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Title: Development and investigation on the dehumidification and corrosion resistance performance of a new mixed liquid desiccant

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Abstract: The liquid desiccant cooling system (LDCS) is regarded as a promising alternative for the traditional vapor compression cooling system due to its energy saving potential and accurate control ability of both temperature and humidity. However, metal corrosion of mass exchanger plate caused by the liquid desiccant greatly restricts the application of LDCS. The present study developed a new kind of mixed liquid desiccant to reduce the corrodibility, and the corrodibility of new mixed solution was examined as well as the dehumidification performance. The vapor pressure of the mixed solution was measured by static method firstly, and the corrosion characteristics were tested by electrochemical method and compared with the ones of normal lithium chloride (LiCl) solution. Comparative investigations were also conducted to study the dehumidification performance under various operating conditions. The experimental results indicate that the corrodibility of new mixed solution is far smaller than that of normal LiCl solution, and the dehumidification performance in terms of absolute moisture change and effectiveness has a significant improvement of 8.7-14.3% and 5.8-15.2% for the newly mixed solution compared with LiCl solution because of the excellent wettability of mixed solution on dehumidifier. The wetting area increases from 0.172m^2 for LiCl solution to 0.184m^2 for mixed solution. In addition, a correlation to predict the dehumidification effectiveness of the mixed solution was also proposed with the average mean absolute relative deviation of 4.51%. The newly developed mixed liquid desiccant is a promising alternative for the commercial application of LDCS with small corrodibility and better dehumidification performance.

Key words: Liquid desiccant, dehumidification, corrosion, electrochemical test, falling film

Nomenclature			
$CaCl_2$	Calcium chloride		
d	Absolute humidity(g/kg)	Greek symbols	
E	Corrosion potential(V)	ρ	Density($\mathrm{kg/m^3}$)
G	Flow rate(kg/s)	η_{eff}	Dehumidification effectiveness (Dimensionless)
h	Enthalpy(kJ/kg)	Δ	Change value
I	Corrosion current($\mu\mathrm{A/m^2}$)	Subscripts	
$LiCl$	Lithium chloride	a	Air
$LDCS$	Liquid desiccant cooling system	corr	Corrosion
$LiBr$	Lithium bromide	e	Equilibrium
$MARD$	Mean absolute relative deviation	eff	Effectiveness
P	Vapor pressure(Pa)	exp	Experiment
Re	Reynolds number	in	Inlet
T	Temperature($^{\circ}\mathrm{C}$)	out	Outlet
TEG	Triethylene glycol	s	Solution
VCS	Vapor compression system	sat	saturation
X	Concentration(%)	w	Cooling water

1 Introduction

The traditional vapor compression cooling system is the main way adopted worldwide by people to get suitable indoor temperature and humidity. According to the Energy End-use Data 2015 released by the Hong Kong government [1], the energy consumed by air conditioning and refrigeration systems accounts for as high as 35% the total energy consumption. Similar high proportions can also be found in America and European countries [2]. In the future, with the quest of higher quality life among people, more energy will be required by air conditioning system to keep a comfortable indoor environment. As a result, it is quite necessary and meaningful to improve the system efficiency or to find some alternatives for the traditional vapor compression system. Among such endeavors, the liquid desiccant cooling system (LDCS) stands out for its brilliant advantages. Compared with the traditional VCS, the LDCS has the potential of energy conservation up to 20~40% according to previous studies [3-5]. What is more, it can take advantage of the low-grade renewable energy [6-9], such as solar energy, geothermal energy, during the regeneration process, which caters for requirements of energy conservation and carbon dioxide emission reduction.

Liquid desiccant is the medium that circulates in the LDCS. It absorbs water vapor from the processed air driven by the vapor pressure difference between air and solution and then becomes weak. After that, it is pumped into the regenerator. With high temperature and vapor pressure in the regenerator, regeneration would occur to make the weak solution strong for next circulation. The selection of liquid desiccant is of vital importance due to its direct influence on the heat and mass transfer performance and system efficiency in LDCS. Many factors [10, 11], such as thermal properties, dehumidification capacity, regeneration temperature, toxicity and cost, should be taken into consideration when selecting the liquid desiccant. Among which, the vapor pressure is the one that determines the mass transfer driving force during dehumidification/regeneration processes directly. As so many factors influence the selection of liquid desiccant, and in a lot of situations, these factors are not in consistence with each other. Therefore, keeping a balance during the selection is necessary.

In the early time, investigators tried organic polyalcohol for liquid desiccant, such as triethylene glycol (TEG) [12]. However, the inherent high viscosity of TEG greatly hindered its widely application, and its low toxicity and small volatility made the situation even worse. This is due to the fact that during the dehumidification process, the processed air which will be sent into the air conditioning room contacts directly with the liquid desiccant. The toxic TEG may be carried into the room and threats the health of occupants. Afterwards, the organic desiccant solution was replaced by inorganic salt solution. Lithium chloride (LiCl), lithium bromide (LiBr) and calcium chloride ($CaCl_2$) are the most often adopted ones for liquid desiccant. Compared with the organic desiccant solution, their viscosities are much smaller which is suitable for circulating in the solution loop. Due to the low vapor pressure, the concentration of salt solution ranges from 30% to 50% which is quite lower than the 90% or more for organic desiccant solution [10]. Due to its great application potential, a large number of studies were carried out concerning the thermal properties [13, 14] and heat and mass transfer performance [15-17] of salt solution during dehumidification and regeneration.

When conducting experiments to identify the heat and mass transfer characteristics of salt solution in metal based dehumidifier, serious corrosion phenomenon on metal was observed, as shown by Fig. 1. Even the stainless steel 304 cannot resist the corrosion from lithium chloride solution, needless to say the commonly used aluminum and copper [18-21]. The corrosion on mass transfer component can not only affect the dehumidification/regeneration performance but also reduce the system reliability dramatically. In order to avoid or alleviate the corrosion caused by salt liquid desiccant, various attempts have been made by previous researchers. Generally speaking, they can classified into two groups: material improvement and solution modification. For the material improvement, studies mainly concentrated on the surface treatment technology to improve the corrosion resistance performance of original metal. The surface treatment technology of electroplating was employed by Luo et al. [18] in their study to investigate the dehumidification performance of an internal cooling fin-tube dehumidifier. Some antiseptic materials were adhered to the surface of the fin through electroplating. Comparative corrosion resistance tests demonstrated the good anti-corrosion performance of the adopted fin-tube dehumidifier. Wen et al. [19] firstly introduced the technology of anodic oxidation into the production of aluminum based plate dehumidifier/regenerator. Compared with the normal aluminum dehumidifier, the anodized one can not only alleviate the corrosion greatly but also increase the mass transfer performance obviously. However, pitting corrosion under high solution temperature during regeneration makes the technology worthy improving before application in regenerator. Other researchers gave up the application of metals directly and adopted plastics for replacement [22, 23]. The thermally conductive plastic was used by Liu et al. [23] for the production of an internally-cooling dehumidifier. Naturally, the dehumidifier made of plastic has excellent corrosion resistance ability. And the dehumidification performance was also comparable with that of metal based dehumidifier. Another kind of plastic called heat-resistant acrylonitrile butadiene styrene was employed by Lee et al. [22] to produce a dehumidifier. They sprayed the hydrophilic coating on the surface of plastic plate to improve the wettability. Systematical experiments were conducted based on the developed dehumidifier to study the dehumidification performance under various conditions. Even though the adoption of plastic during the manufacture of dehumidifier/regenerator can avoid the corrosion, the poor wettability, complex manufacturing processes and relative week structure strength are all considerable issues before its large scale application.

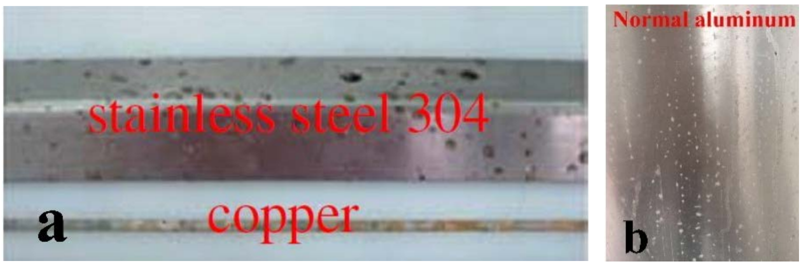

Fig. 1. Corrosion phenomenon of liquid desiccant on metals [18, 19].

Different from the various attempts made in the material improvement, the studies on solution modification are relatively limited. Some scholars put forward the adoption of mixed salt liquid desiccant with organic alcohol [24-26], LiCl/TEG/H_2O, LiBr/TEG/H_2O for example, to replace the traditional salt liquid desiccant. Even though such mixed solutions have suitable vapor pressure to provide sufficient mass transfer driving force during dehumidification, the introduction of polyalcohol makes these mixed solutions improper due to the potential of volatilization. What is more, no detailed experimental study has been conducted to investigate the dehumidification performance quantitatively.

Therefore, the present study intended to reduce the corrodibility of the liquid desiccant by the means of solution modification. A direct guidance for such purpose is to lower the concentration of the salt solvend in the liquid desiccant. Therefore, the search and selection of the possible candidate for the mixed liquid desiccant becomes one of the key aims. During the selection process, basic principles, such like non-toxic, non-volatile, easy availability, should be obeyed. Of course, suitable vapor pressure of the mixed liquid desiccant to support the mass transfer driving force is another pretty important factor that needs to be taken into consideration. After so many trials, a promising candidate named hydroxyethyl urea was selected for subsequent detailed study on corrosion and dehumidification characteristics. The hydroxyethyl urea has excellent moisture retention capacity which is widely used in the field of cosmetics [27]. Therefore, considering its mature application in different areas, the safety of it can be guaranteed.

Based on the selected hydroxyethyl urea, the present study determined the formula of the mixed liquid desiccant firstly according to the measured vapor pressure. The vapor pressure was acquired by static method on a purpose-built test rig. After that, comparative electrochemical tests were carried out to analyze and compare the corrosion characteristics of different liquid desiccants. Then, experiments were conducted to identify the dehumidification performance in a single channel falling film dehumidifier with internal cooling. The dehumidifier was made of stainless steel 316L with the size 500mm*500mm (Length*Width). The influences of various parameters which included air mass flow rate, temperature, humidity and desiccant solution flow rate, temperature were analyzed and compared. Finally, an empirical correlation for the purpose of dehumidification effectiveness prediction was developed and validated.

2 Measurement of vapor pressure and determination of formula for the new mixed solution

2.1 Description of vapor pressure test rig and system validation

Static method has been successfully used by previous researchers [28, 29] to measure the vapor pressure of solution. The principle for static method is that when the solution and vapor keep in balance under a certain temperature, the pressure of the vapor is the saturated pressure for the solution under this temperature. Based on this method, a test bench was designed and built, as shown by Fig. 2.

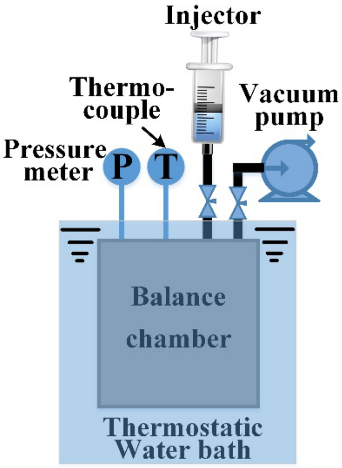

Fig. 2. Test bench for the vapor pressure measurement.

During the experiments, the temperature of water in the water bath was regulated to the set value firstly. Then, the balance chamber was evacuated to high vacuum with the absolute pressure less than 1 Pa inside. The actual value of the pressure can be obtained from an absolute pressure meter with the accuracy of 0.075%. After closing the value connecting with the vacuum pump, the prepared solution sample was injected into balance chamber. When the liquid and gas phase achieved a balance, in other words, the values of both the solution temperature and pressure kept unchanged, the values were recorded and regarded as the equilibrium temperature and vapor pressure of liquid sample. Before the formal vapor pressure measurement, the saturation vapor pressures of water under different temperatures were measured by the test bench to validate the system. The results are shown in Fig. 3 and the referred values are from the NIST standard reference database [30]. The relative deviation is 1.28% for all the vapor pressure ranging from 2000Pa to 18000Pa under the temperature of 21.5°C to 58°C. As a result, it is reasonable to conduct the subsequent experiments for vapor pressure measurement.

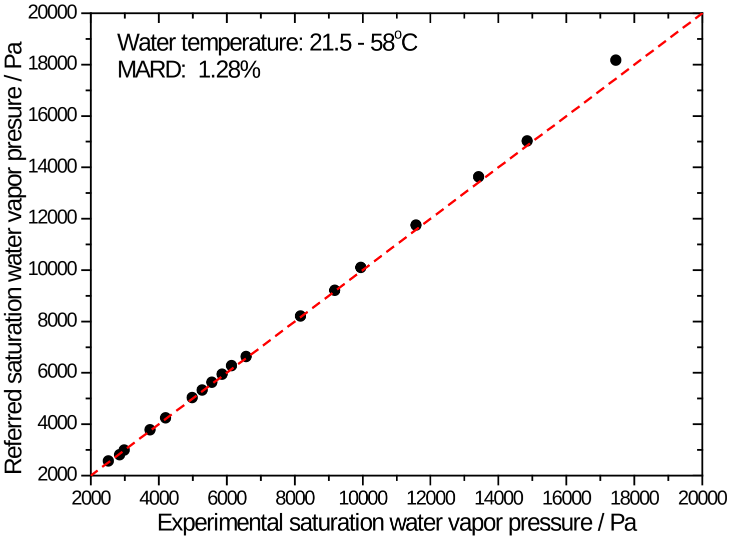

Fig. 3. Comparison between the experimental and referred vapor pressure.

2.2 Formula of the new mixed liquid desiccant

Based on the above test bench, we wanted to find a formula for the mixed solution which has comparable dehumidification performance with LiCl solution and is less corrodibility. One of the practical ways to reduce the corrodibility of liquid desiccant is to reduce the concentration of LiCl and replace it by other promising alternatives. As the processed air dehumidified by liquid desiccant will be directly sent into the air-conditioning room, the possible alternatives should be non-volatile, odorless and nontoxic for the benefit of residents' health. Therefore, the attempts on searching for possible candidates are focused on hygroscopic materials widely used in the fields of food and cosmetics as they are safe for people. After a lot of investigations, the possible candidates of trimethylglycine, sorbitol, triethylene glycol, polyethylene glycol 200, potassium formate, sodium lactate and hydroxyethyl urea were initially selected. During the following experiments, it was found that the triethylene glycol and polyethylene glycol 200 were not appropriate as they had obvious smell. For the candidates of sodium lactate and potassium formate, sediments or chemical reactions were observed when mixing with LiCl. Obviously, they were not suitable. The rest candidates of trimethylglycine, sorbitol and hydroxyethyl urea were promising but needed more validation. Their vapor pressures were measured by the abovementioned experimental system. Unfortunately, the vapor pressures for the mixed solutions with trimethylglycine and sorbitol were still pretty high even under high concentration. Differently, the mixed solution with hydroxyethyl urea shown quite low vapor pressure under considerable concentration. Consequently, it was selected as the promising alternative for further study.

In present study, the 25% concentration of LiCl was selected firstly, which was a compromise between solution viscosity, dehumidification performance and corrodibility. The explanation is that even though the solution with higher LiCl concentration has better dehumidification performance, the corrodibility is also high. It is feasible to reduce the concentration of LiCl by adding enough hydroxyethyl urea into the mixed solution. However, it was found that the solution viscosity of the mixed solution increased obviously with the increase of hydroxyethyl urea. The high viscosity of liquid desiccant would not only lead to high power consumption of pump in the system but also the problems of hydrops and flow instability. After serious consideration, the concentration of LiCl was set as 25%. In order to obtain intuitive comparative results of dehumidification performance, the 35% LiCl solution was selected as reference. The concentration of hydroxyethyl urea in the whole mixed liquid desiccant was determined according to the vapor pressure of 35% LiCl solution. After lots of measurements, the formula of 25% LiCl/39% hydroxyethyl urea/36% water was finally determined. The vapor pressure under the temperature ranging from 20^{o}C to

40°C was measured and presented in Table 1. A temperature-based polynomial which is presented by Equation 1 was also proposed to give prediction of vapor pressure under different temperatures. The mean absolute relative deviation (MARD) which is defined by Equation 2 between the experimental and fitted values is 1.4%. The comparison of vapor pressure between LiCl and the new developed mixed solution (25% LiCl/39% hydroxyethyl urea/36% water) is illustrated by Fig. 4 based on Conde [31] and present experimental results. Compared with the 25% LiCl solution, the addition of 39% hydroxyethyl urea greatly reduces the vapor pressure from 1777Pa to 920Pa at the temperature of 25°C. Consequently, the vapor pressure of the mixed solution is almost the same with that of the 35% LiCl solution of 919Pa at 25°C. The vapor pressure of 920Pa corresponds to the equivalent humidity content of 5.6g/kg which provides enough mass transfer driving force during the process of dehumidification.

Table. 1. Experimental and fitted values for mixed liquid desiccant.

Tem. / °C	20.6	23.8	24.4	29.2	30.3	35.3	36.3	40
Exp. / Pa	689	823	874	1182.5	1303	1712	1848	2254
Fitted / Pa	683	851	885	1196	1284	1735	1840	2273
MARD / %	0.90	3.40	1.28	1.17	1.44	1.35	0.44	0.83

$$P_{\text{sat}} = -624.2118 + 113.2677T - 4.4309T^2 + 0.1109T^3 - 6.4138*10^{-4}T^4 \quad (1)$$

$$MARD = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{P_{exp} - P_{fitted}}{P_{exp}}\right| \quad (2)$$

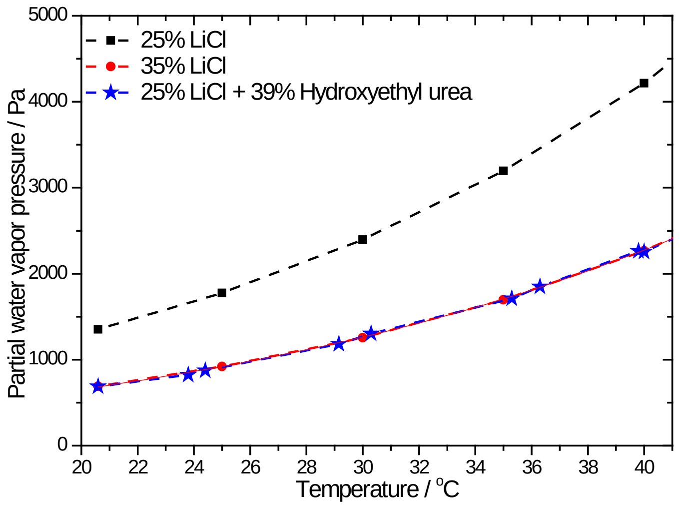

Fig. 4. Comparison of the vapor pressure between LiCl and the new mixed solution.

3 Experimental investigation on dehumidification performance

3.1 Introduction to experimental apparatus

An experimental apparatus was designed and built to investigate the water vapor absorption performance by both LiCl and the new mixed liquid desiccant. Fig. 5 presents the schematic diagram and real photograph of the test rig. Three different loops which are differentiated by the color of the arrow in the figure stand for the processed air loop, liquid desiccant loop and cooling water loop respectively. Neoprene foam was wrapped at the outside of each loop to prevent the heat exchange between the experimental system and outer environment.

During the experiments, the liquid desiccant with known concentration was stored in the solution tank. After heating to the desired temperature by an automatic Proportion-Integration-Differentiation (PID) controller, the desiccant solution was pumped into the plastic pipe. The mass flow rate in the loop was regulated by adjusting the opening degree of a by-pass value, as shown in Fig. 5. After filling the cuboid distributor at the top of the single channel dehumidifier, the solution flowed along the surface of the plate dehumidifier in the form of falling film. Simultaneous heat and mass transfer occurred in the channel between processed air and liquid desiccant solution. Then, the solution was collected by a collector at the bottom of the dehumidifier and flowed back to another solution tank. The flow rate and temperature of the cooling water were also adjusted to set value before experiments. Water in the cooling water loop was reserved in a tank in a water chiller. The water chiller with automatic temperature control system could cool the water to the required temperature. A chiller pump distributed cold water into the water channel of the dehumidifier through the pipes. The introduction of cold water at the back side of the falling film is to enhance the dehumidification performance. This is based on the fact that during the absorption process, water vapor transforms from gas phase to liquid phase. Therefore, latent heat would release due to the phase transformation and would be absorbed by the liquid desiccant. After absorbing the latent heat, the temperature of the falling film will increase along the flow direction. Higher solution temperature corresponds to lower mass transfer driving force and contributes to worse dehumidification performance. After the absorption of heat from liquid desiccant, the water flowed backed to the chiller for next circulation. When the required operating conditions in the solution and cold water loop were satisfied, the processed air was delivered into the air duct channel by the suction of a fan installed at the head the channel. The air temperature was controlled by an electrical heat with an automatic PID controller. In order to investigate the influence of air humidity on dehumidification characteristics, an electrical humidifier was employed and installed in the air duct. By regulating the input voltage of the humidifier, different levels of humidity can be obtained according to the requirement of the experiments. Finally, the processed air with known temperature and humidity flowed into the dehumidifier and contacted with the liquid desiccant flowing on the plate. After that, it was discharged through the duct to the environment. During the experiments, all real-time experimental data were collected and displayed by a data logger. When all the parameters reached a steady level, all the data were recorded and stored by the data logger for subsequent analysis.

All temperatures of air, solution and cooling water inlet and outlet were measured by thermocouples Pt100 with the accuracy of $\pm 0.1K$. Both the solution and cooling water flow rate were obtained by a turbine flow rate meter with the relative accuracy of $\pm 3\%$. For the air flow rate, it was acquired by a pitot tube. The pitot tube was installed at the outlet duct and connected with a micro-manometer. Another two important parameters, namely the inlet and outlet air humidity, were measured by two humidity sensors installed in the air loop before and after the dehumidifier. The accuracy of these two sensors are $\pm 2.5\%$. In fact, the values obtained by the humidity sensors were relative humidity. By combining the air temperature obtained by thermocouple, the absolute humidity content could be calculated finally.

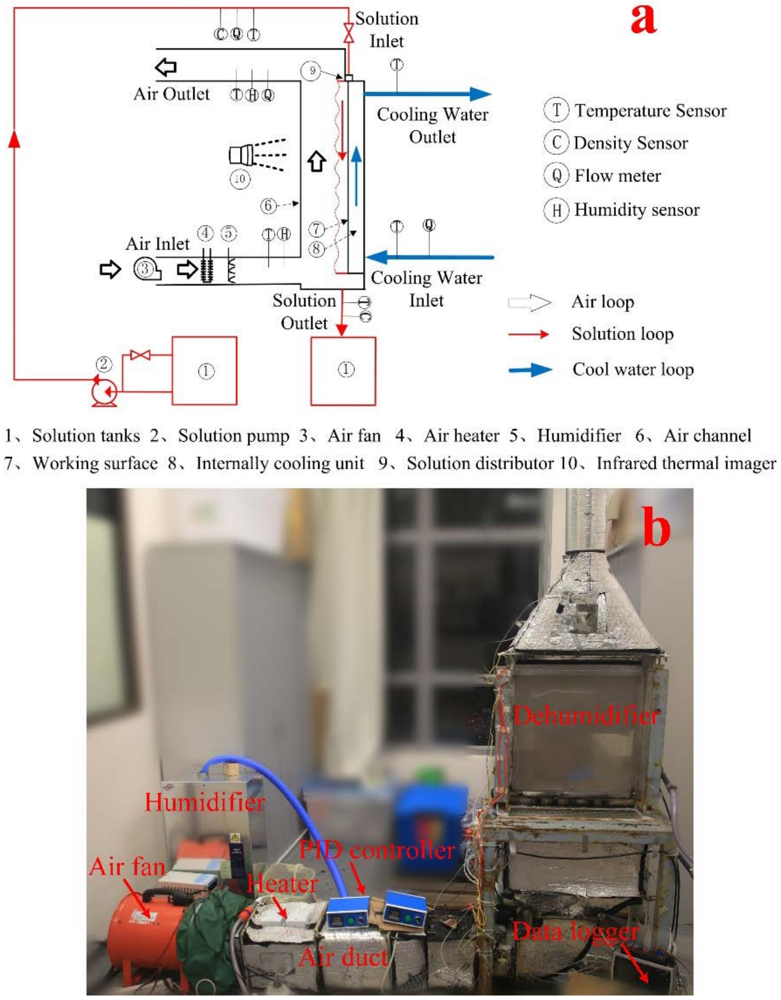

Fig. 5. Picture of the experimental system: (a) Schematic diagram, (b) Real photograph.

3.2 Dehumidification index and conservation equations

Two criteria, namely absolute moisture removal and dehumidification effectiveness, were chosen to evaluate the dehumidification performance under various operating conditions. The absolute moisture removal indicates the absolute moisture content difference between the inlet and outlet of processed air. The bigger the value is, the more excellent the dehumidification performance is. What is more, in the real application, the humidity of supply air is the key parameter associated with the total moisture load in the air conditioning room. In the LDCS, the humidity of supply air is directly determined by the processed air at the outlet of dehumidifier. Therefore, the absolute moisture content is of vital importance in practical application. The definition is shown by Equation 3 as follows:

$$\Delta d = d_{a,in} - d_{a,out} \tag{3}$$

where d_a means the absolute humidity content of air and the subscripts in, out correspond to inlet and outlet parameters.

The dehumidification effectiveness can reflect the efficiency of the dehumidifier by calculating the ratio between the absolute moisture removal and potential greatest moisture removal. The formulation can be presented as:

$$\eta_{eff} = \frac{d_{a,in} - d_{a,out}}{d_{a,in} - d_{\mathrm{e}}} \tag{4}$$

in which, d_{e} stands for the equivalent absolute moisture content of solution in the condition of equilibrium at its inlet concentration and temperature.

When dehumidification occurs in the dehumidifier, simultaneous heat and mass transfer also happens. The heat transfer between processed air, liquid desiccant and cooling water should obey the energy conservation equation which is shown by Equation 5.

$$G_s(h_{s,out} - h_{s,in}) + G_a(h_{a,out} - h_{a,in}) = G_w(h_{w,in} - h_{w,out}) \tag{5}$$

where G is the mass flow rate and the subscripts s, a, w stand for the solution, processed air and cooling water respectively. h means the enthalpy.

The water vapor in the humid processed air is absorbed by the desiccant solution which dilutes the strong solution. Their relationship can be described by the mass conservation equation which is shown in Equation (6).

$$G_a(d_{a,in} - d_{a,out}) = G_s X_{s,in}\left(\frac{1}{X_{s,out}} - \frac{1}{X_{s,in}}\right) \tag{6}$$

where X is the concentration of solution.

3.3 Uncertainty analysis and experimental validation

Uncertainties for different parameters were analyzed according to the accuracy of sensor and the uncertainty propagation method. In present study, all the temperatures, water flow rates and relative humidity were measured by corresponding sensors and their uncertainties are the accuracies of these sensors. Other parameters, such as absolute moisture content, concentration, absolute moisture removal and dehumidification effectiveness, were determined by conservation indirectly. Therefore, their uncertainties should be calculated according to the uncertainty propagation method [32]. The expression is presented by Equation.

$$\frac{\delta y}{y}=\sqrt{(\frac{\partial \ln f}{\partial x_1}\delta x_1)^2+(\frac{\partial \ln f}{\partial x_2}\delta x_2)^2+...+(\frac{\partial \ln f}{\partial x_n}\delta x_n)^2} \tag{7}$$

In Equation 7, y is the indirect measured value. δx_n stands for the uncertainty of the n_{th} direct measured parameter. A summarization for all the uncertainties is illustrated in Table 2.

Table 2. Summarization of the uncertainties in present study.

Parameter	Uncertainty	Parameter	Uncertainty
Temperature/ T	± 0.1K	Cold water flow rate/ G_w	± 3%
Solution flow rate/ G_s	± 3%	Air absolute humidity/ d	2.7%
Air flow rate/ G_a	± 2.2%	Dehumidification rate/ Δd	3.7%
Air relative humidity/ φ	± 2.5%	Dehumidification effectiveness/ ξ	5.2%

During the dehumidification process, both the heat and mass conservation which are shown in Equation 5 and 6 should be satisfied. However, during our experiments, we found that the change of solution concentration could be hardly checked due to the limited absorption of water vapor during one cycle. Roughly, the relative change of solution concentration was less than 0.15% in one cycle. However, the measurement uncertainty of concentration was about 0.32% which was bigger than 0.15%. Therefore, it is unscientific and unreasonable to measure the outlet solution concentration due to its negligible change during the experiments. Consequently, in present study, we only checked the energy balance as presented by Equation 5. Before the formal experiments, validation experiments were carried out under a wide range of working conditions. The results were shown by Fig. 6. It is worth noting that due to the unknown heat capacity of the new mixed liquid desiccant developed by present study, the enthalpy of the mixed solution could not be calculated. As a result, only the energy balance for 35% LiCl during dehumidification was checked. According to previous studies, the absolute relative enthalpy differences usually fall into the range of 0-30% [33]. As most differences between the enthalpies fall into the error band of $\pm 20\%$, it is reasonable to say that the subsequent experiments are rational to investigate the dehumidification characteristics. The random fluctuations of the enthalpy differences were caused by the accuracies of sensors and small amount of heat exchange between the experimental system and ambient environment.

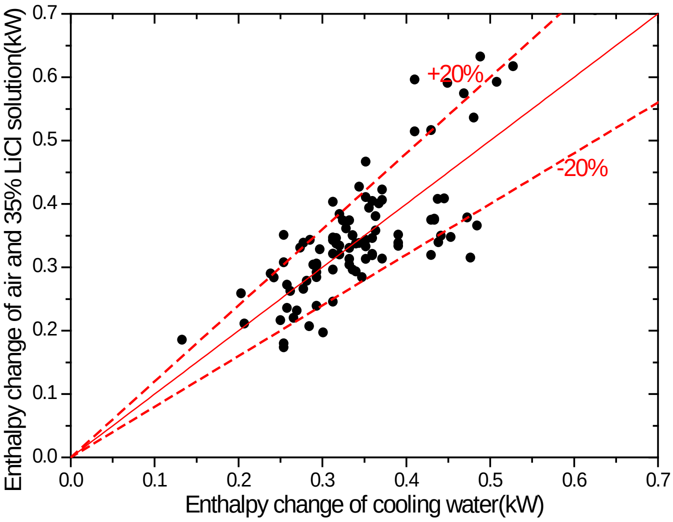

Fig. 6. Energy balance validation of the experimental system.

4 Results and discussion

4.1 Comparison of corrosion characteristics

In order to test the corrosion characteristics of the dehumidifier made of stainless steel, a stainless steel sample with the size of 1.5cm*1.5cm exposing outside was prepared firstly. The rest surfaces of the sample were covered by the non-conducting silicone rubber. The surface was polished and cleaning by ultrasonic cleaner. After that, the sample was immersed into the prepared liquid desiccant for corrosion test. An electrochemical station produced by Wuhan Corrtest Instruments Corp., Ltd was used to measure the polarization curve for the stainless steel sample in both 35% liquid desiccant and the new mixed liquid desiccant. The scanning speed for polarization curve was 1 mV/s and the scanning range was -0.25V to 0.25V relative to the open circuit potential. The results for the polarization curves are illustrated in Fig. 7. By analyzing the curves in Fig. 7, the self-corrosion current and potential of stainless steel sample can be obtained as given in Table. 3.

The relationship between the corrosion rate and the self-corrosion current and potential is that larger corrosion potential means smaller occurrence possibility of corrosion. For self-corrosion current, greater current corresponds to faster corrosion [34]. Therefore, from Table 3, it clearly indicates that the corrosion rate of the sample in the mixed solution is much smaller than that in 35% LiCl solution in terms of both the bigger potential and smaller self-corrosion current. In other words, the corrodibility of the new mixed desiccant solution is much smaller than that of 35% LiCl solution.

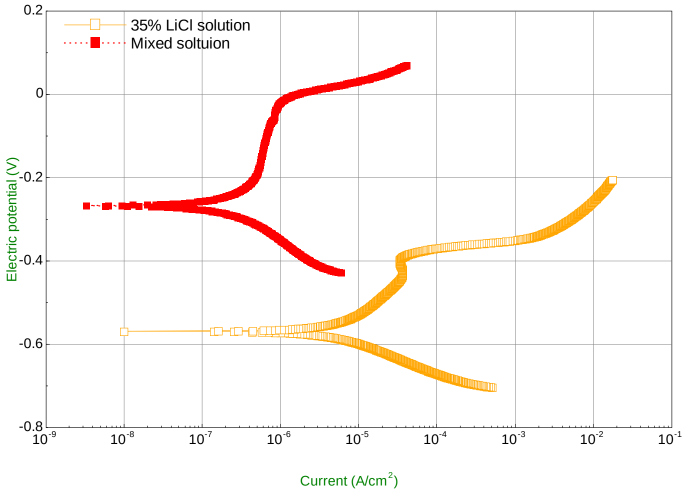

Fig. 7. Tafel polarization curves of stainless steel in different solutions.

Table. 3. Corrosion parameters of stainless steel in different solutions.

Solution	$E_{corr}\,(\,V\,)$	$I_{corr}\,(\mu A / cm^2)$
35% LiCl solution	-0.5683	6.799
New mixed solution	-0.2521	0.2265

4.2 Influence of solution flow rate on dehumidification

Fig. 8 shows the influence of solution flow rate on dehumidification performance in terms of absolute moisture removal and dehumidification effectiveness. For absolute moisture removal, it maintains around 2.32g/kg and 2.77g/kg for 35% LiCl and mixed solution respectively under the working conditions as shown in this figure. The same trend goes for dehumidification effectiveness and it fluctuates around 15.5% and 17.5% respectively. The main reason for such trends is that the change of solution flow rate in the range of present study does not change the wetting area significantly and so does the mass transfer driving force. During the experiments, the wetting areas for 35% LiCl and mixed liquid desiccant maintained at 0.172m^2 and 0.184m^2 nearly. It is worth noting that the same pump was used during the experiments. The mass flow rate of 35% LiCl solution changed from 0.08kg/s to 0.15kg/s. However, the change for mixed liquid desiccant was only from 0.068kg/s to 0.11kg/s which was much smaller than that of 35% LiCl solution. It is the difference in soluiton viscosity which causes such phenomenon.

For example, under the temperature of 27.8°C in Fig. 8, the dynamic viscosity of the 35% LiCl solution is only 4.90 mPa.s. Nevertheless, the value is as high as 12.73 mPa.s for mixed liquid dessiccant. Consequently, the mass flow rate of mixed solution is much smaller than that of 35% LiCl soluiton even delivered by the same pump. On average, the absolute moisture removal and dehumidification effectiveness have a relative increment of 13.2% and 11.4% respectively for mixed solution compared with the 35% LiCl solution.

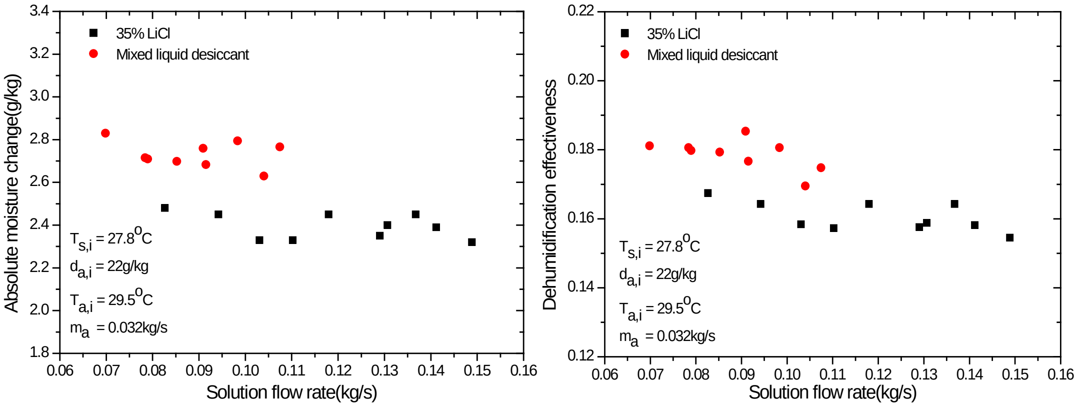

Fig. 8. Influence of solution flow rate on dehumidification performance.

4.3 Influence of solution temperature on dehumidification

The dehumidification characteristics of both 35% LiCl solution and mixed solution under various solution temperatures are presented and compared in Fig. 9. Both the absolute moisture change and dehumidification effectiveness decrease with the increase of solution temperature. When the temperature of 35% LiCl solution increase from 28°C to 35°C, the equivalent absolute moisture content also increases from 6.89g/kg to 10.58g/kg which reduces the mass transfer driving force between the processed air and liquid desiccant and deteriorates the dehumidification performance. The explanation can also be applied to the mixed solution. The equivalent absolute moisture content of the mixed solution has an increment of 3.73g/kg from 6.91g/kg to 10.64g/kg when the solution temperature has such an increase. An obvious increment for both absolute moisture change and dehumidification can be observed in the figure for the mixed solution.

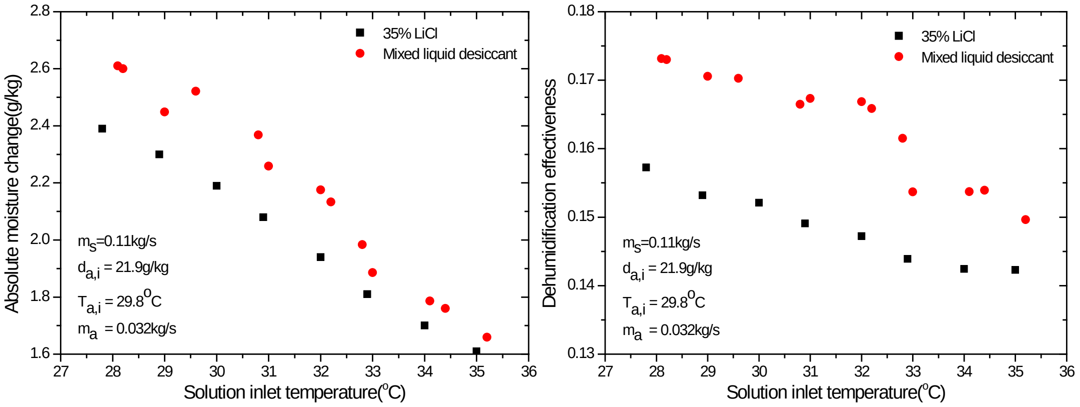

Fig. 9. Influence of solution inlet temperature on dehumidification performance.

4.4 Influence of air flow rate on dehumidification

From Fig. 10, the dehumidification performance under various air flow rates can be observed and compared. When the air flow rate increases from 0.023kg/s to 0.06kg/s, the absolute moisture removal decreases from 2.58g/kg to 1.81g/kg for 35% LiCl solution and 2.84g/kg to 2.10g/kg for mixed liquid desiccant. The decrease tendency also goes for the dehumidification effectiveness for both liquid desiccants. The explanation for the declining trend is that with the increase of the air mass flow rate, the velocity of the processed air in the dehumidifier also increases. Higher air velocity results in shorter contact time between the processed air and liquid desiccant and lead to smaller absolute moisture removal. Compared with the 35% LiCl solution, the absolute moisture removal has a relative improvement of 12.0% for the new mixed liquid desiccant. For dehumidification effectiveness, the value is 9.3%.

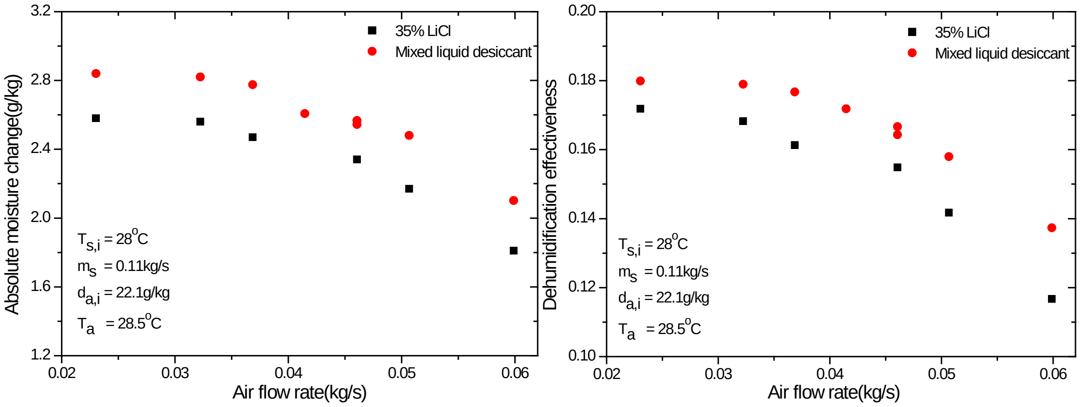

Fig. 10. Influence of air flow rate on dehumidification performance.

4.5 Influence of air temperature on dehumidification

The experimental results concerning the water vapor absorption characteristics under different air temperatures are illustrated in Fig. 11. From this figure we can see that the dehumidification performance does not change much at different temperatures. The absolute moisture removal keeps around 2.34g/kg and 2.56g/kg for 35% LiCl solution and mixed solution respectively. For dehumidification effectiveness, the values fluctuate around 15.2% and 16.7%. This is caused by the insignificant influence of air temperature on both mass transfer driving force and wettability of falling film on plate dehumidifier. The adoption of mixed liquid desiccant slightly increases both the absolute moisture removal and dehumidification effectiveness with the average relative increments of 9.7% and 10.1% respectively.

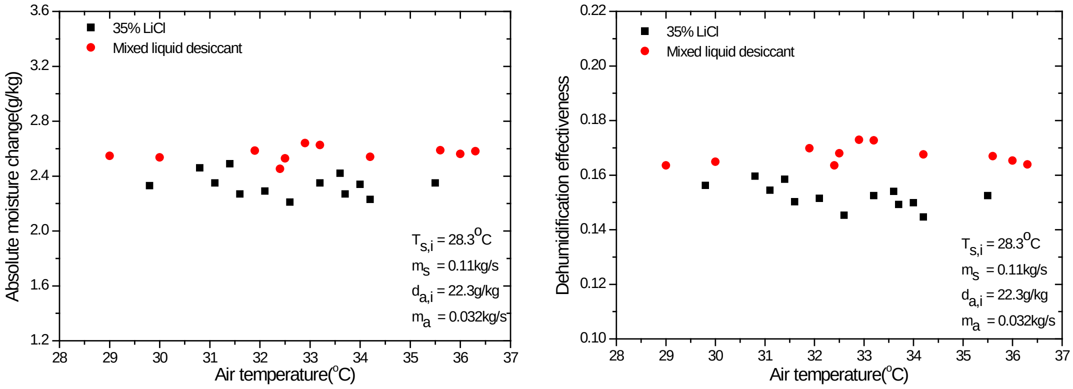

Fig. 11. Influence of air temperature on dehumidification performance.

4.6 Influence of air inlet humidity on dehumidification

Fig. 12 describes and compares the dehumidification characteristics of two liquid desiccants under different air inlet humidity. It can be concluded from the experimental results that both the absolute moisture removal and dehumidification effectiveness increase with the increase of air inlet humidity. For the 35% LiCl solution, the absolute moisture removal has an increment of 2.57g/kg from 0.36g/kg to 2.93g/kg when the inlet humidity increases from 14.9g/kg to 25.1g/kg. The dehumidification effectiveness also changes from 4.5% to 16.1% for 35% LiCl solution. In terms of the mixed liquid desiccant, it improves from 0.55g/kg to 3.17g/kg under the inlet humidity ranging from 13.5g/kg to 24.7g/kg. For dehumidification effectiveness under the same range of inlet humidity, it increases from 8.4% to 17.9% correspondingly. The increasing tendency is attributed to the increment of mass transfer driving force during dehumidification. The increase of the inlet air humidity enlarges the difference between the air humidity and equivalent absolute moisture content of solution which is the mass transfer driving force during dehumidification. Different levels of increment are observed in terms of both absolute moisture removal and dehumidification effectiveness under all operating conditions.

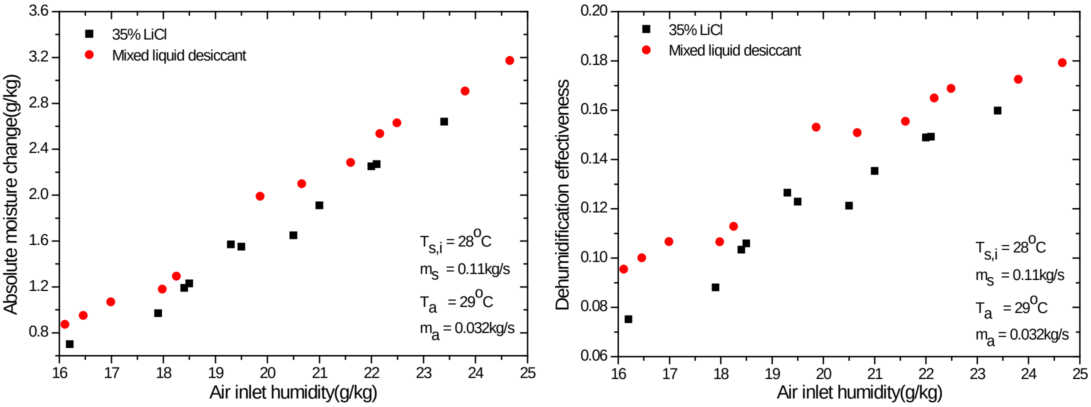

Fig. 12. Influence of air inlet humidity on dehumidification performance.

4.7 Discussion

By introducing hydroxyethyl urea into the LiCl liquid desiccant, the concentration of the LiCl solution can be reduced but with comparable vapor pressure. The present study added 39% hydroxyethyl urea into the 25% LiCl solution to reduce the corrodibility of the liquid desiccant. The mixed 25% LiCl/39% hydroxyethyl urea/36% water desiccant solution has nearly the same vapor pressure with that of 35% LiCl liquid desiccant under the solution temperature ranging from 20°C to 40°C. The corrodibility of the new mixed liquid desiccant on metal has been proven to be much smaller than that of 35% LiCl solution by the electrochemical test. What is more, according to the experimental results from Fig. 8 to 12, the dehumidification performance of mixed solution is much better than that of 35% LiCl solution even though they almost have the same vapor pressure which is also the key determinant of the mass transfer driving force. On the whole, the relative improvement for absolute moisture removal and dehumidification effectivness is 6.2-14.3% and 5.8-15.2% correspondingly. In the present study, the slightly enhancement is attributed to the improvement of wettability of falling film on plate dehumidifier. This conclusion can be validated by Fig. 13 which clearly shows the wetting area of different liquid desiccant on the plate dehumidifier. The infrared pictures shown in Fig. 13 were captured by a high resolution infrared thermal imager of FLUKE company. The wetting area increases from 0.172m^2 for 35% LiCl solution to 0.184m^2 for mixed solution with a relative increment of about 7%. The increment of wetting area directly increases the contact area between processed air and liquid solution. Under the same operating conditions, greater mass transfer contact area naturally leads to better dehumidification performance as shown in present study.

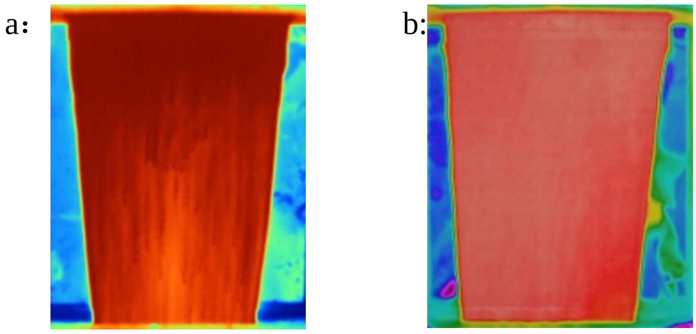

Fig. 13. Comparison between the wettability of: (a) 35% LiCl solution, (b) mixed solution

5 Correlation development for dehumidification effectiveness

As the newly developed mixed liquid desiccant, namely 25% LiCl/39% hydroxyethyl urea/36% water, was firstly developed and investigated, no experimental data were reported in the previous publications. For the convenience of engineering application in the future time, an empirical correlation to predict the dehumidification effectiveness was proposed based on the experimental data. According to the abovementioned experimental data, it is clearly indicated that the dehumidification effectiveness is closely related with the air flow rate, air inlet humidity and solution temperature but rarely related with air temperature and solution flow rate. As a result, we adopted the parameters: the Reynolds number of air Re_a, air inlet humidity d_{in} and equivalent absolute moisture content of solution d_e for the expression of the correlation. The final formulation for the dehumidification effectiveness is shown by Equation 8.

$$\eta_{eff} = 159.97 Re_a{}^{-0.161} d_{in}{}^{1.151} (d_{in} - d_e)^{0.254} \tag{8}$$

The detailed prediction values under various air inlet humidity and solution temperature are illustrated and compared with experimental data in Fig. 14. We can see that both the variation tendency and values for the calculated dehumidification effectiveness agree well with the experimenal data under various working conditions. The comparison between all the experimetnal and predicted effectiveness is presented by Fig. 14. Most the effectiveness differences have the MARD less than 10% and for the whole experimental data, the MARD is only 4.51%. In fact, in order to further validate the proposed correlation, it is better to check its rationality by experimetnal data from other studies. Unfornately, as noted before, the new mixed liquid desiccant was firstly developed and studied by us. No other experimental data is available in published papers. In the future, if suitable data sources are available, further validation and improvement for the proposed correlation will be conducted.

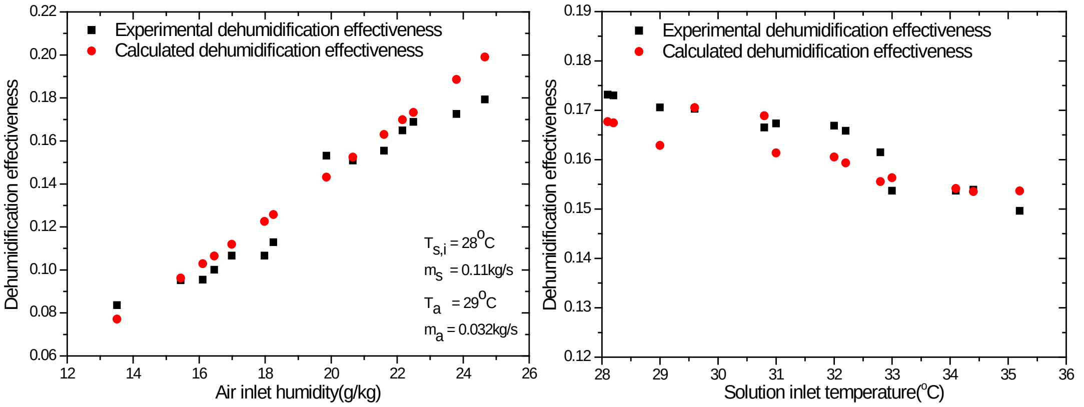

Fig. 14. Comparison results of effectiveness in various conditions.

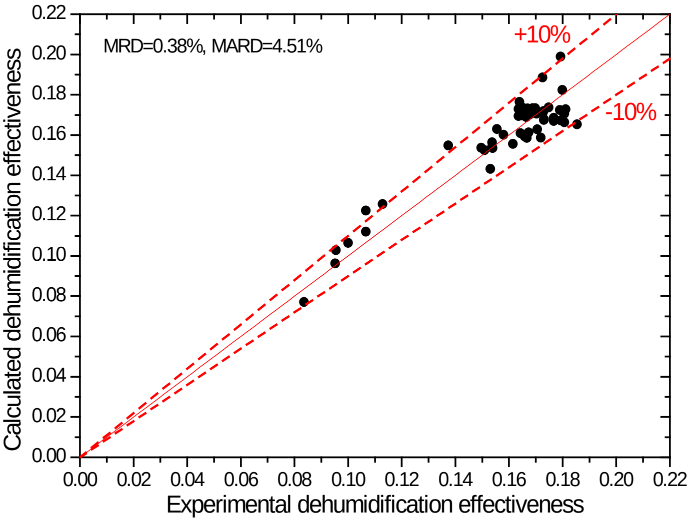

Fig. 15. Comparison between experimental and predicted effectiveness.

6 Conclusion

The present study newly developed a mixed liquid desiccant with the formula of 25% LiCl/39% hydroxyethyl urea/36% water with smaller corrodibility and better dehumidification ability. Its vapor pressure under different temperatures were measured, and comparative experiments in terms of corrosion characteristics and dehumidification performance were conducted and analyzed under various working conditions. Empirical correlation to predict the dehumidification effectiveness was also proposed lastly. Some main conclusions are drawn as follows:

(1) The newly developed mixed liquid desiccant of 25% LiCl/39% hydroxyethyl urea/36% water has almost the same vapor pressure with 35% LiCl solution ranging from 653Pa to 2273Pa during the temperature from 20°C to 40°C, which is suitable for the application of dehumidification. A temperature-based polynomial was developed to calculate the vapor pressure of the mixed liquid desiccant with the prediction accuracy of 1.4%.

(2) The corrodibility of the mixed solution on metal is much smaller than that of the 35% LiCl solution even though they have comparable vapor pressure.

(3) Compared with the 35% LiCl solution, the absolute moisture removal and dehumidification effectiveness has a relative improvement of 6.2-14.3% and 5.8-15.2% respectively for the mixed solution. The dehumidification enhancement is resulted by the improvement of wettability. The wetting area of falling film on the plate dehumidifier has a relative increment of 7.0% from 0.172m^2 for 35% LiCl solution to 0.184m^2 for mixed solution.

(4) A new correlation to predict the dehumidification effectiveness for the new mixed solution was proposed with the MARD of 4.51% which is applicable for its engineering application.

To conclude, the present study introduced a new kind of mixed liquid desiccant with suitable vapor pressure and small corrodibility which provides a promising alternative for the conventional salt liquid desiccant. The experimental data in terms of vapor pressure and dehumidification performance for the new mixed liquid desiccant can also provide meaningful guidance for the design and application of LDCS.

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