact angle is up to 30.5^{o} from 58.5^{o} to 28^{o}. Nevertheless, only 4.1^{o} reduction is detected even though the surfactant concentration increases from 0.4% to 3%. Therefore, in the present study, the surfactant concentration of 0.4% was selected for regeneration investigation. Fig. 6 shows the contact angles of LiCl solution without surfactant and with the surfactant concentration of 0.4%. It is obvious the adding of the surfactant could reduce the contact angle significantly.

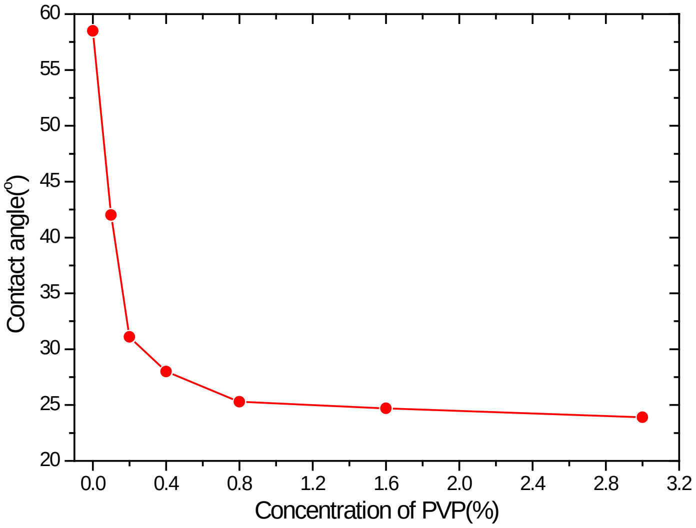
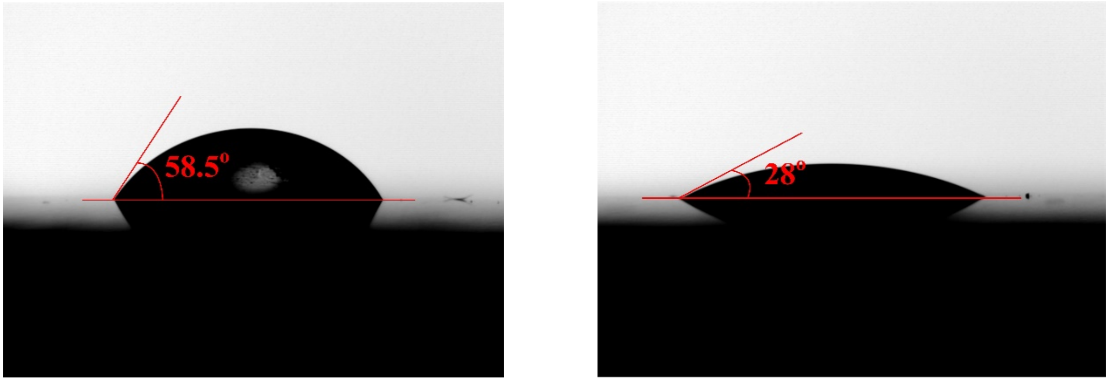


Fig. 5. Contact angle of LiCl solution under different surfactant concentrations.



Without surfactant With 0.4% surfactant

Fig. 6. Pictures of contact angles with and without surfactant.

3.2 Wettability

As shown in Fig. 7, the influence of solution flow rate on wetting area with and without surfactant is indicated. The concentration and temperature of solution were 34% and 50°C. The wetted areas for solution with and without surfactant keep constant at around 0.209m^2 and 0.174m^2 respectively when the mass flow rate is bigger than 0.08kg/s. Therefore, it is concluded the wettability will not change when the mass flow rate of solution reaches a certain value. During the experiments, a distinct rim part of the falling film was observed as shown by Fig. 8. An explanation for the unobvious change of wetting area under different solution flow rates is that no enough energy can be provided to overcome the resistance at the rim streamline to make it expand outward. As a result, the rim streamline keeps nearly motionless and so does the wetting area. By comparing the data with and without surfactant, a remarkable relative increment of 20.1% can be found by adding surfactant with the concentration of 0.4%.

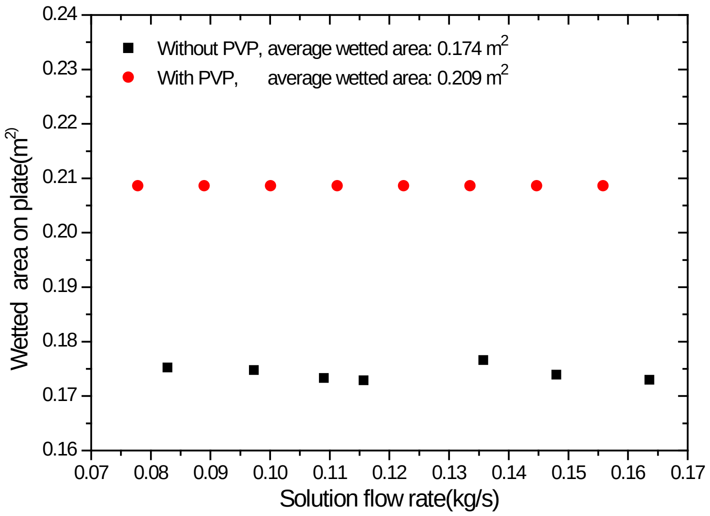


Fig. 7. Influence of solution flow rate on wetting area with and without surfactant.

Fig. 8. Information of the rim part of the falling film on plate.

3.3 Film thickness

The film thicknesses under different solution flow rates are presented in Fig. 9. The film thickness has a gradual increase when the flow rate increases from 0.088kg/s to 0.156kg/s. The film thickness increases from 0.671mm to 0.730mm for solution without surfactant and from 0.555mm to 0.625mm for solution with surfactant. The average film thicknesses for solutions with and without surfactant are 0.696mm and 0.593mm respectively. A reduction of 0.103mm is detected by adding 0.4% surfactant. Comparison is also shown between the experimental film thickness and predicted value of Nusselt equation [29] in Fig. 9. The formulation for the Nusselt is described by Equation (6) as follows:

$$\delta = 0.909(\mathrm{Re}_s \frac{\mu_s^{2}}{\rho^{2} g})^{1/3} \tag{6}$$

As the dynamic viscosity of liquid desiccant with PVP is unknown, the comparison is only conducted for LiCl solution without surfactant. The predicted film thicknesses by Nusselt equation match well with the experimental ones with the mean absolute relative deviation of 4.1% for all experimental data.

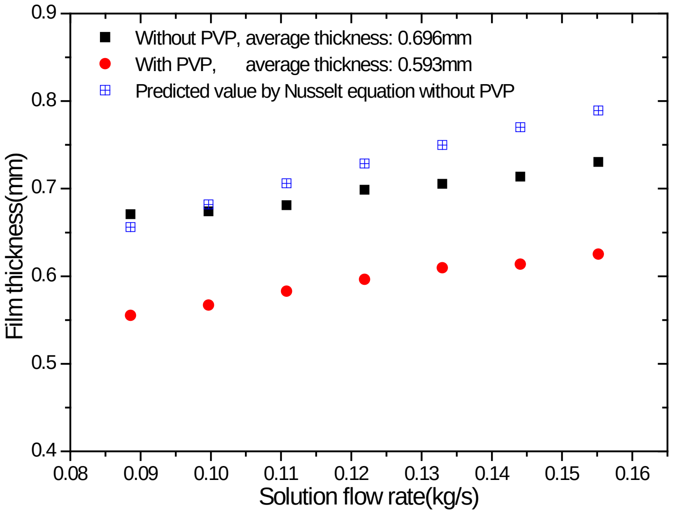


Fig. 9. Influence of solution flow rate on film thickness with and without surfactant.

4. Regeneration performance and discussion

4.1 The influence of air temperature

Fig. 10 shows the effect of air inlet dry bulb temperature on the regeneration rate. No distinct trend can be observed when the air temperature increases form 28.5°C to 35.5°C. The regeneration rate keeps around 0.097g/s and 0.132g/s for desiccant solution without and with surfactant respectively. It can be explained by the unaltered mass transfer coefficient and wetting area under ascending temperature. However, significant increment of regeneration rate can be found by adding the surfactant. The average relative increment is up to 36.1% for regeneration rate under the same experimental conditions.

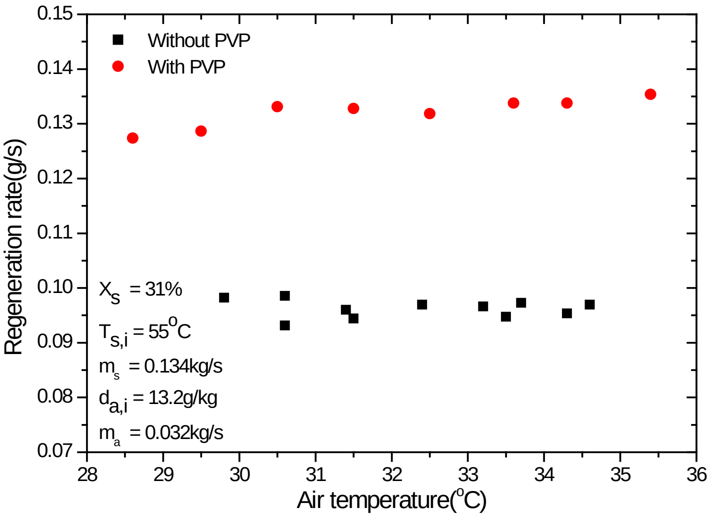


Fig. 10. Influence of air inlet dry bulb temperature on regeneration rate.

4.2 The influence of air flow rate

The influence of air flow rate on the regeneration performance is given in Fig. 11. It is obvious that the regeneration rates show an ascending trend with the increase of air flow rate for both solutions. It can be attributed to the increase of mass transfer coefficient with the increment of air flow rate. For desiccant solution with surfactant, when the air flow rate increases from 0.023kg/s to 0.065kg/s, an increment of 0.0193 kg/(m^2.s) from 0.0146 kg/(m^2.s) to 0.0339 kg/(m^2.s) is found. The relative enhancement after the addition of surfactant ranges from 24.4% to 40.4% under comparable operating conditions.

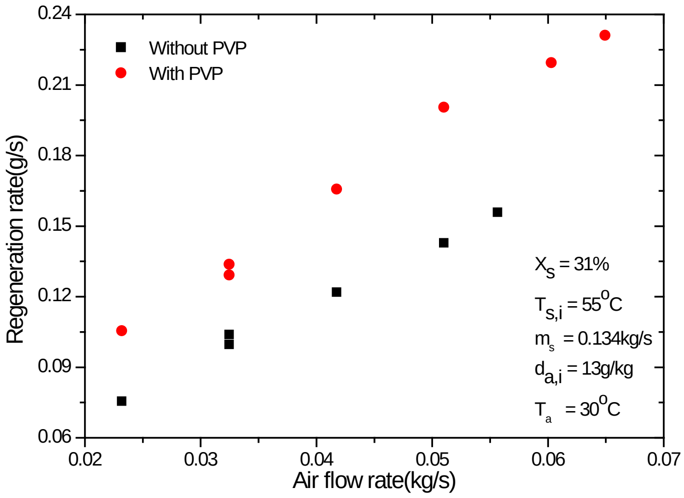


Fig. 11. Influence of air flow rate on regeneration rate.

4.3 The influence of air inlet humidity

As shown in Fig. 12, the influence of air inlet humidity on regeneration rate is illustrated. The regeneration rate decreases with the increase of air inlet humidity. This can be easily understood in terms of mass transfer driving force. The regeneration process is driven by the partial water vapor pressure difference between air and solution. The inlet humidity is directly related with the partial water vapor pressure in air. When the inlet humidity has an increment, the mass transfer driving force has a corresponding decrement, and so does the regeneration rate. The enhancement in terms of regeneration rate is clearly presented in Fig. 12.

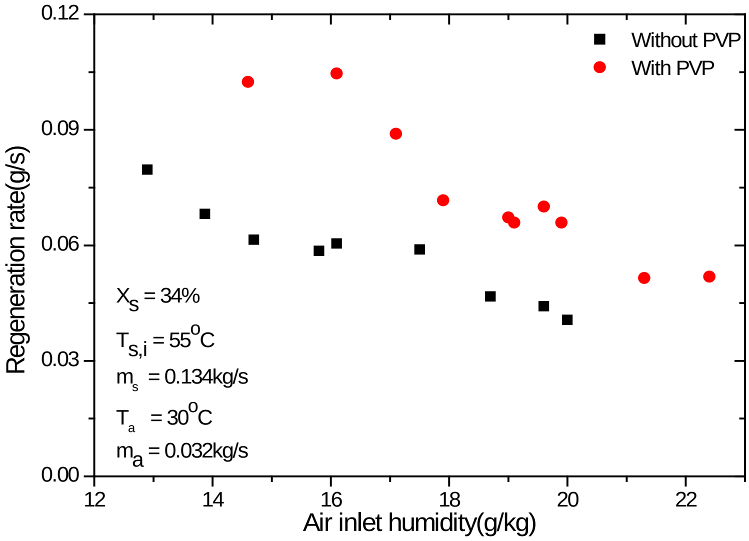


Fig. 12. Influence of air inlet humidity on regeneration rate.

4.4 Influence of solution temperature

The results of regeneration rates with four different temperatures are compared in Fig. 13 for desiccant solution with and without surfactant. When the solution temperature changes from 48°C to 55°C, the regeneration rate also increases from 0.10g/s to 0.14g/s for solution without surfactant and from 0.13g/s to 0.20g/s for solution with surfactant. The ascending trends are owing to the increment of partial water vapor pressure of solution. The partial water vapor pressure has an increment of 2021.8Pa from 4653.8Pa to 6675.6Pa (The partial water vapor pressure in air is 2230.4Pa under the working conditions of Fig. 13) which corresponding to the increment of equivalent moisture content from 30g/kg to 43.9g/kg for solution. Consequently, the mass transfer driving force in the form of the difference between solution and processing air also increases from 16g/kg to 29.9g/kg. A noteworthy relative increment of 40.4% is found at the temperature of 55°C with the adding of surfactant.

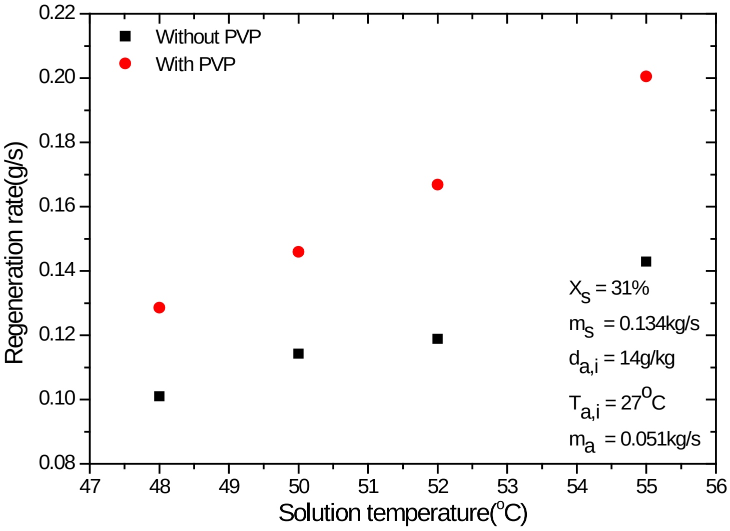


Fig. 13. Influence of solution inlet temperature on regeneration rate.

4.5 The influence of solution flow rate

As shown in Fig. 14, the mass flow rate of solution has negligible influence on the regeneration characteristics. Even when the flow rate increases from 0.080kg/s to 0.145kg/s by two times, the regeneration rate fluctuates around the values of 0.077g/s and 0.102g/s for situations without and with surfactant. The relatively stable values of regeneration rate can be interpreted by the falling film characteristics described above. The increase of solution flow rate will not increase the wetting area and change the falling film thickness obviously, so solution flow rate has insignificant effect on the regeneration rate. The average absolute increment for regeneration rate is 0.025g/s from 0.077g/s to 0.102g/s for solution without and with surfactant.

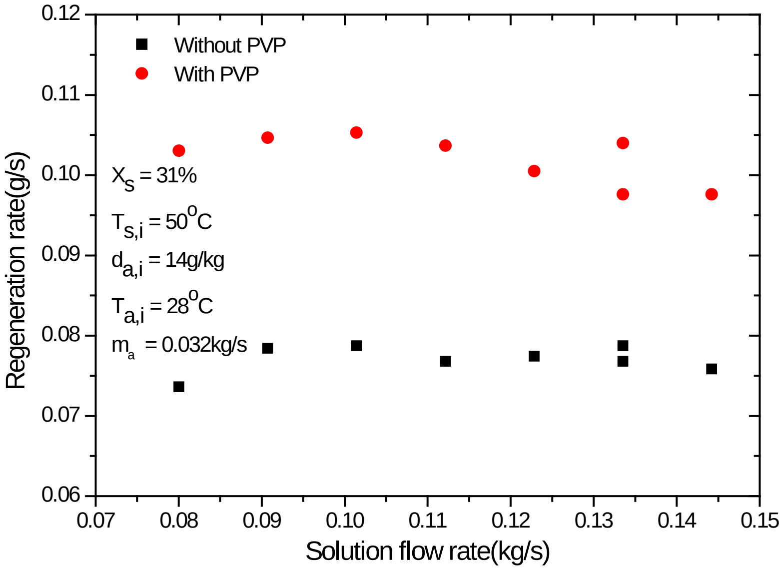


Fig. 14. Influence of solution flow rate on regeneration rate.

4.6 Influence of solution concentration

Fig. 15 provides the experimental data on the influence of solution concentration. As shown, the increase of solution concentration leads to the decrease of regeneration rate. This descending trend is caused by the decrement of partial water vapor pressure at the surface of solution. When the solution concentration increases from 31% to 35% under the operating temperature of 55°C, the equivalent moisture content at the surface of the solution decreases from 43.9g/kg to 33g/kg. As a result, the mass transfer driving force which is the difference between the equivalent moisture content of solution and the processed air also decreases from 30.4g/kg to 19.5g/kg. The decrement of mass transfer force results to the reduction of regeneration rate from 0.1g/s to 0.082g/s and 0.133g/s to 0.105g/s for solution without and with surfactant respectively. The relative enhancement for regeneration rate is 31.2% averagely under comparable experimental conditions.

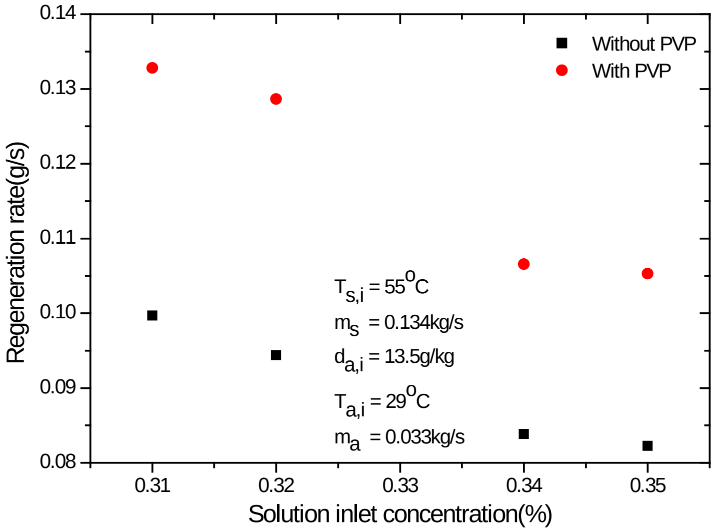


Fig. 15. Influence of solution concentration on regeneration rate.

4.7 Discussion

As demonstrated from Fig. 10 to Fig. 15, the adding of surfactant PVP-K30 results in significant improvement in regenenetion rate. Under different experimental conditions, the increasement rate is different, but 26.3% on average under all comparable conditions. One of the main reasons of the mass transfer enhancement is the increment of wetting area. According to the test results, the average increment of wetted area is around 20.1%, which directly results in the corresponding increment in the regeneration rate. However, the increasing rate of wetting area is relatively smaller and not enough to generate so bigger increase of regeneration rate. In our mind, another contributor to regeneration rate improvement is the enhancement of internal heating performance. Therefore, it can be described in the following two aspects. On one hand, the enlargement of wetting area leads to greater heat exchange area between solution and hot water. Larger heat tranfer area between liquid desiccant and hot regenreator plate will help to maintain the solution temperature at a higher level. On the other hand, the decrement of film thickness results in the reduction of heat exchange resistance between falling film and hot regenerator plate. As a result, the internal heating performance is enhanced, which can be validated by the higher temperature at the outlet of regenerator during the experiments with surfactant. The outlet temperature of solution with surfactant is 0.1°C to 0.3°C higher than that without surfactant under the same operating conditions. The slightly higher average solution temperature caused by better internal heating performance leads to greater regeneration rate.

5 Correlation development

For the purpose of mass transfer coefficient prediction, correlations are proposed for the stainless steel plate falling film regenerator with and without surfactant PVP-K30. The mass transfer coefficient h_m is expressed in Equation 7.

$$h_m = \frac{\rho_a D}{l} Sh \tag{7}$$

in which ρ_a is the density of air. l is the characteristics length. For the rectangular channel in present study, it can be calculated by Equation 8. D is the diffusion coefficient of moist air determined by Equation 9 which is proposed by Fuller et al. [30]. Sh is the dimensionless Sherwood number which can be obtained by equation 10.

$$l = \frac{2ab}{a+b} \tag{8}$$

where a and b denote the length and width of rectangular channel respectively.

$$D = \frac{10^{-3} * T^{1.75} \sqrt{\left(\frac{1}{M_a} + \frac{1}{M_w}\right)}}{P[(\Sigma v)_a^{1/3} + (\Sigma v)_w^{1/3}]^2} \tag{9}$$

In Equation 9, T represents temperature of air. M_a and M_w stand for the molar mass of air and water vapor severally. P means the pressure of air. $(\sum v)_a$ and $(\sum v)_w$ are the diffusion volume of molecule for air and water vapor respectively.

$$\begin{aligned} &Sh = 0.0139 * Re_a^{0.75} * Sc_a^{4.81} * d_{a,i}^{-0.53} d_e^{-0.68} \quad && without\ surfactant \\ &Sh = 0.0146 * Re_a^{0.75} * Sc_a^{4.81} * d_{a,i}^{-0.53} d_e^{-0.68} \quad && with\ surfactant\ PVP-K30 \end{aligned} \qquad (10)$$

where Re_a is the Reynolds number of air and described in Equation 11. Sc_a stands for the Schmidt number of air and defined in Equation 12.

$$Re = \frac{\rho v l}{\mu} \qquad (11)$$

in which v and μ are the velocity and dynamic viscosity of air respectively.

$$Sc = \frac{\mu}{\rho D} \qquad (12)$$

The most important point of the proposed correlations is the prediction of Sherwood number. The form of this correlation is developed according to the regeneration experiments as shown above. The influences of air flow rate can be involved by the parameters of Re_a and Sc_a. $d_{a,in}$ and d_e can indicate the effects of air inlet humidity, solution temperature and concentration. The constants at the front of correlations in Equation 10 are slightly different due to the regeneration enhancement of surfactant PVP-K30. Mean Relative Deviation (MRD) and Mean Absolute Relative Deviation (MARD) are used to evaluate the prediction accuracy of new correlations.

$$MRD = \frac{1}{N}\sum_{i=1}^{N} \frac{h_{m,pre} - h_{m,\exp}}{h_{m,\exp}} \qquad (13)$$

$$MARD = \frac{1}{N}\sum_{i=1}^{N} \left| \frac{h_{m,pre} - h_{m,\exp}}{h_{m,\exp}} \right| \qquad (14)$$

Fig. 16 shows the comparison between experimental data and correlation predictions in terms of mass transfer coefficient, from which good agreement can be observed. Both the MARDs for solutions with and without surfactant are less than 8%. 117 out of 130 experimental data points have the MRD within $\pm 15\%$ for solution without surfactant and 107 out of 110 points for solution with surfactant. To further validate the prediction accuracy of the proposed correlations, experimental data from other research need to be used for comparison. However, few studies gave comprehensive investigation on the regeneration performance of an internal heating regenerator, especially with the application of surfactant. What is more, the mass transfer area, i.e., the wetting are of falling film, is an important factor to determine the mass transfer coefficient, but it is seldom measured by previous researchers. As a result, the prediction accuracy of the new empirical correlations could only be checked with the present experimental results.

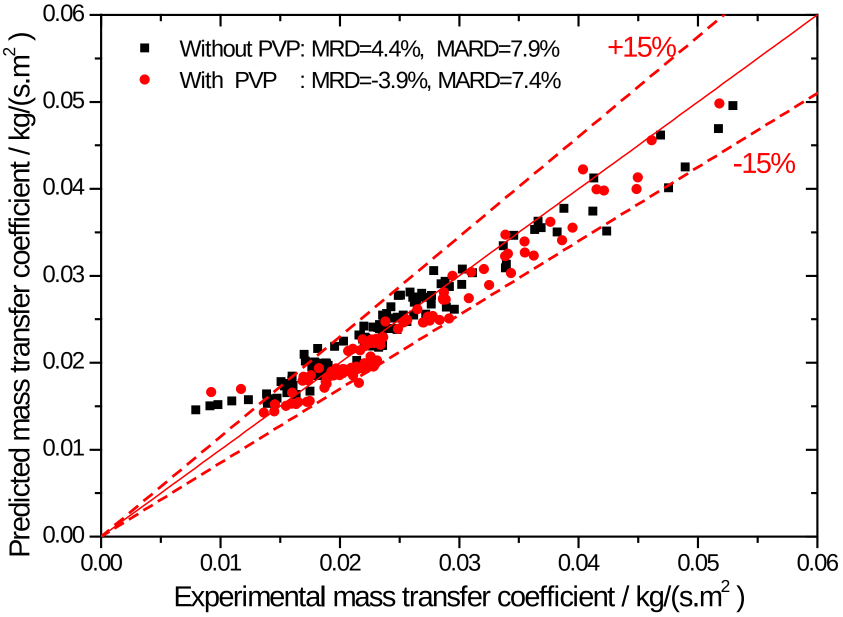


Fig. 16. Comparison between the experimental and predicted mass transfer coefficients.

6 Conclusion

Surfactant PVP-K30 was newly introduced in this paper, and the regeneration performance of LiCl solution in a single channel regenerator with and without surfactant PVP-K30 was studied and compared. The falling film characteristics were identified in the aspects of contact angle, wetting area and film thickness. The effects of different parameters on the regeneration rate were investigated. Some conclusions are drawn, as below:

(1) The surfactant PVP-K30 was firstly introduced to improve the mass transfer between process air and LiCl solution in LDCS. This surfactant is non-volatile, odorless and nontoxic which is suitable for the open loop LDCS.

(2) The contact angle of LiCl solution decreased dramatically with the increase of surfactant concentration to a certain value and then kept almost constant. The wetting areas maintained at a stable value and film thicknesses had a gradual increase with the increase of solution mass flow rates. By adding 0.4% surfactant,

the average wetting area increased from 0.174m^2 to 0.209m^2 with a relative increment of 20.1%. The film thickness decreased from 0.696mm to 0.593mm with a 0.103mm decrement on average.

(3) Influencing factors, such as inlet air humidity, solution concentration and temperature, determined the mass transfer driving force directly and had distinct effect on the regeneration characteristics. Other parameters, such as air temperature and solution flow rate, had negligible influence of regeneration performance. The regeneration rate increased with the increase of air flow rate.

(4) Under the same operating conditions, the regeneration rate had a relative increment of 26.3% by even tiny addition of surfactant. The regeneration enhancement was resulted from the decrement of surface tension by adding surfactant. The reduction in surface tension resulted in greater mass transfer area and better performance of internal heating.

(5) New correlations were proposed to predict the mass transfer coefficients with and without surfactant. The developed correlations had high prediction accuracy with the MARDs within 8% for all the experimental data.

The study demonstrated that the newly introduced PVP-K30 could be a suitable surfactant candidate to improve the regeneration performance of LiCl in LDCS. In addition, the experimental data and new correlations were valuable for the design of regenerator and LDCS.

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