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Study on the Performance of Heat and Mass Transfer of Cross Flow Dehumidifier in an Industrial Plant

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Abstract

Liquid desiccant air conditioning (LDAC) system has been more and more widely used in some commercial and industrial buildings which require a relative lower humidity ratio of supply air. This paper mainly focuses on the investigation of the dehumidification performance of a cross-flow dehumidifier for an industrial plant. The theoretical model of the cross-flow dehumidifier is established based on the energy and mass conservation. The numerical solutions are obtained according to the finite difference method within the MATLAB environment. The influences of the different operation parameters and the dehumidifier geometric size on the dehumidification performance are analyzed and discussed for various operation conditions. The results show that the solution mass concentration has the most critical effect on the dehumidification performance, follows by the solution mass flow rate and air mass flow rate. The air temperature has little influence on the performance.

Keywords: Cross flow dehumidifier, heat and mass transfer, theoretical model, Dehumidification efficiency

1. Introduction

In the process of some industrial production, the humidity ratio of the indoor air is required to be quite lower compared with the commercial buildings. In this case, the traditional vapor compression dihumidification (VCD) system may consume a significant amount of electricity in order to cool the air below the dew point temperature.

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Nomenclature

L	the length of the dehumidifier (m)	h	enthalpy (kJ/kg)
H	the height of the dehumidifier (m)	W	the width of the dehumidifier (m)
c_s	mass concentration of solution (%)	ε_m	dehumidification efficiency
A_v	the specific volume of packing (m^3)	c_p	specific heat capacity (J/(kg·K))
k	coefficient of heat transfer (W/(m^2·°C))		
k_m	coefficient of mass transfer (kg/(m^2·s))		Subscripts
t	temperature (°C)	a	air
r	latent heat of vaporization (J/kg)	s	solution
w	humidity ratio(g/kg)	in	inlet
m	mass flow rate (kg/s)	out	outlet
P_L	vapor pressure of solution surface (kpa)	w	water

Recently the liquid desiccant air conditioning (LDAC) system has become more prominent due to its advantages in handling the latent load of buildings with a high-efficient and environmentally friendly way. During the last two decades, liquid desiccant dehumidification (LDD) systems have attracted considerable attention(Liu et al. 2004, Yin et al. 2007) because of their great energy saving potentials[1,2]. A LDAC system includes some major components, such as a dehumidifier, a regenerator, solution heating and cooling equipment and a solution heat exchanger, among which the dehumififier is critical for determining to a large extent the energy efficiency of the whole system. Hence many researches focused on the dehumidification performance of the dehumidifier. The performance of dehumififier is strongly dependent on the type of desiccant solution used, and thus several studies have been conducted on the thermodynamic properties and economics of different desiccant solutions [3, 4, 5]. Bansal et al. [6] compared the experimental performances of an adiabatic and an internally-cooled packed-bed dehumidifiers. It was found that the effectiveness of the internally-cooled packed bed is 28 – 45% higher than the effectiveness of the adiabatic packed bed, depending on the operating conditions. Liu and Jiang [7] theoretically studied the influence of the configuration of air and solution streams on the performance of a dehumidifier. It was found that the counter flow configuration has the highest effectiveness for a process of air dehumidification, compared to parallel-flow and cross-flow configurations.

In order to find the critical operating parameters and analyze their influences on the dehumidification performance of the dehumidifier, this study establishes a mathematical model of an adiabatic type cross-flow dehumidifier based on the energy conservation and mass conservation.

2. Project Description

In this paper, the performance of dehumidifier is simulated based on actual engineering. The factory which has two workshops is located in Shanghe County of Ji'nan, China. The two workshops require constant temperature at 20 + 1 ℃ and humidity in the range of 45-50%. It is estimated that the humidity ratio of the supply air should be handled down to 5.34 g/kg with an extremely low dew point of 5 ℃. This is impossible to implement by the conventional condensation dehumidification. Therefore, the independent temperature and humidity control system is employed in this project. The ground source heat pump system provides heating and cooling for the workshops, while the air dehumidification is realized by a solar liquid desiccant system. The flow chart of the dehumidification system is shown in Fig 1. The objective of this study is to analyze the heat and mass transfer of the dehumidification and to improve the efficiency of the dehumidification system.

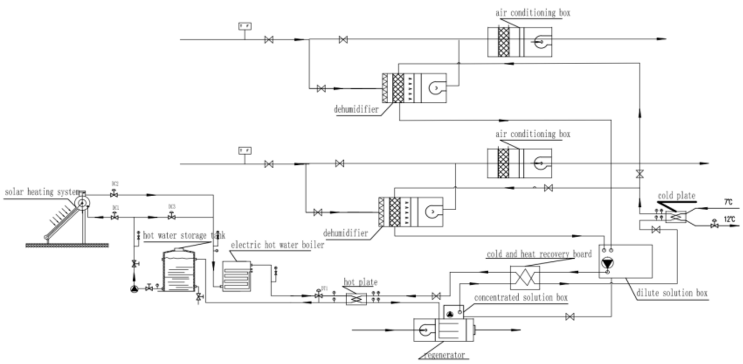


Fig.1. Schematic diagram of the Dehumidification system flow chart

3. Mathematical Models of Dehumidifier

The dehumidifier is the core unit of a LDAC system, which can determine to a large extent the dehumidification performance of the system. However, it is known that the heat and mass transfer process of the dehumidification is quite complex. Therefore, the following assumptions are made in order to solve the mathematical model:

(1)The heat and mass transfer process is assumed to be a steady state, i.e. the variables keep constant during the operation;

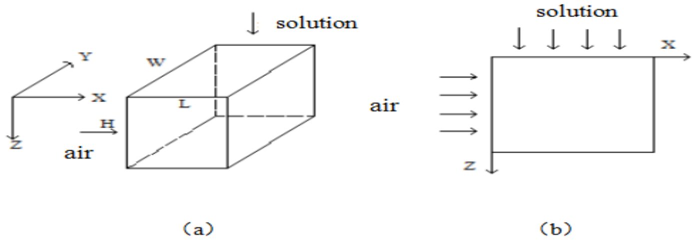
(2) The thermal properties of the air remain constant during the process;

(3)An adiabatic boundary condition is applied to the surroundings of the dehumidifier;

(4)The solution is sprayed down evenly from the top of the dehumidifier making a uniform interface between the air and the solution for heat and mass transfer;

(5)The heat and mass transfer along the width direction is neglected.

According to the aforementioned assumptions, the physical model of the cross-flow dehumidifier has been established, as shown in Fig.2. The solution flows from top to bottom along *Z* axis and the air flows from left to right along the *X* axis. The heat and mass transfer is assumed to be a 2-D model, i.e. the transfer along the width direction is neglected, as shown in Fig. 2(b).



（a） the cross-flow dehumidifier （b）x-z profile

Fig.2. Simplified schematic of the cross-flow dehumidifier

Based on the theorem of the mass and energy conservation, the mass and energy governing equations for the heat and mass transfer process can be easily derived:

$$\frac{m_a \partial w_a}{H\partial x} + \frac{\partial m_s}{L\partial z} = 0 \quad (1)$$

$$\frac{\partial (m_a h_a)}{H\partial x} + \frac{\partial (m_s h_s)}{L\partial z} = 0 \quad (2)$$

The sensible heat transfer between the air and solution can be introduced as follows:

$$\frac{m_a}{WH} dzWc_{p,g} \frac{\partial t_a}{\partial x} dx = k(t_s - t_a)A_v dxdzW \quad (3)$$

The mass transfer between the air and solution can be expressed as follows:

$$\frac{m_a}{WH} dzW \frac{\partial w_a}{\partial x} dx = k_m(w_e - w_a)A_v dxdzW \quad (4)$$

The total heat transfer between the air and the solution equals to the total heat loss of the air, i.e.:

$$\frac{m_a}{WH} dzW \frac{\partial h_a}{\partial x} dx = k(t_s - t_a)A_v W + rk_m(w_e - w_a)A_v W \quad (5)$$

The *NTU* and *Le* can be calculated according to the following formula:

$$NTU = \frac{k_m A_v V}{m_a} \quad (6)$$

$$Le = \frac{k}{k_m c_{p,m}} \quad (7)$$

Based on the equations, it is convenient to derive a simplified expression for the total heat transfer process:

$$\frac{\partial h_a}{\partial x} = \frac{NTU \cdot Le}{L}\left[(h_e - h_a) + r(\frac{1}{Le} - 1)(w_e - w_a)\right] \quad (8)$$

When *Le*=1, equation (3.8) can be further simplified as:

$$\frac{\partial h_a}{\partial x} = \frac{NTU \cdot Le}{L}(h_e - h_a) \quad (9)$$

Similarly, the mass transfer equation between the air and the solution can be described as the following expression:

$$\frac{\partial w_a}{\partial x} = \frac{NTU \cdot Le}{L}(w_e - w_a) \quad (10)$$

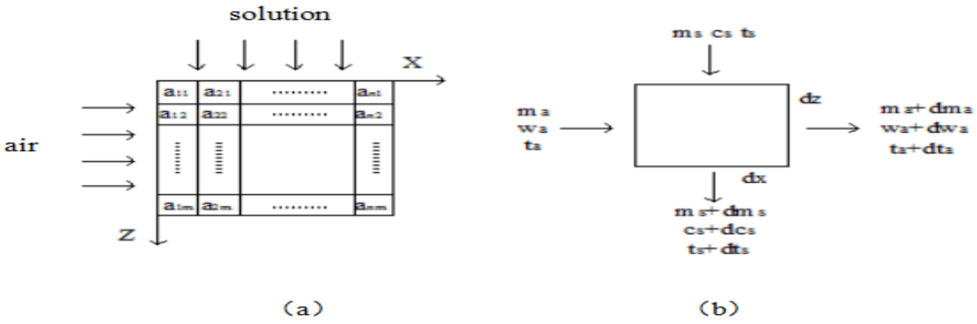
The mass governing equation of the solute can be described as follows:

$$\frac{\partial (m_s c_s)}{\partial z} = 0 \quad (11)$$

The inlet variables are assumed to be given:

$T_s= T_{s,in}$, $c_s=c_{s,in}$, $m_s=m_{s,in}$ when x=0; $T_a= T_{a,in}$, $w_a=w_{a,in}$, $m_a=m_{a,in}$ when z=0.

4. Numerical Simulation model



（a） Mesh generation of x-z profile （b）one control unit

Fig.3. discrete grid diagram of the cross-flow dehumidifier

The finite difference model [8] between the air and solution that has been proposed in a previous study that will be used for theoretical analysis in this paper. In order to make calculation convenient, take *Le*=1 and simplify the discrete equations. The mathematical model can be solved by using the Matlab and the outlet variables can be easily obtained. Then the dehumidification capacity and the dehumidification efficiency can be calculated according to the following equations:

$$m_w = m_a(w_{a,in} - w_{a,out}) \quad (12)$$

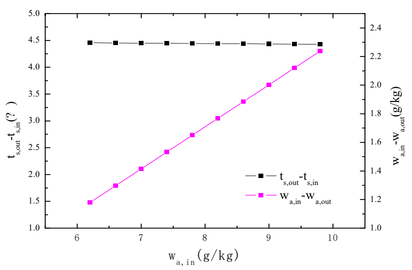
$$\varepsilon_m = \frac{w_{a,in} - w_{a,out}}{w_{a,in} - w_{e,in}} \quad (13)$$

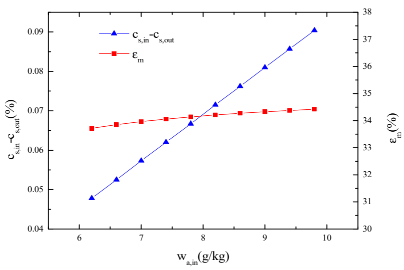
In this study, the operating range of the variables of the dehumidifier are given as shown in Table1.

Table1. The range of variables of dehumidifier

parameter	w_a	m_a	t_a	m_s	c_s	t_s
unit	（g·kg-1）	（kg·s-1）	（℃）	（kg·s-1）	（%）	（℃）
value range	6.2-9.8	0.6-3	16-32	0.8-3.5	30-38	11-27

5. RESULTS AND DISCUSSION





5.1 Influence of air humidity ratio

Fig.4. Influence of $w_{a,in}$ on $t_{s,out}$-$t_{s,in}$ and $w_{a,in}$-$w_{a,out}$

Fig.5. Influence of $w_{a,in}$ on $c_{s,in}$-$cs_{,out}$ and ε

Fig.4 and Fig.5 show the influence of air humidity ratio on the performance of the dehumidifier. It can be seen from the Figures that the humidity ratio difference between the import and export of dehumidifier ($w_{a,in}$-$w_{a,out}$) is remarkably increased with the increase of the $w_{a,in}$.; while changing $w_{a,in}$ has little effect on the heat transfer of the system. Increasing $w_{a,in}$ which means an increased vapor pressure of the air will result in an increased mass transfer driving force, which is beneficial to the dehumidification. Therefore, the dehumidification efficiency (ε_m) shows a slowly increasing trend the amount of dehumidification increases.

5.2 Influence of air mass flow rate

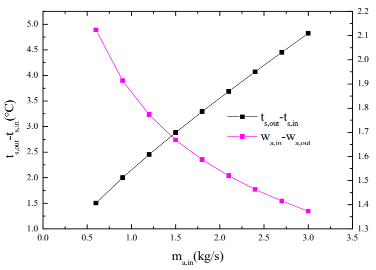


Fig.6. Influence of $m_{a,in}$ on $t_{s,out}$-$t_{s,in}$ and $w_{a,in}$-$w_{a,out}$

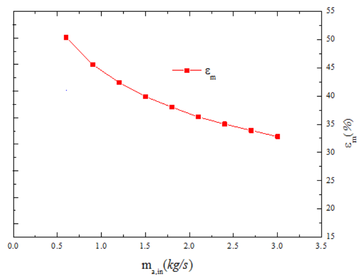


Fig.7. Influence of $m_{a,in}$ on and ε_m

As shown in Fig.6, in general, increasing the air mass flow rate can increase the total moisture content dehumidification while reducing the moisture content of dehumidification per unit mass of air. Hence, $t_{s,out}$ realtively increases. It is noticed that the efficiency of heat and mass process becomes lower with the increase of air mass flow rate as the contact surface and time between the air and the solution is is smaller, as shown in Fig. 7.

5.3 Influence of air temperature

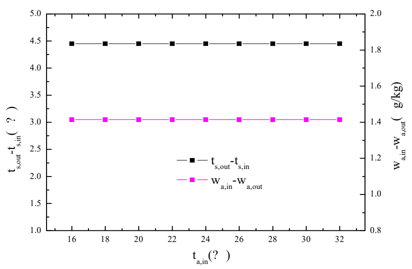


Fig.8. Influence of $t_{a,in}$ on $t_{s,out}$-$t_{s,in}$ and $w_{a,in}$-$w_{a,out}$

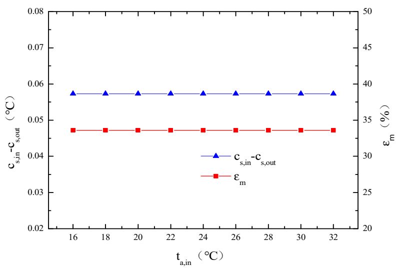


Fig.9 Influence of $t_{a,in}$ on $c_{s,in}$-$c_{s,out}$ and ε_m

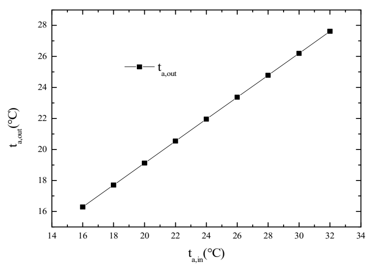


Fig.10. Influence of $t_{a,in}$ on $t_{a,out}$

Figures 8 and 9 show the air temperature plays a nonsignificant role in the process of heat and mass exchange between air and solution in terms of the influences on the outlet moisture content, the oulet temperature and concentration of the solution, and the mass transfer efficiency becuase of the the critical variable of air vapor pressure keeps constant during the operation range. Fig.10 shows the $t_{a,out}$ is linear with the $t_{a,in}$, and the fitting formula is $t_{a,out}=0.7079t_{a.in}+4.9617$.

5.4 Influence of solution mass flow rate

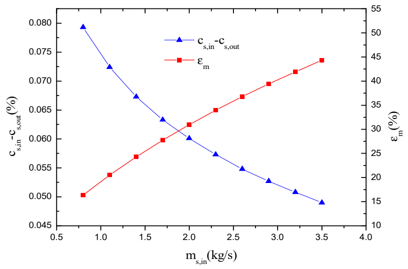


Fig.11. Influence of $m_{s,in}$ on $c_{s,in}$-$c_{s,out}$ and ε_m

As can be seen from Figure 11 increasing the solution mass flow rate can significantly increase the efficiency of the dehumification. The fitting formula is $\varepsilon_m=-1.191m_{s,in}^2+15.36m_{s,in}+4.979$.

5.5 Influence of solution mass concentration

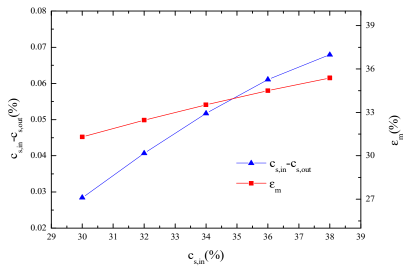


Fig.12 Influence of $c_{s,in}$ on $c_{s,in}$-$c_{s,out}$ and ε_m

Fig.12 shows that with the increase of the $c_{s,in}$, the P_L drops rapidly, So the $w_{a,in}$- $w_{a,out}$ and $c_{s,in}$- $c_{s,out}$ increased. Obviously the dehumification efficiency can increase with the rise of the inlet solution concentration as the mass transfer driving force between the solution and air increases rapidly.

5.6 Influence of solution temperature

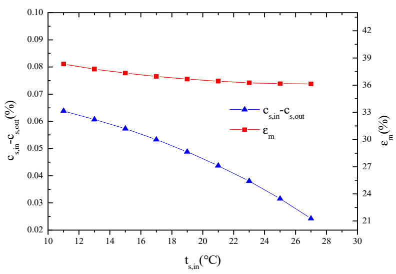


Fig.13 Influence of $t_{s,in}$ on $c_{s,in}$-$c_{s,out}$ and ε_m

As can be seen from Fig.13,ε_m shows a slightly down trend with the increase of $t_{s,in}$ as the driving force of the dehumification reduces. The fitting formula is given as $\varepsilon_m=0.0089t_{s,in}^2-0.5473t_{s,in}+42.436$.

5.7 Influence of the size of dehumidifier

In order to find an optimal configuration fo the dehumifdifier, the effect of the changes of the length(*L*) and height(*H*) of the dehumidifier on dehumidification performance is analyzed and shown in Fig. 14. In this case, the operation variables are given as follows:

$m_{a,in}$=2.7kg/s, $w_{a,in}$=7.26g/kg, $t_{a,in}$=20 ℃, $m_{s,in}$ =2.3kg/s, $c_{s,in}$=35%, $t_{s,in}$=15 ℃;

The initial size of the dehumidifier is given: H_0=1000mm , W_0=1200mm, L_0=800mm.

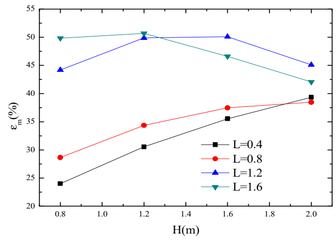


Fig.14 Influence of *H* and *L* on ε_m

Based on the calculation results, the optimal configuration of the dehumidifier is suggested to be *H/L=1.3*.

6. Conclusion

The mathematical model of dehumidifier is established according to the conservation principle of energy and mass. The governing equations are solved by using the finite difference method and the Matlab. The influences of different variables on the dehumidification performance are studied and analyzed. The conclusions are summarized as follows:

(1)As for the solution variables, the increase of $c_{s,in}$ and $m_{s,in}$ is beneficial to the dehumidification process; while the increased $t_{s,in}$ can slightly reduce the dehumidification capacity. As for air side, the increase of $w_{a,in}$ can also improve the dehumification performance desiccant dehumidifier, and the $t_{a,in}$ has little effect on dehumidification capacity. In general, the solution mass concentration has the most critical effect on the dehumidification performance, follows by the solution mass flow and the air mass flow.

(2)When the packing volume is constant, different ratios of the length to the height of the dehumidifier have a great influence on the performance of the dehumidification. In this case study, the optimal ratio is found to be *H/L=1.3*.

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