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Title: Enhancing the dehumidification performance of LiCl solution with surfactant PVP-K30

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Abstract: Adding additives into liquid desiccant cooling system (LDCS) can enhance its mass transfer performance. However, the additives proposed by previous researchers are volatile and odorous which is a great threat to the indoor air quality. Therefore, this study introduced a new kind of non-volatile, odorless and nontoxic additive, i.e. polyvinyl pyrrolidone (PVP-K30), into LDCS for better dehumidification performance. Comparative studies were carried out to investigate the dehumidification performance of LiCl solution with and without the additive PVP-K30. The mass fraction PVP-K30 was chosen to be 0.4%. The results show that the dehumidification rate and dehumidification effectiveness have an average relative increment of 22.7% and 19.9% respectively with the addition of surfactant. The enhancement is attributed to the reduction of surface tension of liquid desiccant which is demonstrated by the decrement of contact angle from 58.5^{o} to 28.0^{o}. Correspondingly, the wetting ratio of desiccant falling film on plate has a relative increment of 16.9% from 82.7% to 96.7%, and the film thickness of falling film decreases from 0.681mm to 0.583mm. To sum up, the adding of additive PVP-K30 into LDCS provides an effective and practical way to enhance the vapor absorption performance in an absorber and so does the system efficiency.

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Key words: PVP-K30, surfactant, dehumidifier, falling film, liquid desiccant

Nomenclature			
d	Absolute humidity(g/kg)	ξ	Dehumidification effectiveness (Dimensionless)
G	Flow rate(kg/s)	Δ	Change value
h	Enthalpy(kJ/kg)	Subscripts	
$LDCS$	Liquid desiccant cooling system	a	Air
Δm	Dehumidification rate (g/s)	dry	Dry bulb
T	Temperature(^{o}C)	e	Equilibrium
X	Concentration($\%$)	in	Inlet
Greek symbols		out	Outlet
φ	Relative humidity($\%$)	s	Solution
ρ	Density(kg/m^3)	w	Cooling water

1 Introduction

According to the statistics, people spend 70%~90% of their life time inside the buildings nowadays [1]. In this point of view, the indoor thermal comfort, which is closely related with the indoor temperature and humidity, plays a vital role in determining the quality of people’s life. The traditional way to deal with the indoor heat and humidity load is vapor compression cooling system. However, this system has been criticized by its energy wastage, limited ability of humidity control and so on [2, 3]. To make the situation even worse, it has the possibility of breeding bacteria because of the water condensation on the surface of cooling units [4]. As a promising alternative for the traditional vapor compression system, the liquid desiccant cooling system has been attracting attentions in recent years.

As a key component in the liquid desiccant cooling system, dehumidifier or absorber has the ability to absorb water vapor from processing air via the partial water vapor difference between liquid desiccant and moist air. Due to the different water vapor removal principle, the liquid desiccant system does not need to cool the processing air under dew point temperature for the purpose of moisture removal. On one hand, it can greatly reduce the possibility of bacteria breeding. On the other hand, it can avoid the process of reheat which usually occurs in the conventional cooling system to achieve higher efficiency. Moreover, compared with the traditional system, the liquid desiccant system can control the humidity more accurately by handling the heat load and moisture load separately with the help of cooling unit and absorber.

To make the dehumidifier compact, it is necessary to enhance the heat and mass transfer between liquid desiccant and process air or dehumidification ability in a dehumidifier. Some researchers tried to add certain kind of surfactant into the liquid desiccant to increase the water vapor absorption efficiency [4-15]. Such exploration started from the 1990s, when Cosenza and Vliet [5] studied the water vapor absorption characteristics in a tube falling film absorber. By employing 2-ethyl-1-hexanol as an additive, the mass transfer rate was three to four times bigger than that without additive. After that, 2-ethyl-1-hexanol was widely adopted by other researchers both in tube and plate absorbers [6-9]. Different degrees of absorption enhancement ranging from 20% to 500% were observed in their studies. Hozawa, Inoue [10] employed two kinds of surfactants, namely n-octanol and n-decanol, to investigate the static absorption performance of lithium bromide (LiBr) in 1991. They found that the initial absorption rate increased up to 2.5 times with the addition of n-octanol. They also measured the surface tension under different concentrations of n-octanol. It was found that the surface tension decreased with the increase of additive concentration to a certain degree and then kept constant. In 1996, Ziegler and Grossman [11] presented a review related to the recent progress of heat and mass transfer enhancement by additives. From this review, some commonly used additives, such as n-octanol, n-heptanol, 2-ethyl-1-hexanol and 6-methyl-2-heptanol, were introduced and so did the influence of their addition amount on absorption enhancement. Generally, the above studies could be classified into four categories: field test, horizontal and vertical falling film absorber (both on tubes and plates) and stagnant pool absorption experiments. Then other kinds of surfactant were also investigated by latter researchers. The attempts included 2-methyl-1-pentanol [12], Alkyl Glucoside [13] and Triton X-100 [14] and other multicomponent solutions such like LiBr+1, 3-propanediol+water solution [15] and $LiBr+CHO_2Na$+water solution [16]. Various degrees of absorption increment were detected in these studies.

In order to reveal the mechanism of absorption enhancement by adding additives, some studies concentrated on the measurement of physical properties, mainly surface tension and viscosity. Daiguji, Hihara [17] stated that the surface tension of solution had an effect on the absorption performance in the falling film absorber. However, they also indicted that the absorption enhancement could not result from the reduction of surface tension alone. Some other reasons, Marangoni convection for example, might be the contributor. The surface tensions of aqueous lithium bromide with and without additives were measured by a drop weight method by Kulankara and Herold [18]. It showed that the addition of additives reduced the surface tension up to a critical level with the increase of additive concentration. Then, the surface tension kept almost the same for all four kinds of additives, namely 2-ethyl-1-hexanol, 3,5,5-trimethyl-1-hexanol, 2-methyl-1-hexanol, 3-phenyl-1-propanol. They also mentioned that the additive vapor around the liquid interface was of great importance to the reduction of surface tension. Different from Kulankara and Herold [18], Carazzo, Wohlfeil [19] measured the dynamic surface tension of LiBr solution with surfactant 1-octanol. In their mind, the contact time between vapor and solution was pretty short and the equilibrium of solution could hardly reach the steady state. They also gave a correlation to predict the dynamic surface tension.

Even so, the foregoing literature related to the measurement of surface tension can just give a guidance rather than convincing explanation to understand the enhancement mechanism. There is a general consensus that the absorption enhancement is caused by the Marangoni convection. But, the trigger mechanism under this phenomenon is still unclear. Some models developed previously tried to uncover the truth. Firstly, Kashiwagi [20] put forward a model called Kashiwagi model. He thought that the surface tension gradient caused by the presence of additive islands was the reason. However, the additive islands was shown to be unnecessary for Marangoni convection observed by subsequent researchers [21, 22]. After that, Daiguji, Hihara [17] developed a salting-out model for the initial cause of Marangoni convection. They indicated that the absorption of water vapor broke the balance of original solution due to the stronger hydration force between water molecules and electrolyte ions of Li^+ and Br^-. It caused the segregation of additive molecules from bulk solution. As a result, Marangoni convection occurred in the solution. Nevertheless, this model could not be applied to the situation when the concentration of surfactant exceeded the solubility limit. For example, absorption enhancement was reported even at oversaturated solubility by

Beutler, Greiter [23]. To be a supplement, Kang, Akisawa [24] proposed the solubility model in 1999. They indicated that the salting-out model was the trigger for inducement of Marangoni convection before solubility limit of additives, while after the limit, the trigger could be contributed to the imbalance of surface tension and interfacial tension. Different from the abovementioned three models, Kulankara and Herold [25] put their concentration on the additive vapor and proposed the vapor surfactant theory. They explained that the inhomogeneous distribution of additives on the solution surface caused by the non-uniform absorption at the interface resulted in surface tension gradients, and then produced Marangoni convection in the solution. However, additives, such like Triton X-100, have negligible volatility. In such situation, the additive vapor is unlikely to exist in the gas phase. It can conclude that certain model can only give reasonable explanation for absorption enhancement for some additives, but there is no general criterion for all additives.

In addition, most researches are about the additives used in the absorption refrigeration system. In such systems, the aqueous solution circulates in a closed loop. The odour and volatility of the additives, such as n-octanol, n-heptanol and 2-ethyl-1-hexanol, do not make much difference in these systems. However, different from the closed type absorption refrigeration system, the liquid desiccant system works in an open loop, in which the moist processing air contacts directly with the liquid desiccant. Therefore, almost all of the additives mentioned above cannot be applied to the liquid desiccant system due to their odour, volatility and toxicity which is a great threat to the indoor air quality.

Therefore, the present study newly introduced a surfactant, namely polyvinyl pyrrolidone (PVP-K30), to the liquid desiccant system. Compared with those abovementioned surfactants, the odorless, non-volatile and nontoxic PVP-K30 [26] is improbable to pollute the processing air which is suitable for the open loop liquid desiccant cooling system. Comparative experiments were conducted in a single channel plate dehumidifier with the size of 500mm*500mm (Length*Width). In order to avoid the influence of corrosion caused by LiCl solution on dehumidification performance, the stainless steel 316L with excellent corrosion resistance performance was adopted for plate dehumidifier. In fact, researcher used plastic for the production of dehumidifier [27]. However, the complex processing technologies, weak structure strength and poor wettability greatly restricts its practical application. Therefore, metals are still the most suitable and promising material to produce plate type dehumidifier. The influences of various parameters, such as air inlet humidity, air flow rate, solution temperature and solution concentration, were investigated quantitatively. The dehumidification rate and effectiveness were chosen to evaluate the dehumidification performance. The contact angles of additives at different concentrations were measured. The wetting ratio and film thickness were also obtained with and without additive PVP-K30.

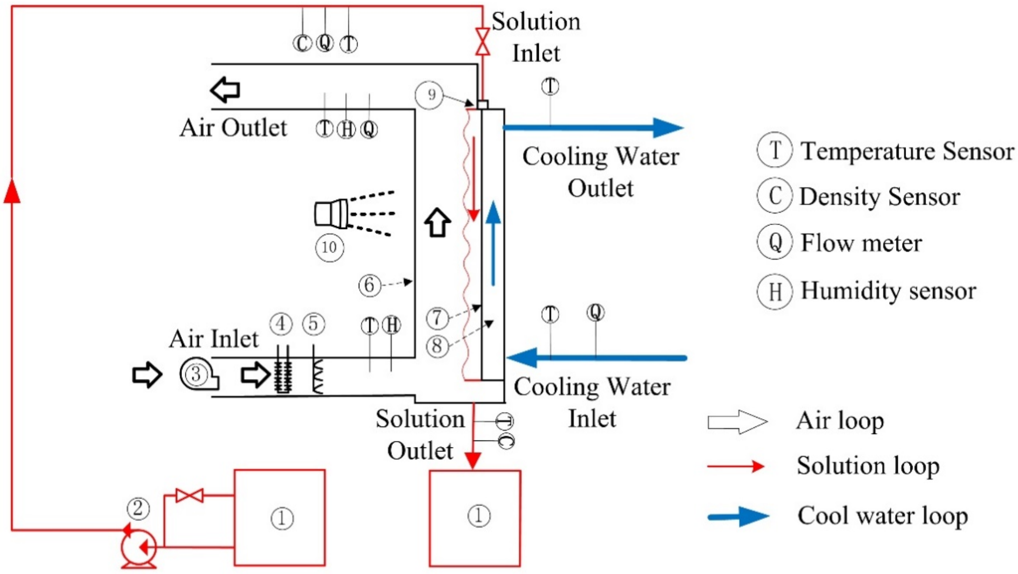
2 Experimental method

2.1 Experimental apparatus

In order to identify the influences of various parameters on the dehumidification characteristics, an experimental bench was purpose-built. The detailed schematic diagram of the test bench is shown in Fig. 1. It consisted of three loops distinguished by the color of the arrows. They were cooling water loop, liquid desiccant loop and processing air loop. For the purpose of thermal isolation, all loops were packed with neoprene foam on the surfaces. The whole system was installed in a laboratory with the ability to keep the temperature and moisture at relative stable level. The real picture for the whole experimental system is presented by Fig. 2. As the whole system is slightly big, only part of the equipment can be found in Fig. 2.

The cooling water loop was introduced for the purpose of dehumidification performance improvement. Because during the dehumidification process, water vapor in the processing air is absorbed by the contact surface of the liquid desiccant. The phase of water changes from gas to liquid, in which latent heat of liquidation is released. This part of energy is mainly absorbed by the liquid solution and contributes to the temperature rise in liquid desiccant. Higher temperature means lower mass transfer driving force which is determined by the thermal properties of liquid desiccant. Therefore, in order to alleviate the deterioration of absorption performance, internal cooling was introduced to slow down the rise of solution temperature. The cooling water firstly cooled by a water chiller and then driven by a pump to circulate around the cooling water loop. The inlet and outlet temperatures of water were measured by Pt-100 thermocouples. A turbine flow rate sensor was employed to get the flow rate of cooling water.

For the liquid desiccant loop, Lithium chloride (LiCl) was adopted as the solvend in the desiccant solution. The LiCl solution was stored in a tank which was connected to a pump. The flow rate of solution was controlled through a by-pass valve by adjusting the opening. After the adjustment of flow rate, the solution flowed into a distributor with a slot. The desiccant solution would spill from the slot after filling the distributor and fell along the surface of the single channel stainless steel dehumidifier. Heat and



1、Solution tanks 2、Solution pump 3、Air fan 4、Air heater 5、Humidifier 6、Air channel 7、Working surface 8、Internally cooling unit 9、Solution distributor 10、Infrared thermal imager

Fig. 1. Schematic diagram of the test rig.

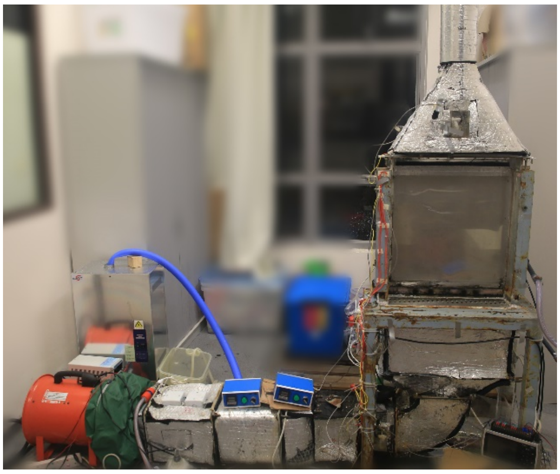


Fig. 2. Real picture of the experimental system.

mass transfer would proceed in the dehumidifier when solution contacted with the moist air. After that, it flowed back to another solution tank. A controllable electric heater was installed in the solution tank for the purpose of solution temperature adjustment. The inlet and outlet solution temperatures were also obtained by two Pt-100 thermocouples. The flow rate of solution was measured by a turbine flow rate sensor. Because the change of solution concentration in one cycle was too smaller to be detected, only the inlet concentration was measured by an indirect method. The solution temperature and density were obtained by a thermocouple and a specific gravity hydrometer respectively. Then, the concentration was got by the equation provided by Conde [28]. Fig. 3 shows the detailed configuration of the single channel dehumidifier. The LiCl liquid desiccant was uniformly distributed on the stainless steel plate dehumidifier by a cuboid distributor with a gap in the front. In order to segregate the processing air from the ambient air and guarantee the processed air flow in the channel, a cover was employed as shown in Fig. 3. The cooling water channel which is used to improve the dehumidification performance is also illustrated in the figure. By an axial flow fan, the processing air was pumped into the air duct. A damper was installed in the air duct to adjust air flow rate as acquired. A heater with an automatic Proportion-Integration-Differentiation (PID) controller was employed to regulate the inlet air temperature. The required inlet moisture content was obtained by an electric humidifier by adjusting the input heating voltage. When all the required parameters reached the steady state, the air was fed into the dehumidifier channel to contact with the liquid desiccant. Both the temperatures and relative humidity were measured by humidity sensors. A Pitot tube which connected with a micro-manometer was installed at the outlet duct on behalf of air flow rate measurement. All experimental data, including temperatures, humidity, flow rates, were collected, displayed and stored by a data logger.

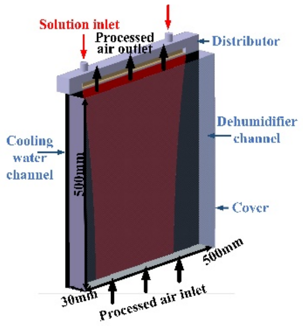


Fig. 3. Detailed configuration of the single channel dehumidifier.

2.2 Data processing

In order to evaluate the dehumidification performance, several indices have been selected by previous researchers. The dehumidification rate and dehumidification effectiveness were used to identify the performance of dehumidifier with and without surfactant in present study. The dehumidification rate can reflect the moisture amount that absorbed by the liquid desiccant directly. For the dehumidification effectiveness, it indicates the ratio between the actual moisture change and the potential greatest moisture change. Their definitions are explained as follows.

The definition for dehumidification rate is:

$$\Delta m = G_a.(d_{a,out} - d_{a,in}) \qquad (1)$$

in which G_a stands for the mass flow rate of processing air. $d_{a,out}$ and $d_{a,in}$ donate the inlet and outlet absolute humidity respectively. The absolute humidity was calculated by the following equation:

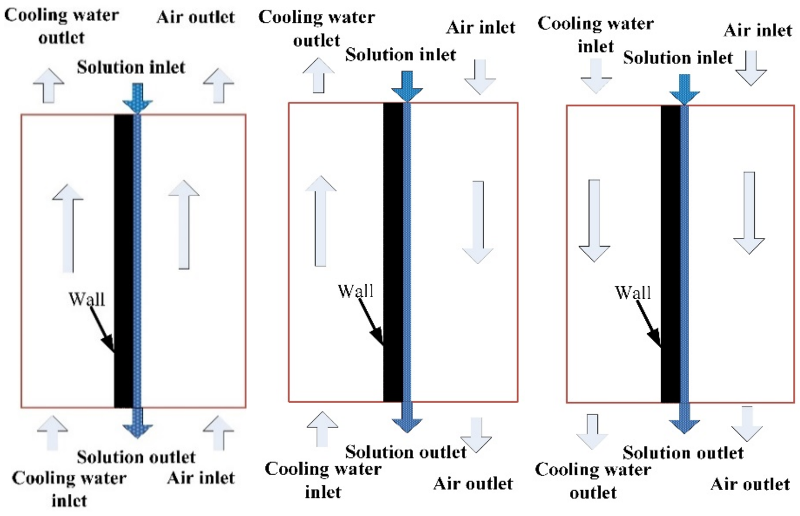
$$d = f(T_{dry}, \varphi) \qquad (2)$$

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

For dehumidification effectiveness, the formulation is presented as:

$$\xi = \frac{d_{a,in} - d_{a,out}}{d_{a,in} - d_{\mathrm{e}}} \qquad (3)$$

In this formulation, d_e represents the absolute moisture content of the processed air in the condition of equilibrium with desiccant solution at its concentration and temperature. What is also worth noting is that in present study the flow pattern between processed air and solution is countercurrent which is illustrated by Fig. 4-a. The outlet processed air humidity $d_{a,out}$ is no smaller than the equivalent moisture content of d_e. Therefore, the effectiveness is no bigger than 1. However, when the flow pattern between processed air and solution is parallel as shown by Fig. 4-b and Fig. 4-c, due to internal cooling effect of cooling water channel, the outlet humidity content of processed may be smaller than that of the equivalent moisture content determined by the solution inlet temperature. This may make the dehumidification effectiveness bigger than 1, which is inappropriate. Therefore, in such circumstance, the cooling water inlet temperature can be adopted when calculating d_e [27].



(a) (b) (c)

Fig. 4. Configurations of the flow pattern of fluid in dehumidifier.

All these heat and mass processes should obey the conservation theories, namely energy and mass conservation principle. In present study, they can be expressed in the following equations.

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

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

Equation 4 represents the energy conservation. G and h indicate the mass flow rate and enthalpy respectively. The subscripts s, a, w denote the solution, air and cooling water correspondingly. The inlet and outlet parameters are differentiated by the other letter i, o in the subscript. The mass conservation is formulated by Equation 5, in which X stands for solution concentration.

2.3 Uncertainty analysis and experimental validation

The uncertainty is the degree of uncertainty for measured outcome which is caused by the measurement errors. The smaller the uncertainty is, the more reliable the measured results is. However, the measurement errors which caused by a serious of factors, such as accuracy of sensor, experiment method, experiment operation, can not be totally avoided in the real experiments. The error caused by the accuracy of sensor is hard to avoid due the limitation of measurement techniques. However, reasonable and rigorous experiment design and proper operation during experiment can decrease the uncertainty greatly.

Parameters, such as temperature, flow rate, relative humidity, were measured by sensors directly. In consequence, their uncertainties were determined by accuracies of sensors. Other parameters, such as concentration, absolute humidity and dehumidification rate, were obtained through conversion. To get their uncertainties, the uncertainty propagation method should be employed. The detailed calculation process of indirect uncertainties is presented as follows [29]:

$$\frac{\delta y}{y}=\sqrt{(\frac{\partial \ln f}{\partial x_1}\delta x_1)^2+(\frac{\partial \ln f}{\partial x_2}\delta x_2)^2+...+(\frac{\partial \ln f}{\partial x_n}\delta x_n)^2} \tag{6}$$

where y indicates the indirect measured parameter and δx_n represents the uncertainty of the n_{th} direct measured parameter. The relationship between y and x_i can be described by Equation (7).

$$y = f(x_1, x_2, ..., x_i, ..., x_n) \tag{7}$$

Table 1 summarizes all the uncertainties of parameters involved in present study.

Table 1. Summary of parameters' uncertainties.

Parameter	Uncertainty	Parameter	Uncertainty
Temperature/ T	$\pm\ 0.1K$	Solution concentration/ X_s	0.2%
Solution flow rate/ G_s	± 3%	Air absolute humidity/ d	2.5%
Solution density/ ρ_s	$\pm\ 1kg/m^3$	Dehumidification rate/ Δm	4.1%
Air flow rate/ G_a	± 2.2%	Dehumidification effectiveness/ ξ	5.0%

Air relative humidity/ φ	± 2.5%	Contact angle/ $^{\circ}$	0.1
Cold water flow rate/ G_w	± 3%	Film thickness/ μm	0.8

As stated above, the simultaneous heat and mass transfer in the dehumidifier have to meet the conservation of energy and mass. However, the mass conservation which described in Equation 5 was unlikely to be checked because of the negligible change of solution concentration in one cycle. Therefore, only the energy conservation in Equation 4 was examined. Before the formal experiments to investigate the effects of different parameters on dehumidification performance, 95 experiments were carried out randomly under various operating conditions that covered all the possible situations. After that, the energy conservation equation was checked according to these results. The result is shown in Fig. 5. From this figure, one can see 79 experimental data out of 95 fall into the error band of $\pm 20\%$. According to previous references, the enthalpy difference always fall into the error band of 0~30% [27, 30, 31]. Therefore, the present maximum absolute energy difference of 20% is in the acceptable range. The random fluctuation of the enthalpy difference can be contributed to two reasons: (1) the uncertainties of sensors which include flow meters, Pt100 thermocouple. It is worth noting that even though the accuracy for the Pt100 thermocouple is as high as 0.1°C, the difference between the inlet and outlet cooling water is relative small (smaller than 1°C in most of the experimental conditions). As a result, even the 0.1°C uncertainty may cause relative big difference in energy difference. (2) although thermal isolation material was covered on the surface of all ducts, small amount of heat exchange still existed between the experimental system and ambient environmental. These two factor, mainly the former one, led to the energy difference as shown by Fig. 5. Considering all these factors, the rationality of the test rig can be proved adequately.

After the system validation, systematical experiments were conducted to investigate the influence of difference parameters on dehumidification performance. The specifications of the experimental conditions are presented in Table. 2. In Table 2, the velocity and Reynolds number of air are determined by the following equations:

$$V_a = \frac{G_a}{\rho_a A_c} \tag{8}$$

$$Re_a = \frac{\rho_a V_a D_e}{\mu_a} \tag{9}$$

in which, A_c is the cross section area of channel and D_e is the equivalent diameter.

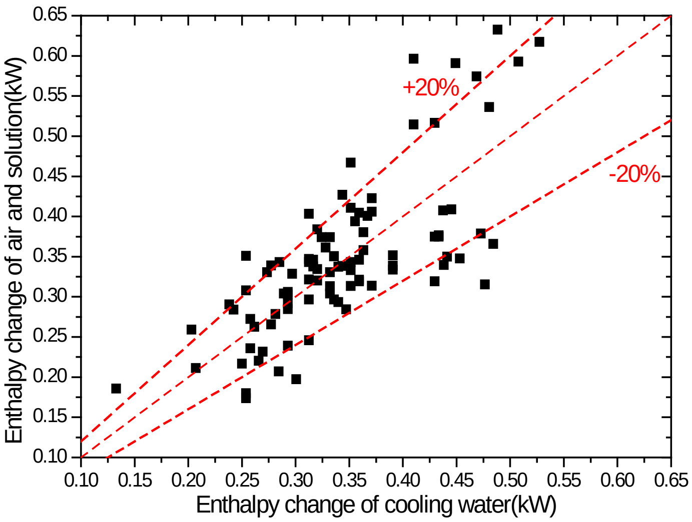


Fig. 5. Energy balance validation of the test rig.

Table. 2. Specification of the experimental conditions.

Material	Parameter	Range
Solution	Concentration (wt%)	32~40
	Mass flow rate (kg/s)	0.08~0.16
	Inlet temperature (°C)	28~35
Processed air	Inlet humidity (g/kg)	16~25
	Mass flow rate (kg/s)	0.023~0.069
	Inlet temperature (°C)	29~36.5
	Air velocity (m/s)	1.2~3.7
	Air Reynolds number	4330~13300
Cooling water	Mass flow rate (kg/s)	0.11
	Inlet temperature (°C)	14~22
PVP	Concentration (wt%)	0.4

3 Results and discussion

3.1 The contact angles of liquid desiccant under different concentrations

The initial trials newly found that adding surfactant PVP-K30 could reduce the contact angle of desiccant solution on the stainless steel plate. To measure the contact angles of solution on plate with various concentrations accurately, a standard contact angle goniometer made by Rame-hart instrument Co. was employed. The goniometer has the resolution of 0.1°. According to our literature review, we found that the addition amount of surfactant into solution was small. Therefore, we selected the percentage of 0.1% for the minimum concentration for our initial trials. As the solubility of PVP in water is 100mg/mL(water), that is to say the maximum concentration of PVP in water is nearly 9.1%. Concerning the influence of temperature on the solubility, a smaller concentration should be selected in the real application. Another important consideration is that the large amount addition of surfactant into liquid desiccant may change the thermal properties of solution and have obvious effect on the dehumidification performance. Therefore, we chose the concentration of 3% for the maximum one temporarily. The measurement results are presented in Fig. 6 and Fig. 7.

Fig. 6 indicates the contact angle of desiccant solution without surfactant under the solution concentration of 35%. Fig. 7 shows the contact angles of solutions under various surfactant concentrations. As one can see, the contact angle decreases from the original 58.5^{o} without surfactant to 23.9^{o} with the concentration of 3.0%. The reduction of contact angle reaches up to 34.6^{o}. What is more, from the results, we can find that when the concentration reaches 0.4%, the decrement of contact angle becomes level-off. Therefore, in the following study, the surfactant concentration of 0.4% was chosen to identify the dehumidification performance.

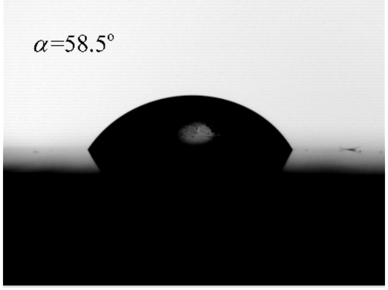


Fig. 6. Contact angle of LiCl solution on stainless steel plate.

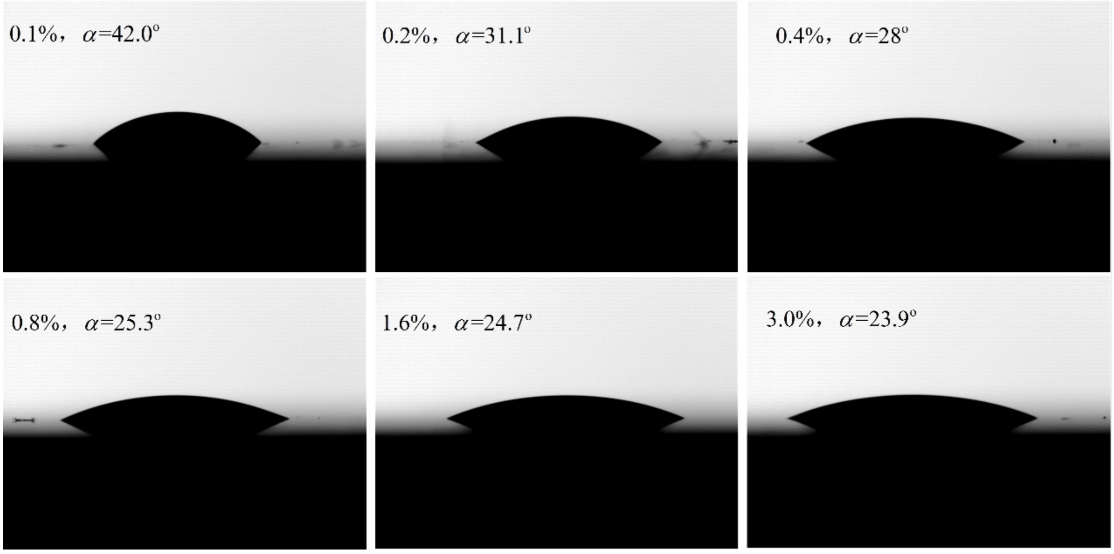


Fig. 7. Contact angles of LiCl solution with different concentration of PVP-K30.

3.2 Influence of solution flow rate

As shown in Fig. 8, the influences of solution flow rate on dehumidification performance with and without surfactant are indicated. The average dehumidification rate and effectiveness are 0.079g/s and 14.5% respectively for liquid desiccant without surfactant. For desiccant solution with surfactant, the values are 0.093g/s and 16.6% respectively. It can be concluded from this figure that with the addition of PVP-K30, both the dehumidification rate and effectiveness have a distinct increment. The relative increments are 18.0% and 14.3% respectively under certain situations. For both operating conditions with and without surfactant, these two performance indices do not change much with the increase of solution mass flow rate. In order to explain this constant trend of dehumidification performance, the wetting ratio of falling film under different mass flow rates were measured by a high resolution infrared thermal imager of FLUKE company. It was found that the wetting ratios almost kept around 82.7% and 96.7% for solutions with and without surfactant even the solution flow rate had a two times increment. The detailed values are shown in Table 3. Consequently, the absorption performance did not show obvious change with the change of solution flow rate. And, another reason concern about the film thickness will be interpreted below.

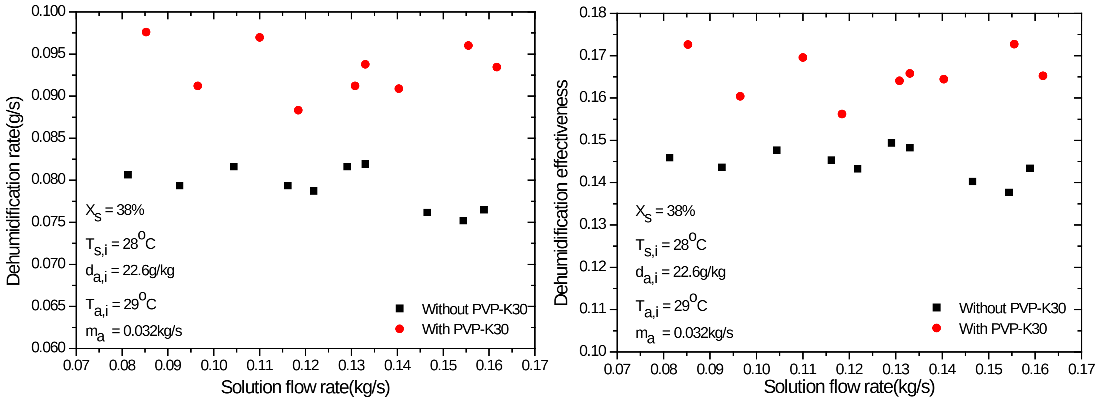


Fig. 8. Influence of solution flow rate on dehumidification performance.

Table. 3. Wetting ratio at diffenent solution flow rate.

Without surfactant		With surfactan PVP-K30	
Solution flow rate/kg/s	Wetting ratio/%	Solution flow rate/kg/s	Wetting ratio/%
0.083	83.2	0.078	97.0
0.097	83.0	0.089	97.0
0.109	82.3	0.100	97.6

0.116	82.1	0.111	97.5
0.136	83.9	0.122	95.0
0.148	82.6	0.134	95.4
0.164	82.1	0.145	97.8
		0.156	96.5

3.3 Influence of solution temperature

Fig. 9 shows the influence of inlet solution temperature on the dehumidification characteristics. The dehumidification rates have a distinct decrease when the solution temperature increases from 28°C to 35°C for both situations. This can be contributed to the rise of partial water vapor pressure on the surface of solution with the increase of temperature. When the inlet air humidity keeps unchanged, the increment of surface partial water vapor pressure of solution reduces the mass transfer driving force. However, the dehumidification effectiveness does not show a descending trend because the equilibrium humidity of solution also increases with the increase of solution temperature. The reduced amplitudes on the numerator and denominator are close to each other, resulting in the negligible trend of dehumidification effectiveness. The absorption enhancement by adopting surfactant can also be easily detected from this figure with the average relative increments of 24.5% and 17.1% for dehumidification rate and effectiveness respectively.

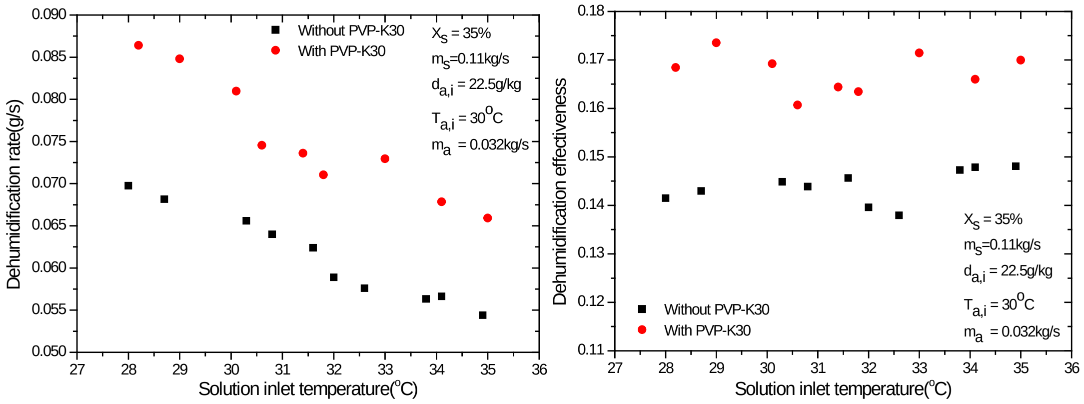


Fig. 9. Influence of solution inlet temperature on dehumidification performance.

3.4 Influence of solution concentration

The influence of the solution concentration on dehumidification characteristics is presented in Fig. 10. As shown, the increase of solution concentration leads to the rise of dehumidification rate. This trend is caused by the decrement of partial water vapor pressure on the surface of solution resulted from the increase of concentration. Different from the increasing trend of dehumidification rate, the other index, namely dehumidification effectiveness, does not show an apparent tendency. Even though the concentration increases from 32% to 40%, the effectiveness varies around the values of 14.5% and 17.6% with and without surfactant. This can be attributed to the comparable amount of growth on the numerator and denominator in Equation 3. For these four solution concentrations, the relative enhancements for both dehumidification rate and effectiveness are 22% averagely.

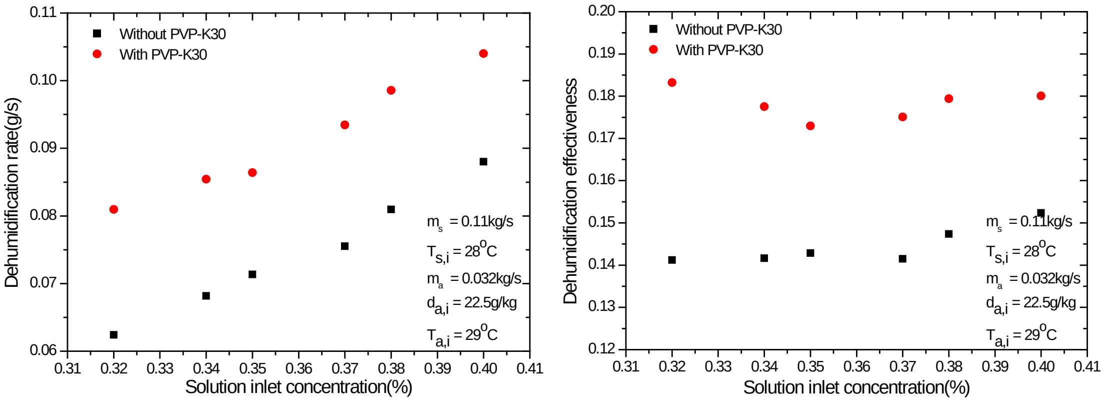


Fig. 10. Influence of solution concentration on dehumidification performance.

3.5 Influence of air flow rate

From Fig. 11, the influence of air flow rate on dehumidification ability can be analyzed. It is obvious that the dehumidification rate increases with the increment of air flow rate. The explanation is that greater mass flow rate corresponds to higher mass transfer coefficient. In this study, when the air flow rate changes from 0.023kg/s to 0.06kg/s, the mass transfer coefficient rises from 0.02 kg/(m^2.s) to 0.037 kg/(m^2.s) for liquid desiccant without surfactant. Interestingly, the dehumidification rate drops significantly at the great mass air flow rate as shown in Fig. 11. The same trend goes for the dehumidification effectiveness. In order to validate such strange trend, repeated experiments were conducted at the air mass flow rate of 0.065kg/s and 0.069kg/s under the same working conditions. For the mass flow rate of 0.065kg/s, the dehumidification effectiveness ranges from 5.4% to 6.0% without surfactant and 7.78% to 8.41% with surfactant. As a result, the fluctuation of the results is very small when the air flow rate is 0.065kg/s and the same conclusion also goes for the flow rate of 0.069kg/s. In our opinion, it may be caused by the short contact time of processing air with liquid solution at greater mass flow rate. The difference of absolute moisture content between the inlet and outlet air is too small within a short contact time. On the contrary, the dehumidification effectiveness shows an ascending trend. This can be easily understood in terms of the definition of this index. The numerator which indicates the absolute moisture removal keeps decreasing because of the reduction of contact time when the air mass flow rate has a growing trend. On the other hand, the denominator is constant under the same operating conditions. As a result, the effectiveness presents a declining trend with the increase of air flow rate.

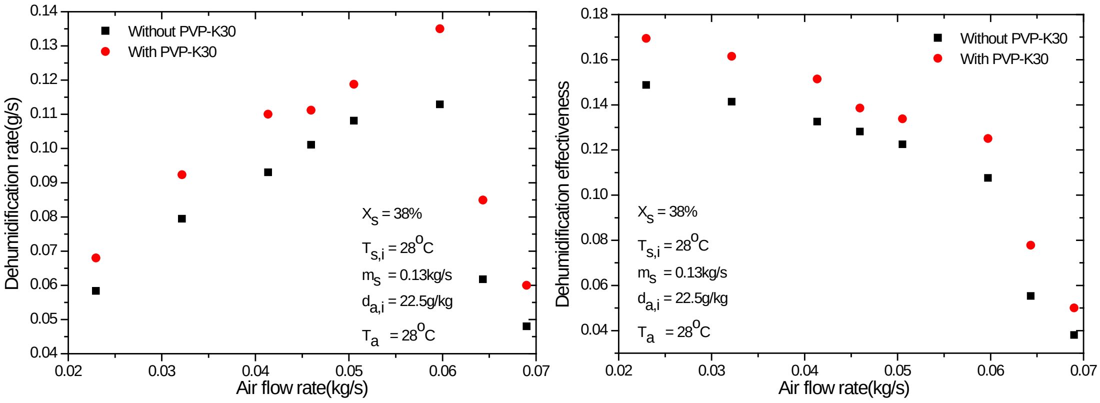


Fig. 11. Influence of air flow rate on dehumidification performance.

3.6 Influence of air dry bulb temperature

The experimental results under different air temperatures are illustrated in Fig. 12. Both of the two performance criterions maintain steady under various temperatures ranging from 29.5°C to 36.5°C. The average dehumidification rates with and without surfactant are 0.067g/s and 0.086g/s with a relative increment of 28.4%. For the dehumidification effectiveness, the values are 13.7% and 17.0% respectively. The stable trend of these two indices can be interpreted from the following two aspects. On one hand, the increasing of air temperature does not have a distinct effect on the mass transfer force. On the other hand, the influence of air inlet dry bulb temperature on the falling film flow characteristics is very weak.

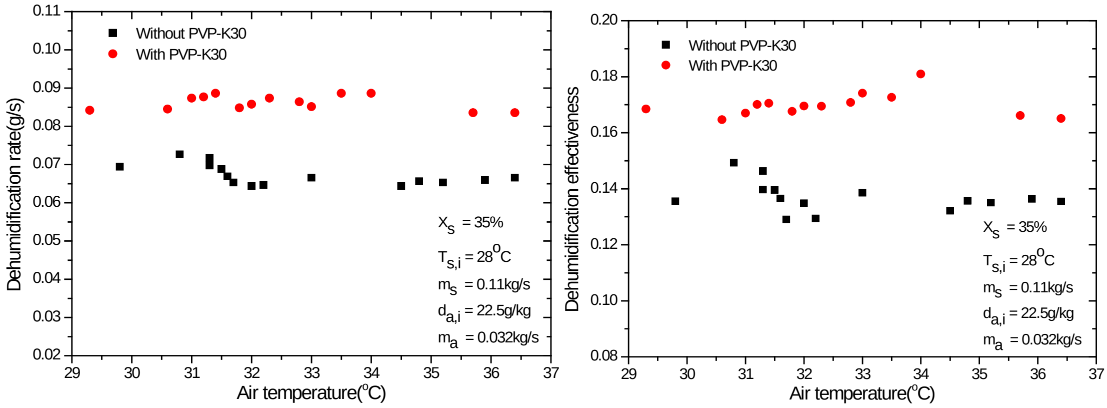


Fig. 12. Influence of air inlet bulb temperature on dehumidification performance.

3.7 Influence of air inlet humidity

It can be seen from the experimental points in Fig. 13 that the dehumidification rates increase obviously with the increase of inlet air humidity. When the inlet humidity changes from 16.5g/kg to 24.6g/kg, the rate has a 0.07g/s increment from 0.04g/s to 0.11g/s for the situation with surfactant. Greater absolute humidity of the processing air means bigger mass transfer force when other parameters of liquid desiccant keep unchanged. Similar tendency can also be observed for dehumidification effectiveness in this figure. It can be understood in two aspects. On one hand, the increase of inlet air humidity leads to the increment of mass transfer. On the other hand, the increase amplitude on the denominator which indicates the difference between equilibrium humidity and inlet air humidity is smaller compared with that of numerator. Under the same operating conditions, the employment of surfactant PVP-K30 can enhance the dehumidification performance significantly, which can also be demonstrated in Fig. 13.

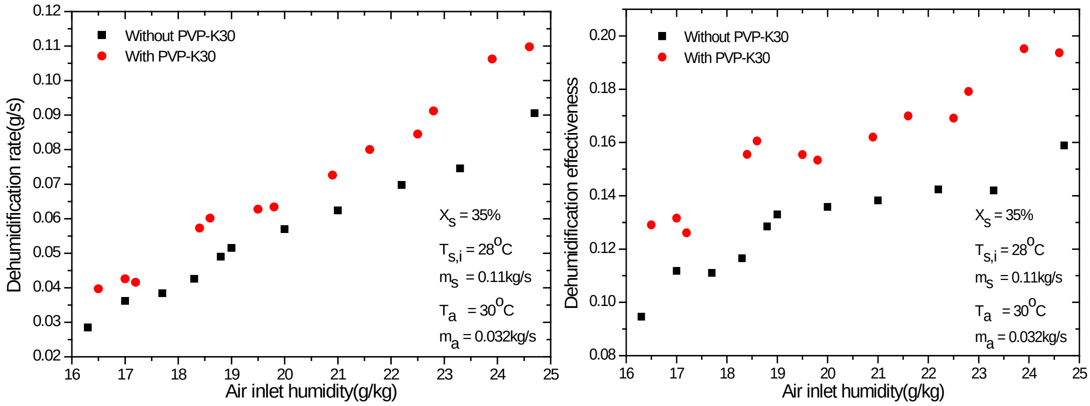


Fig. 13. Influence of air inlet humidity on dehumidification performance.

3.8 Influence of cooling water temperature

The influence of cooling water inlet temperature on the dehumidification performance of internal cooling falling film dehumidifier is presented by Fig. 14. It is clear that when the cooling water temperature increases from 14ºC to 22ºC, the dehumidification rate and effectiveness decrease from 0.075g/s to 0.065g/s and 15% to 13% for solution without surfactant. The adding of surfactant does not change the decreasing trend but increases the value for these two index under the same working conditions. Under the working condition with low cooling water temperature, the solution temperature will also maintain at low value or even decrease along the flow direction of the falling film. Lower dehumidification temperature corresponds to higher mass transfer driving force and contributes to greater dehumidification rate and effectiveness. The relative average increments for these two index are both 21.4%.

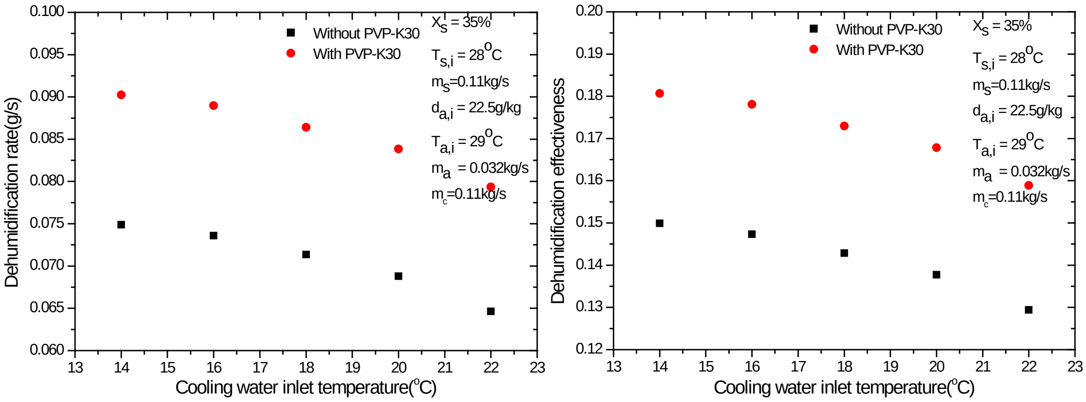


Fig. 14. Influence of cooling water temperature on dehumidification performance.

3.9 Comparison of experiment result with previous studies

Table 4 compares the experimental conditions and dehumidification effectiveness of present study with those from previous studies for internal cooling dehumidifier. From the table, we can see both the working conditions and effectiveness are different with each other. Compared with the results from Liu et al [27], Zhang et al. [32] and Yin et al. [33], present outcomes in terms of effectiveness seems quite small. However, compared with that from Luo et al. [31] and Lee et al. [34], the effectiveness in present study seems quite normal. After serious consideration on the working conditions and configuration of the dehumidifier, we thought the main reason that contributes to the difference is the velocity of air in the dehumidifier channel. The explanation can be verified when we compare the results with that from Lee et al. [34]. Fig. 15 shows the dehumidification effectiveness under different air velocity from the study of Lee et al.

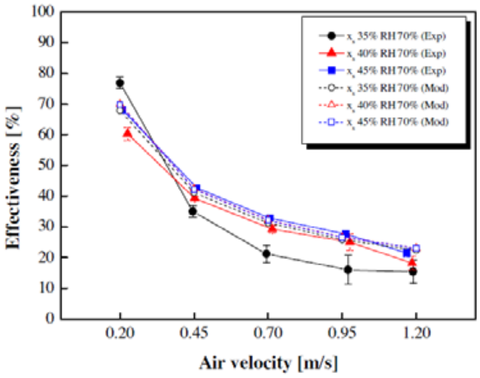
[34]. The results shown in Fig. 16 are from present study. We can see under the same air velocity, the effectiveness is comparable rather than quite different. In summary, the dehumidification performance is not only determined by the working conditions but also closely related with the configuration of the dehumidifier. However, in the authors' limited knowledge, relative few studies have systematic study to investigate the effect of channel configuration on dehumidification performance. Further study will be conducted in the future time to cover the research gap.

Table. 4. Summary of the experimental results of internal cooling dehumidification.

Author	Desic-cant	Flow pattern[a]	G_a / G_s	X_{in} / %	$T_{w,in}$ /° C	Efficiency [b] /%
Liu et al. [27]	LiBr	Cr	0.8-3.4	38.8-42.4	11.1-17.0	High
Zhang et al. [32]	LiBr	Cr	2.1-9.0	43.0-45.5	16.3-25.5	High
Yin et al. [33]	LiCl	Co	0.4-0.9	37.7-38.8	19.5-24.5	28-43
Luo et al. [31]	LiCl	Co	0.4-1.7	35-41	17.5-26.5	15-24
Lee et al. [34]	LiCl	Cr	--	35-45	32	13-87
Present study	LiCl	Co	0.2-0.9	32-38	14-22	9.5-20

a: flow pattern between air and desiccant; Cr indicates cross flow, Co indicates countercurrent

b: High means the efficiency is quite high and can not be calculated according the definition of present study



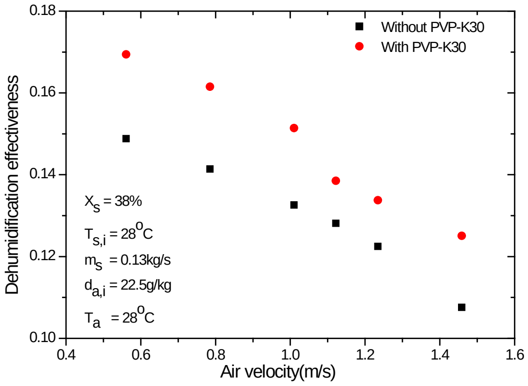


Fig. 15. Dehumidification effectiveness under different air velocity from Lee et al. [34]. (Left)

Fig. 16. Dehumidification effectiveness under different air velocity in present study. (Right)

Comparison were also presented in terms of the surfactant and their properties. The specifications are shown in Table 5. From the table, we can see most studies concentrated on the area of absorption refrigeration and bubble absorption. Few study focused on the dehumidification except the present study. What is more, as the surfactants adopted by other researchers were very similar with alcohol, they are more or less odoriferous that can not be applied to the area of dehumidification due to the direct contact of processed air and solution. The present study introduced the non-volatile, odorless and nontoxic surfactant PVP-K30 for the purpose of dehumidification enhancement.

Table. 5. Comparison between different kinds of surfactant.

Author	Area	Surfactant	Toxicity	Odour	Mass transfer enhancement
Lin et al. [9]	Absorption refrigeration	2-ethyl-1-hexanol	High	Yes	1.9-2.5
Glebov et al. [12]	Absorption refrigeration	2-methyal-1-pentanol	Small	Yes	0.2-0.32
Kim et al. [35]	Bubble absorption	2-ethyl-1-hexanol, n-octanol	Small	Yes	Up to 4.81
Kyung & Herold [36]	Absorption refrigeration	2-ethyl-hexanol	Small	Yes	1.2-1.7
Present study	Dehumdific-ation	PVP-K30	No	No	0.08-0.4

3.10 Discussion

Concluded from the foregoing descriptions, the findings that adding surfactant PVP-K30 into solution can enhance the dehumidication performance obviously. The increment ranges from 9.8% to 37.5% for dehumidification rate and 8.1% to 40.7% for effectiveness under comparable experimental conditions. Averagely speaking, the relative increments are 22.7% and 19.9% for dehumidification rate and effectiveness respectivley. Several tests were carried out to reveal the enhancement mechanism. Contact angle and wetting ratio were two kinds of those tests, from which we concluded that by adding the surfactant, the contact angle of the desiccant solution decreases dramatically even at tiny addition. The decrement of contact angle can directly reflect the reduction of surface tension and leads to the increment of wetting ratio. The average relative increment of wetting ratio was 16.9%, from 82.7% for solution without surfactant to 96.7% with surfactant. Fig. 17 indicates the wettability of falling film on plates at comparative conditions. It is obvious that greater contact area between processing air and liquid dessicant means more water vapor would be absorbed by solution. Therefore, the increment of wetting area caused by the decrement of surface tension is one of the main factors for the absorption enhancement. However, the average increment of 16.9% for wetting ratio is sightly smaller than the enhancement of 22.7% and 19.9% for dehumidification rate and effectiveness. In the subsequent investigation, we measured the film thickness of the falling film at the same point of plate for both situations with and without surfactant. The JDC-2008 accumeasure instrument developed by TianJin Univesity was adopted in present study to obtian the film thickness of the falling film. The resolution and accuracy of this instruement are 0.1 μm and 0.8 μm respectively. It was found that film thickness had a nearly 0.1mm reduction from 0.681mm to 0.583mm for solution with and without surfactant when the mass flow rate of solution was 0.11kg/s. In terms of the internal cooling effect, thin film thickness represents small heat transfer resistance in the process of heat exchange between liquid desiccant and cooling water. As a result, the rise of temperature for surfactant included solution would be smaller than that without surfacant. This explanation can be verified by the experimental observations that the outlet solution temperature with surfactant was 0.1 to 0.2 ^{o}C lower than that of ordinary solution at comparable experimental conditions. Solution with lower temperature has higher mass transfer driving force as mentioned above. So the other possible factor for absorption enhancement can be reasonably contributed to the decrement of film thickness because of the addtion of surfactant. Consequently, when comparing the percentage of dehumidification enhancement with wetting ratio increment and film thickness decrement, the conclusion that the dehumidification increment are caused by the two mentioned factors is in line with the experiment results.

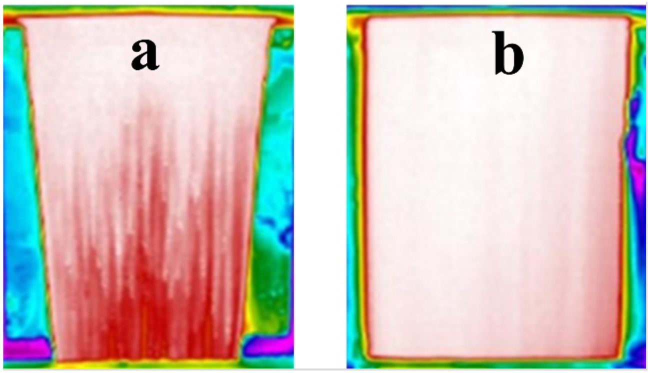


Fig. 17. The contrast of wettability (a) without surfactant, (b) with surfactant PVP-K30.

The present experimental adopted the stainless steel as the material for dehumidifier. In order to furture promote the significance of present study by adopting surfactant PVP to improve dehumidification performance, we had some initial attemps to demonstrate its feasibility on polymer based dehumfidifer. We measured the contact angle of LiCl solution with and without surfactant PVP on Polytetrafluoroethylene (PTFE) surface which is a widely used polymer. The results are shown by Fig. 18 as follows.

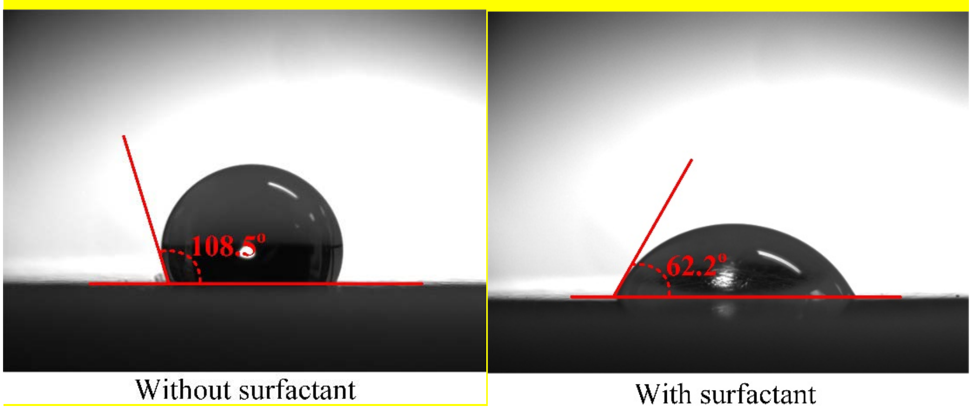


Fig. 18. Comparison of solutions contact angle on PTFE surface

From the above figure, we can clearly see that the contact angle of solution decreases dramatically from the original 108.5° to 62.2° by adding surfactant. According to the fact that smaller contact angle corresponds to better wettability of solution falling film on surface, the adding of PVP into conventional LiCl solution can also greatly improve the wettability of falling film on PTFE. The better the wettability is, the better the dehumidification would be. Therefore, the present study does not only validate the dehumidification performance enhancement by adding surfactant PVP for stainless steel based dehumidifier, but also provides a practical guidance for other material based dehumidifier, polymer for example. However, further study need to be conducted in the future to identify the detailed dehumidification performance on polymer based dehumidifier.

4 Conclusion

The dehumidification characteristics of a single channel dehumidifier was newly studied for LiCl liquid desiccant with and without surfactant PVP-K30. The effects of air flow rate, temperature, inlet absolute humidity and solution flow rate, temperature, concentration on the dehumidification performance were investigated comprehensively. The contact angle, wetting ratio and film thickness were experimentally measured to explain the enhancement mechanism. Some conclusions are drawn, as below:

(1) The non-volatile, odorless and nontoxic surfactant PVP-K30 was newly introduced for improving the dehumidification performance of LDCS.

(2) The adding of surfactant PVP-K30 results in a significant improvement for both the dehumidification rate and effectiveness. The relative increments for them are 22.7% and 19.9% respectivley.

(3) The enhancement mechanism of dehumidification can be attributed to the reduction of contact angle of liquid desiccant after tiny addition of surfactant. Resulted from the decrease of contact angle, the wetting ratio changes from 82.7% to 96.7% with a relative increment of 16.9%. The incremental contact area between processing air and solution results in more absorption of water vapor by liquid desiccant. The film thickness has a decrement of nearly 0.1mm from 0.681mm to 0.583mm. Thinner film thickness of falling film results in higher mass transfer driving force and also contributes to better internal cooling effect and better dehumidification performance.

(4) The increasing of process air mass flow rate increases the dehumidification rate and decreases the dehumidification effectiveness. Parameters, such as air humidity, solution temperature and concentration, directly determine the mass transfer driving force and have obvious effects on dehumidification performance. However, air temperature and solution flow rate has negligible influence on dehumidification characteristics.

To make a brief summarization, the newly proposed surfactant PVP-K30 can be promising to be added into the liquid desiccant cooing system for the purpose of efficiency improvement. Even though the present study focuses on the internal cooling plate dehumidifier, the surfactant can also be applied to the more often adopted packed bed dehumidifier for the purpose of mass transfer enhancement. The experimental results in terms of dehumidification rate, effectiveness, wetting ratio can give valuable guidance for the design of dehumidifiers and liquid desiccant cooling system as well.

Acknowledgement

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