Performance assessment of a liquid desiccant system for formaldehyde removal based on a novel criterion

Jiachun Hu, *Lixia* Wen, *Xingyu* Wang, and *Huangxi* Fu*

School of Civil and Surveying & Mapping Engineering, Jiangxi University of Science and Technology, Ganzhou, China

*Corresponding Authors: fhx635654783@163.com (H. Fu)

Abstract: In the era of requirements in indoor air quality, liquid desiccant (LD) dehumidification is regarded as an energy-saving method removing indoor air contaminants during the dehumidification process, which has made considerable progress in recent years. Many previous studies have confirmed that the heat and mass transfer characteristics associated with absorption characteristics and thermophysical properties in LDs play a vital role in contaminants removal performance. The main purpose of this research is to numerically assess the indoor formaldehyde removal performance of a LD dehumidification system with different LDs. In order to make a fair assessment, a novel criterion based on the same temperature and the same vapor pressure which is the same desiccant condition is proposed. A numerical model integrated with heat, moisture, and formaldehyde transfer is used to predict the system performance. This model can rationally simulate the formaldehyde removal performance of the LD dehumidification system by inputting various operating parameters, including indoor air status parameters and outdoor air status parameters. The simulation results show that the number of mass transfer units of formaldehyde (NTU_{mf}) plays a key role in the formaldehyde removal performance. The formaldehyde removal performances decrease with the increase of temperature and humidity ratio of return air, while they increase with the increase of temperature and humidity ratio of fresh air. With the aforementioned results, the study is expected to be beneficial to further improve the removal ability and potential of LD systems for indoor formaldehyde.
Keywords: Liquid desiccant, Formaldehyde removal, Desiccant condition, Dehumidification

1 Introduction

Indoor air quality, which is mainly related to indoor air humidity and concentration of contaminants, has become a primary issue in buildings as people now spend 60-90% of their life indoors [1]. LD system is considered as an relatively efficient and energy saving technology to remove indoor contaminants during the dehumidification process without using excess energy. In the dehumidification process, desiccants absorb the moisture from return air driven by the vapor pressure difference between them at low temperature. Then, they release the absorbed moisture to fresh air at high temperature in regeneration process. This system can be driven by low-grade heat sources, such as waste heat or solar energy, revealing strong energy saving potential and development prospect [2-3].

As a kind of indoor contaminants, formaldehyde mainly emitted from wooden furniture and people's long-term exposure can lead to the occurrence of diseases. Formaldehyde is currently classified first grade carcinogen and ubiquitous environmental contaminant, so that indoor air has to be purified to meet the formaldehyde concentration standard [4]. An empirical investigation of formaldehyde removal efficiency of a LD system using 36% LiCl solution was proposed by Park et al [5]. The results showed that the formaldehyde removal efficiency of this LD system was 27%. Fu et al. [6] simulated the formaldehyde removal efficiency of a count-flow LD system using three LD aqueous solutions, namely 44% LiBr, 35% $CaCl_2$ and 29% LiCl. The results showed that the formaldehyde removal efficiency of the three LD solutions can reach more than 45%. Zheng et al. [7] measured the Henry's law constant (HLC) of formaldehyde in a 40% LiCl aqueous solution at different temperatures, and then simulated the formaldehyde removal efficiency of a LD dehumidification system. Their results showed that with the given working parameters, the formaldehyde removal efficiency of the system could reach 53% in summer conditions.

The studies mentioned above have proved that LD systems can effectively remove formaldehyde, but the performance assessment between LD systems with different LDs is still a problem. Since the commonly used solution concentrations of different LDs (LiBr aqueous solution: 45~65%; LiCl aqueous solution: 30~40%) in a dehumidification system are not identical, it is hard to make a reasonable performance assessment of them. In this paper, a novel assessment criterion based on the same temperature and the same vapor pressure which is the same desiccant condition is proposed. Moreover, a theoretical model coupled heat, moisture, and formaldehyde transfer is established. With the model, the formaldehyde removal performance of different LDs is analyzed and assessed at a system level. In addition, the effect of other relevant parameters, including NTU_{mf}, return air temperature and humidity ratio, fresh air temperature and humidity ratio, on the formaldehyde removal performance of the LD system has also been analysed and discussed.

2 System and model description

2.1 System description

Fig. 1 shows the workflow of the LD system. The LD system is comprised of two modules, two pumps, a pre-cooler, a pre-heater, and a heat exchanger. Module D and module R stand for the dehumidification module and regeneration module, respectively. Firstly, the solution exchanges heat, moisture, and formaldehyde with the indoor return air in the module D. Secondly, the dehumidified and purified air is discharged into the indoor, and the weakened solution flows into the heat exchanger and pre-heater through the pump 1 for heating to achieve better regeneration performance. Then the weakened and heated solution enters the module R to regenerate into a strong solution. Lastly, the regenerated solution is driven into module D by pump 2 to form a cycle.

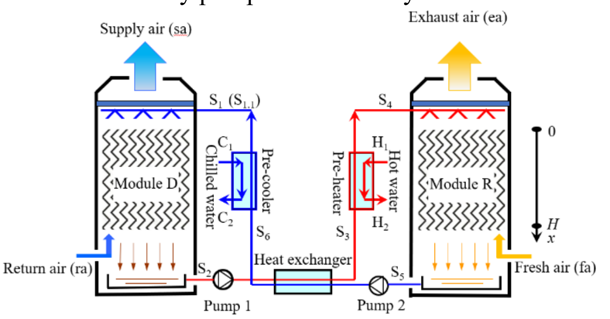

Fig. 1. Schematic of the counter-flow LD system for indoor formaldehyde removal.

2.2 Model description

The model and governing equations for the coupled heat, moisture, and formaldehyde transfer in the LD system have been presented in Ref. [6]. In the model, the parameter of HLC of formaldehyde in solution is required. The most commonly used expression for HLC is below [8]:

$$H_{cc} = \frac{C_{ae}}{C_{se}} \tag{1}$$

where H_{cc} is the HLC (dimensionless); C_{ae} is the equilibrium concentration (mg/m^{-3}) of the formaldehyde in the air, and C_{se} is the equilibrium concentration (mg/m^{-3}) of the formaldehyde in the LD. The HLC is an equilibrium constant, and the temperature dependence of the HLC can be expressed by the Van't Hoff equation (VHe) [9]:

$$\ln H_{cc} = a - \frac{b}{273.15 + t} \tag{2}$$

where a and b are the regression coefficients for the HLC estimation, and t (°C) is the temperature at which the formaldehyde in the gas and liquid phase reach equilibrium.

2.3 Performance assessment index

In this paper, an index is defined to assess the formaldehyde removal performance of the LD system, and is expressed as follow:

$$\varepsilon_{\text{Formaldehyde}} = \frac{C_{ra} - C_{sa}}{C_{ra}} \tag{3}$$

where C_{ra} and C_{sa} are the concentrations (mg/m^{-3}) of the formaldehyde in the return air and supply air, respectively.

3 Result and discussion

3.1 Performance assessment of the LD system

This section mainly assesses the formaldehyde removal performance of LD systems based on the same temperature and the same vapor pressure. Input the VHe and other relevant parameters into the simulation program to simulate the formaldehyde removal performance of the system. The VHes for formaldehyde in 45.7% LiBr solution and 30.7% LiCl solution are presented in Table 1 [6]. The operating parameters and working conditions for the LD system based on the same temperature and the same vapor pressure are listed in Table 2.

Table 1 VHes for formaldehyde in LD solutions [6].

LD solutions	VHes
45.7% LiBr solution	$\ln H_{cc} = 7.726 - 5483/t$
30.7% LiCl solution	$\ln H_{cc} = 6.196 - 5065/t$

Table 2 Working parameters for the LD system.

Parameters	Values
Fresh air state	33°C, 26g/kg
Return air state	26°C,10.5g/kg
Formaldehyde concentration in return air	1mg/m^3
Formaldehyde concentration in fresh air	0mg/m^3
Required humidity ratio of supplied air	7.7g/kg
LD flow rate	1kg/s
Dehumidifier ($NTU_{mf,\ deh}$, $NTU_{m,\ deh}$)	0.75,3
Regenerator ($NTU_{mf,\ reg}$, $NTU_{m,\ reg}$)	0.75,3
Hot water flow rate	1kg/s
Pre-heater (kA)	3 kW/ºC
Cool water flow rate	1kg/s
Pre-cooler (kA)	3 kW/ºC

3.1.1 Effect of the number of mass transfer units of formaldehyde

Fig. 2 shows the relationship between the NTU_{mf} and $\varepsilon_{\text{Formaldehyde}}$ under the same temperature and the same vapor pressure. In order to reach the same temperature and the same pressure, the required salt concentrations of the two solutions are different, resulting in the cool water temperature of the pre-cooler is also different. This is mainly due to their different thermophysical properties and moisture adsorption properties. But the T_{s_1} changes a little as increasing NTU_{mf}. The main reason is that the content of formaldehyde in the air is much lower than that of moisture. Therefore, the absorption heat from formaldehyde is negligible relative to that of moisture.

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As described in Fig. 2, when the NTU_{mf} is less than 3, the $\varepsilon_{\mathrm{Formaldehyde}}$ increases very rapidly as the NTU_{mf} increases. However, when the NTU_{mf} is larger than 3, increasing in the NTU_{mf} has little influence on the $\varepsilon_{\mathrm{Formaldehyde}}$. Although the result is similar to the Ref. [6], their assessment criterions are different between them. The same air dehumidification requirement is considered in Ref. [6], while the same desiccant conditions is considered in this study.

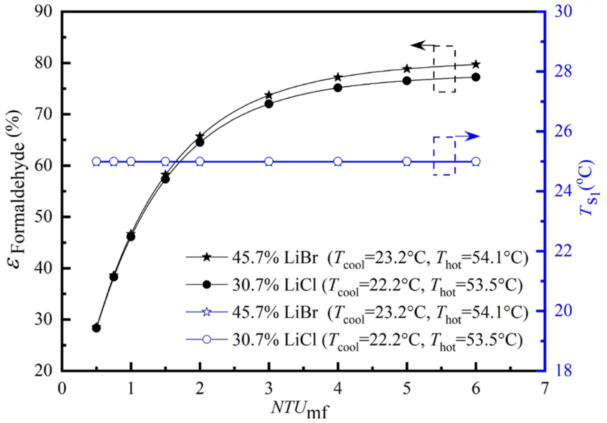

Fig. 2. Effect of NTU_{mf} on $\varepsilon_{\mathrm{Formaldehyde}}$ based on the same temperature and the same vapor pressure.

3.1.2 Effect of the return air temperature

Fig. 3 shows the variations of the $\varepsilon_{\mathrm{Formaldehyde}}$ and T_{s_1} with the return air temperature. It can be seen that with the return air temperature increases, the $\varepsilon_{\mathrm{Formaldehyde}}$ decreases while the T_{s_1} increases. This can be attributed to the below: The water vapor partial pressure difference between the solution and the air increases with increasing return air temperature. The larger the water vapor partial pressure difference, the larger the dehumidification capacity of the LD system resulting the higher the temperature of the diluted solution. Since the power of pre-cooler and pre-heater in the LD system is constant, the higher the temperature of the diluted solution, the higher the solution inlet temperature of module D (t_{s_1}) and module R (t_{s_4}). However, the higher inlet solution temperature is detrimental to the $\varepsilon_{\mathrm{Formaldehyde}}$. As a result, the $\varepsilon_{\mathrm{Formaldehyde}}$ decreases while the T_{s_1} increases.

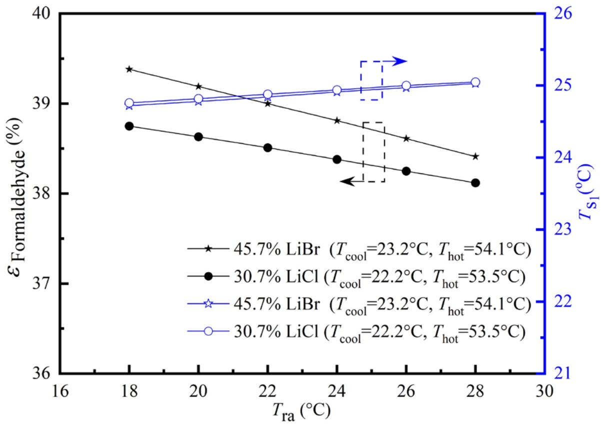

Fig. 3. Effect of return air temperature on $\varepsilon_{\mathrm{Formaldehyde}}$ based on the same temperature and the same vapor pressure.

3.1.3 Effect of the return air humidity ratio

Fig. 4 shows the variations of the $\varepsilon_{\mathrm{Formaldehyde}}$ and T_{s_1} with the return air humidity ratio. It can be seen, both the $\varepsilon_{\mathrm{Formaldehyde}}$ and T_{s_1} increase when the humidity ratio of the return air increases. The changeing trend can be interpreted by the following: When the humidity of the return air increases, the dehumidification performance of the LD system is improved. This means that the moisture exchange and heat exchange during the dehumidification process are further improved, which result in an increase of the temperature of the diluted solution. As explained in section 3.1.2, the higher the temperature of the diluted solution, the lower the $\varepsilon_{\mathrm{Formaldehyde}}$.

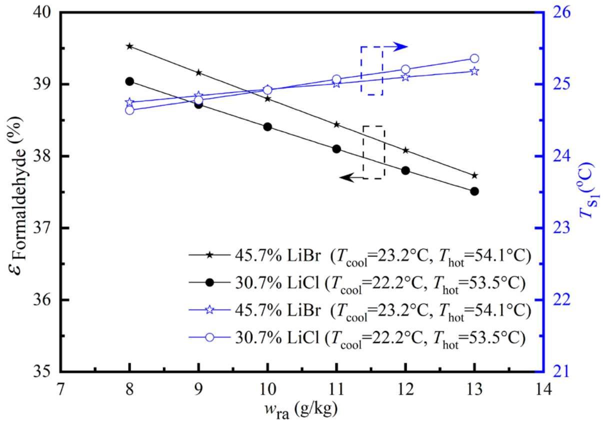

Fig. 4. Effect of return air humidity ratio on $\varepsilon_{\mathrm{Formaldehyde}}$ based on the same temperature and the same vapor pressure.

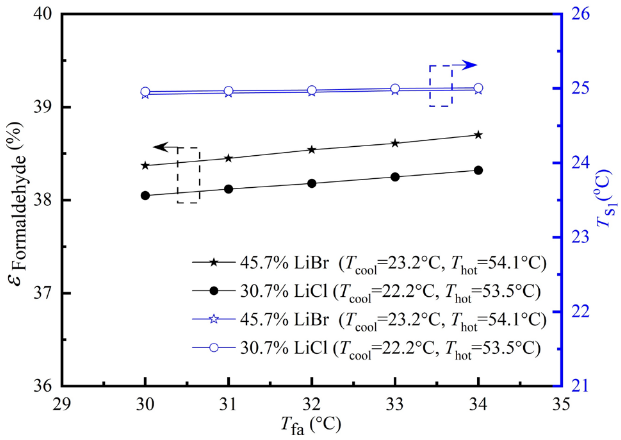

Fig. 5. Effect of fresh air temperature on $\varepsilon_{\mathrm{Formaldehyde}}$ based on the same temperature and the same vapor pressure.

3.1.4 Effect of the fresh air temperature

Fig. 5 shows the variations of the $\varepsilon_{\mathrm{Formaldehyde}}$ and T_{s_1} with the fresh air temperature. With the fresh air temperature increases, the $\varepsilon_{\mathrm{Formaldehyde}}$ increases while the T_{s_1} remains basically unchanged. When the fresh air temperature increases, the regeneration capacity of the LD system becomes weaker. Then it results in the concentration of the regenerated solution decreases. The reason has been explained in Ref. [6] that the lower the solution concentration, the better the $\varepsilon_{\mathrm{Formaldehyde}}$. In addition, as shown in Fig. 5, the formaldehyde removal performance for the two solutions is: 45.7% LiBr > 30.7% LiCl. This result seems to contradict the conclusion mentioned in Ref. [6] that the higher salt concentration is detrimental to the $\varepsilon_{\text{Formaldehyde}}$. It is worth noting that the prerequisite of this conclusion is for the same solution. For different solutions, the $\varepsilon_{\text{Formaldehyde}}$ of the LD system is determined by a combination of the temperature and the solution properties.

3.1.5 Effect of the fresh air humidity ratio

Fig. 6 shows the variations of the $\varepsilon_{\text{Formaldehyde}}$ and T_{s_1} with the fresh air humidity ratio. It can be seen that with the fresh air humidity ratio increases, both the $\varepsilon_{\text{Formaldehyde}}$ and the T_{s_1} increase. The larger the fresh air humidity ratio, the weaker the regeneration capacity of the LD system. This means that the lower the regenerated solution concentration and the higher the regenerated solution temperature. The lower the solution concentration, the better for $\varepsilon_{\text{Formaldehyde}}$; and the higher the solution temperature, the worse for $\varepsilon_{\text{Formaldehyde}}$. However, the final simulation result is that the $\varepsilon_{\text{Formaldehyde}}$ increases. This indicates that the solution concentration variations has a more important impact on the $\varepsilon_{\text{Formaldehyde}}$ than the solution temperature variations.

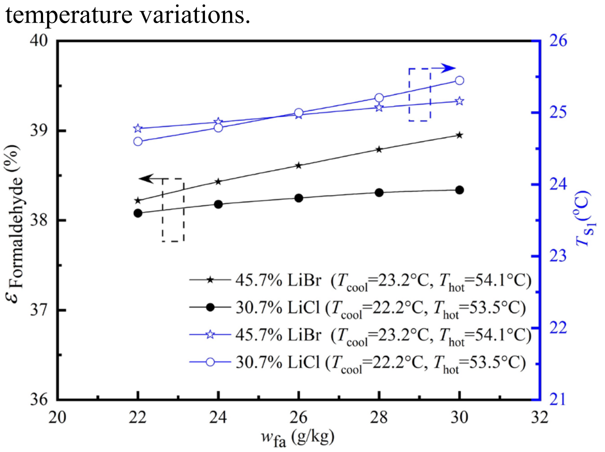

Fig. 6. Effect of fresh air humidity ratio on $\varepsilon_{\text{Formaldehyde}}$ based on the same temperature and the same vapor pressure.

4 Conclusions

In this study, a novel criterion based on the same temperature and the same vapor pressure which the same desiccant condition is proposed. The performances are assessed and considered with the novel criterion, rather than determining formaldehyde removal performance in isolation. The significant conclusions are listed below:

(1) Based on the criterion, the 45.7% LiBr solution shows bettter formaldehyde removal performance than the 30.7% LiCl solution.

(2) With the given simulation parameters, NTU_{mf} plays a important role in the formaldehyde removal performance of the LD system. For different return air conditions, the $\varepsilon_{\text{Formaldehyde}}$ decreases with the return air temperature increases, and it likewise decreases with the increase of return air humidity ratio. However, for different fresh air conditions, the $\varepsilon_{\text{Formaldehyde}}$ increases with the fresh air temperature increases, and it likewise increases with the increase of fresh air humidity ratio.

Acknowledgments

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