

PERFORMANCE NUMERICAL ANALYSIS ON AN INTERNALLY-COOLED LIQUID DESICCANT DEHUMIDIFIER

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ABSTRACT:

In the internally-cooled liquid desiccant dehumidifier (ICLDD), cooling medium is introduced to carry away the vaporization latent heat, which enhances effectiveness of heat and mass transfer process between liquid desiccant and air. Numerical method is adopted in this paper to analyze the performance of ICLDD. Theoretical model of heat and mass transfer process is established and verified by available experimental results. The field-distributions and outlet parameters of three fluids (air, solution, water) in the dehumidifier are then emphatically analyzed to evaluate performance of the dehumidifier. The comparison between adiabatic dehumidifier and internally-cooled one is conducted, and it is found that the moisture removal rate in internally-cooled dehumidifier is 20% higher than the adiabatic one at the same operating condition.

KEYWORDS:

Internally-cooled, dehumidifier, heat and mass transfer, simulation

INTRODUCTION

Liquid desiccant air-conditioning system^[1](LDACS), in which liquid desiccant is used as actuating medium contacting directly with air, is an effective method to deal with the buildings latent load and reduce energy consumption in the air handling process. The dehumidifier is the most important component in the LDACS, where humid air contacts with concentrated liquid desiccant and moisture transfers from the air to liquid desiccant. The heat and mass transfer performance of dehumidifier directly influences the whole system efficiency.

The dehumidifier can be divided into adiabatic and

internally-cooled types. In the adiabatic dehumidifier, the latent heat releases during the mass transfer process, leading to the rising of solution temperature, which is the main reason for the depression of desiccant dehumidifying capability^[2]. The ICLDD, where cooling medium (water/air/refrigerant) is inducted into the dehumidifier to take away the latent heat in the course of heat and mass exchange between liquid desiccant and air, is a device to solve the problem effectively^[3]. Many scholars have utilized simulation method to analyze the ICLDD^[4-6] and some scholars have experimentally tested devices and performance^[3]. In the ICLDD, the flow form of the three fluid influences the field distribution of heat and mass transfer, which influences the performance of ICLDD. However, the field distribution of parameters in the dehumidifier wasn't reported in literatures This paper focuses on this aspect and conducts serious of works using simulation method and compares the performances between adiabatic dehumidifier and ICLDD.

THE SIMULATION METHOD

Structure of the LCLDD

Figure 1 describes the internally-cooled liquid desiccant dehumidifier investigated in this work. The dehumidifier is filled with special packing which is divided into two channels: one channel provides for heat and mass transfer between air and solution, in which, solution sprays on the top and flows along the surface of the packing, and processed air, which directly contacts solution, flows across the dehumidifier; Cooling water flows counter with solution in the other channel, only sensible heat exchange between water and solution is realized.

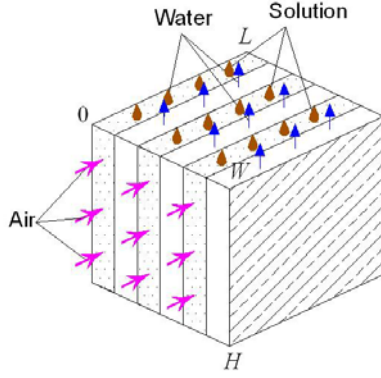


Figure 1 Schematic of ICLDD

Theoretical model

In the heat and mass transfer course of the dehumidifier shown in Figure 1, if three fluids are distributed uniformly, a two-dimension model is obtained, as shown in Figure 2.

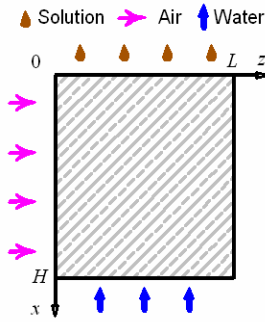


Figure 2 the two-dimension model

In the process of heat and mass transfer in the dehumidifier, the following assumptions are made^[2,4]:

- There is no heat and mass transfer with the environment;
- Heat and mass transfer is steady state;
- Ignore sensible heat exchange between water and air;
- Physical properties of fluids are unchanged; and
- Heat transfer and mass transfer areas are same

Take an infinitesimal volume into account, the energy and mass conservation equations are expressed as:

$$-c_{p,w} \frac{\dot{m}_w}{L} \frac{\partial t_w}{\partial x} + \frac{\dot{m}_a}{H} \frac{\partial h_a}{\partial z} + \frac{1}{L} \frac{\partial (\dot{m}_s h_s)}{\partial x} = 0 \quad (1)$$

$$\frac{\dot{m}_a}{H} \frac{\partial \omega_a}{\partial z} + \frac{1}{L} \frac{\partial \dot{m}_s}{\partial x} = 0 \quad (2)$$

$$d(\dot{m}_s X) = 0 \quad (3)$$

Where, H is height of dehumidifier, L is length of dehumidifier, x is solution flow direction, z is air flow direction, X is concentration of solution, \dot{m}_w is water mass flow rate, \dot{m}_a is air mass flow rate, \dot{m}_s is solution mass flow rate, h_a is air enthalpy, h_s is solution enthalpy, ω_a is humidity ratio of air, $c_{p,w}$ is specific heat of water.

The sensible heat transfer between cooling water and solution can be expressed as:

$$c_{p,w} \dot{m}_w \frac{\partial t_w}{\partial x} = \frac{\alpha_w A}{H} (t_s - t_w) \quad (4)$$

Where, α_w is heat transfer coefficient between water and solution, t_s is solution temperature, t_w is water temperature.

Define the heat transfer unit NTU_w as equation (5), and equation (4) can be diverted to equation (6).

$$NTU_w = \frac{\alpha_w A}{\dot{m}_w c_{p,w}} \quad (5)$$

$$\frac{\partial t_w}{\partial x} = \frac{NTU_w}{H} (t_s - t_w) \quad (6)$$

Consider heat and mass transfer between the air and solution, the fundamental transferring equations can be expressed as:

$$\dot{m}_a \frac{\partial h_a}{\partial z} = \frac{\alpha_a A}{L} (t_s - t_a) + r \dot{m}_a \frac{\partial \omega_a}{\partial z} \quad (7)$$

$$\dot{m}_a \frac{\partial \omega_a}{\partial z} = \frac{\alpha_m A}{L} (\omega_e - \omega_a) \quad (8)$$

Where, α_a and α_m are the heat transfer and mass transfer coefficients between air and solution respectively, r is vaporization latent heat of water at t_s °C.

Substitute equation (8) into equation (7) to gain:

$$\frac{\partial h_a}{\partial z} = \frac{NTU_a}{L} [Le \cdot c_{p,m} (t_s - t_a) + r(\omega_e - \omega_a)] \quad (9)$$

where, the Lewis number Le and mass transfer unit NTU_a are defined as follows:

$$Le = \frac{\alpha}{\alpha_m c_{p,m}} \quad (10)$$

$$NTU_a = \frac{\alpha_m A}{\dot{m}_a} \quad (11)$$

The enthalpy of moist air is expressed as:

$$h_a = c_{p,m} t_a + \omega_a r \quad (12)$$

Combine the above equation and equation (9) to gain:

$$\frac{\partial h_a}{\partial z} = \frac{NTU_a \cdot Le}{L} \times \left[(h_e - h_a) + r_s \left(\frac{1}{Le} - 1 \right) (\omega_e - \omega_a) \right] \quad (13)$$

Substitute the definition of NTU_a into equation (8) to gain:

$$\frac{\partial \omega_a}{\partial z} = \frac{NTU_a}{L} (\omega_e - \omega_a) \quad (14)$$

Equations (1)~(3), (6), (13) and (14) are the control equations of heat and mass transfer in the internally-cooled dehumidifier. The equations can be solved, if inlet parameters of the three fluids, NTU_a and NTU_w are given, which will be introduced in the next content.

The solving method

Divide the module into a number of control volumes firstly, as shown in Figure 3. Then, the infinitesimal equations in section 2.2 can be diverted to discrete form in every control volume.

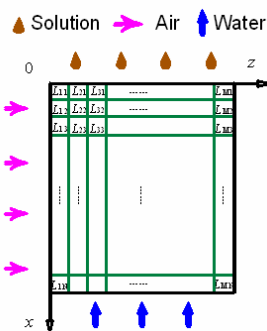


Figure 3 the calculated model

Computation starts from the left top control volume, based on the inlet air and solution parameters and

assumed water exit temperature. Then, the outlet parameters of three fluids of this control volume are obtained, and they are used as inlet parameters of the next control volume in the appointed fluid flow direction, for example, the outlet parameters of water can only be used as inlet parameters of water of the following control volume in the water flow direction. Following this order, the parameters in all control volumes can be calculated step by step. Then, compare the calculated inlet water temperature with the actual entering water temperature, the assumed water temperature is changed and the procedure is repeated until the difference of two temperatures is within 0.1°C. Finally, summed the outlet parameters of the control volumes and acquire the outlet parameters of the dehumidifier, and the assumed water temperature is the water outlet temperature.

VERIFICATION OF MATHEMATICAL MODEL

In order to verify the model established in this study, the experimental data in the literature^[7] are utilized. Table 1 indicates the parameters values in the verification. In addition, the inlet temperature and humidity ratio of air and inlet water temperature is variable in the comparison.

Table 1 Values of parameters in the verification

Parameters	m_a	m_s	m_w	$t_{a,in}$
Unit	kg/s	kg/s	kg/s	°C
Value	1.7	0.16	2.4	29.4~35
Parameters	$w_{,in}$	$t_{s,in}$	X_{in}	$t_{w,in}$
Unit	g/kg	°C	%	°C
Value	15.5~20	30	55	18.3~24

Figure 4~6 shows the comparing result of $t_{a,out}$, $w_{a,out}$ and $t_{w,out}$ between the experimental data in the literature and calculated values respectively, and it can be found that the model predictions and experimental data compare reasonable well, for all of the data differences are within ±10%.

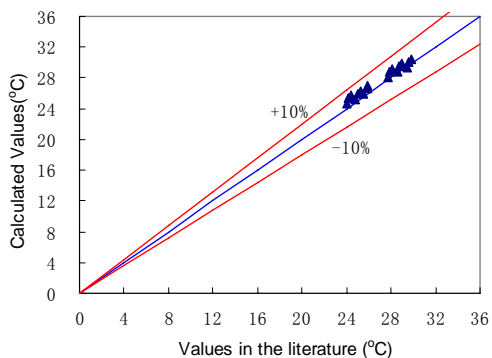


Figure 4 Outlet air temperature

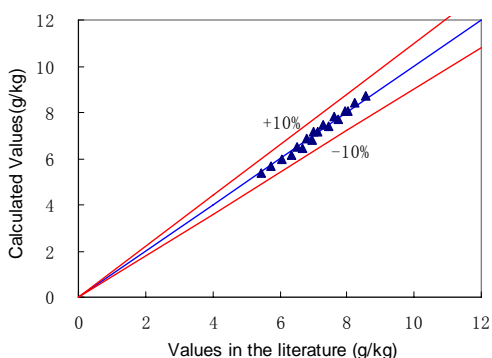


Figure 5 Outlet air humidity ratio

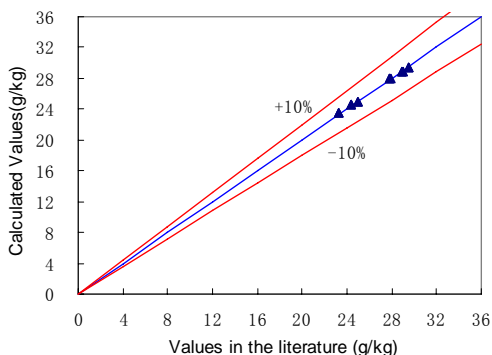


Figure 6 Outlet water temperature

PERFORMANCE ANALYSIS OF THE ICLDD

Analysis of outlet parameters

The outlet parameters of air, solution and water are analyzed in this section, to analyze the performance of this dehumidifier directly. Table 2 shows the inlet parameters of air, solution and water in the model. The outlet parameters are summarized in Table 3.

Table 2 Values of inlet parameters

Parameters	$t_{a,in}$	$w_{a,in}$	$t_{s,in}$	X_{in}	$t_{w,in}$
Unit	°C	g/kg	°C	%	°C
Value	35	20	30	50	20
Parameters	m_a	m_s	m_w	NTU_a	MTU_w
Unit	kg/s	kg/s	kg/s	—	—
Value	1.7	0.16	2.4	1.5	8

Table 3 Values of outlet parameters

Parameters	$t_{a,out}$	$w_{a,out}$	$t_{s,out}$	X_{out}	$t_{w,out}$
Unit	°C	g/kg	°C	%	°C
Value	27.7	9.8	23.3	45.1	25.9

The mass flow rate of solution is about 1/10 of that of air, while mass flow rate of water is a little larger than that of air. The air is cooled from 35°C to 27.7°C, and is dehumidified from 20g/kg to 9.8g/kg, which indicates that the dehumidifier works well under the given conditions.

Analysis of field-distributions of parameters

The field-distributions are important parameters to evaluate the performance of dehumidifier^[2], and the performance of the dehumidifier and its influencing factors can be found visually through the field-distributions of parameters. The following describes the field-distributions of many parameters in ICLDD, which are shown in Figure 7~12.

Figure 7 and Figure 8 describe air temperature and air humidity ratio field-distributions respectively. It can be found in the two figures that the air temperature and humidity ratio decrease along with the air flow direction because air is cooled and dehumidified gradually. Figure 9 and Figure 10 illustrate the temperature distributions of solution and water temperature respectively. Because water cools the solution during the process of heat and mass transfer between air and solution, the temperature of solution and water increase along the water flow direction. Figure 11 describes humidity ratio difference distributions between solution and air. As the humidity ratio is the mass transfer driving force^[2], it distributes uniformly in the solution direction, however, the mass transfer driving force increases

gradually along with the air flow direction.

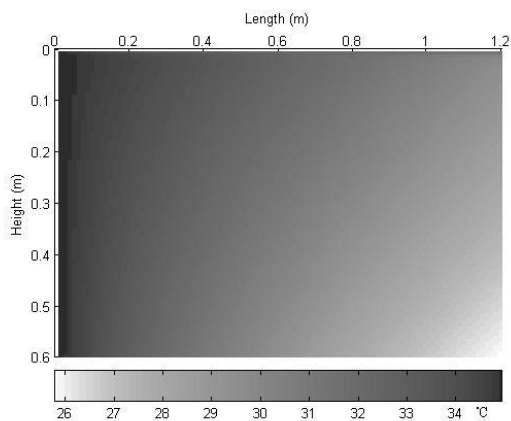


Figure 7 Air temperature distribution

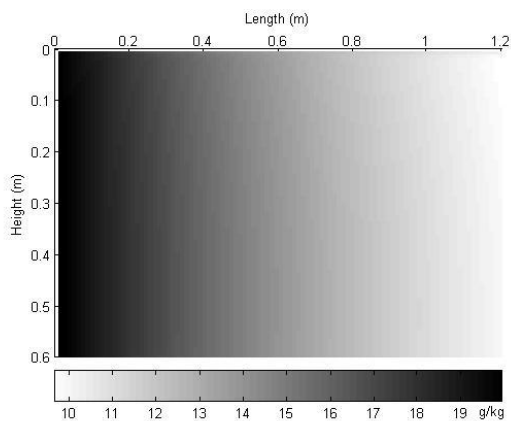


Figure 8 Air humidity ratio distribution

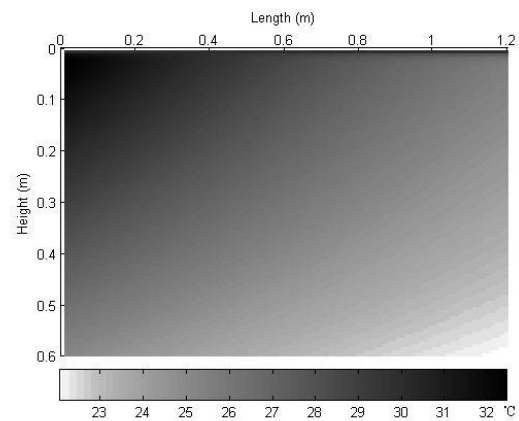


Figure 9 Solution temperature distribution

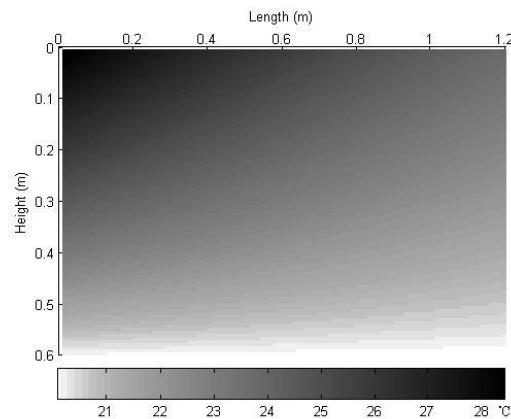


Figure 10 Water temperature distribution

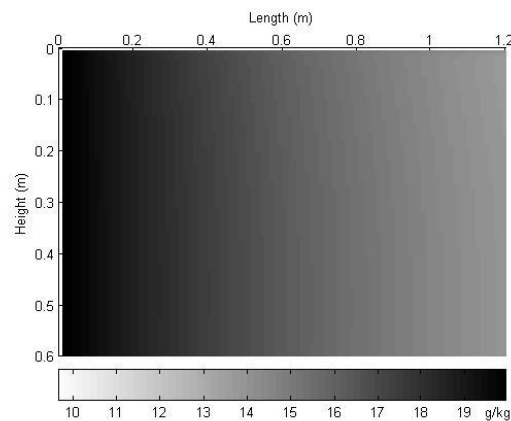


Figure 11 Humidity ratio difference distribution

Analysis of flow form

As shown in Figure 11, the distribution of mass transfer driving force isn't uniform, if the flow directions of the three fluids are changed into the form shown in Figure 12, the mass transfer field will be fairly improved, as shown in Figure 13, and the outlet parameters of air become (27.3°C 9.7g/kg), a little better mass transfer performance than the flow form shown in Figure 2.

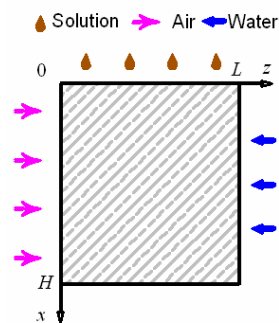


Figure 12 the improved flow form

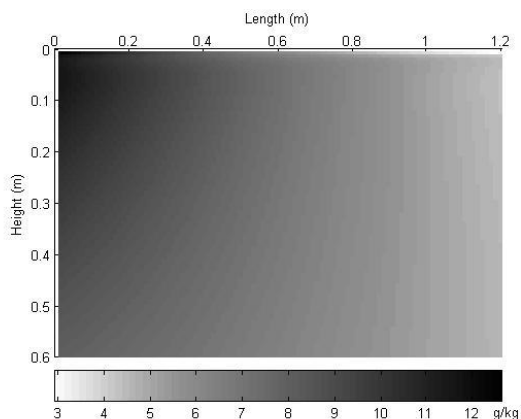


Figure 13 Humidity ratio difference distribution

It is found that changing flow form can improve the performance of dehumidifier. However, mass transfer driving force field-distribution of the improved flow form is still not very uniform, and the performance improved is limited. Therefore, there is still a lot of work to do on the analysis of flow form.

COMPARISON BETWEEN INTERNALLY-COOLED AND ADIABATIC DEHUMIDIFIERS

The performances of adiabatic dehumidifier and internally-cooled dehumidifier are analyzed and compared in this section. In the adiabatic dehumidifier^[1], as shown in Figure 14, solution is cooled by outside cooling source before contacting processed air in the adiabatic packing.

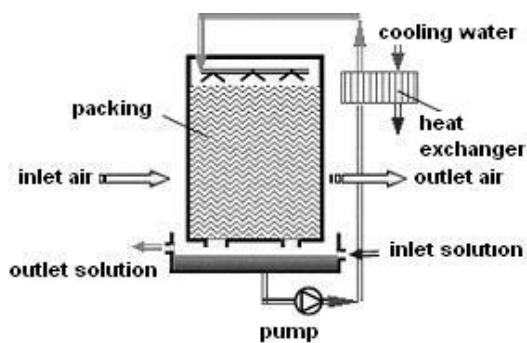


Figure 14 the adiabatic dehumidifier

During the comparison, the input parameters of two dehumidifiers must be the same. Both of the setting inlet parameters of air are 35 °C, 15~21g/kg, and air mass flow rate are both 1.6 kg/s. The inlet temperature and mass flow rate of water are all the

same, they are 20°C and 1.6 kg/s respectively. The inlet parameters of solution are (30°C,50%), however, in the adiabatic device, there are two mass flow rates, the mass flow rate of inlet solution (0.16 kg/s) is same with the internally-cooled dehumidifier, and the cycling mass flow rate of solution is ten times of that than the inlet mass flow rate^[1]. The NTU_a of heat and mass transfer between air and solution are both 1.5, while the NTU_m of heat transfer between water and solution is 8 in ICLDD.

In the comparison, the inlet air humidity ratio is changed, and the value of outlet air humidity ratio is the criterion to evaluate the two dehumidifiers' performance. From Figure 15, it can be found that the outlet air humidity ratio of internally-cooled dehumidifier is much lower than that of adiabatic one and the moisture removal rate in internally-cooled dehumidifier is 20% higher than that of the adiabatic one, which indicates that the performance of dehumidification of internally-cooled unit is better than adiabatic unit.

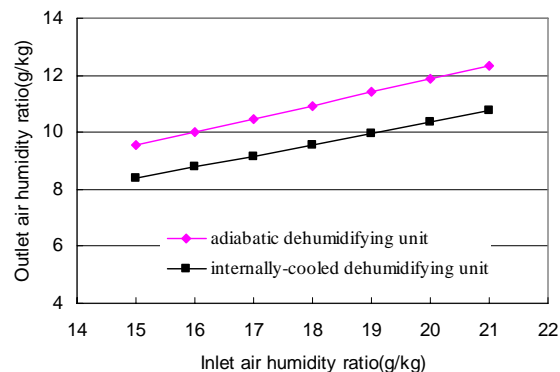


Figure 15 the comparing result

CONCLUSION

A theoretical model is provided in this study, and the heat and mass transfer performance of ICLDD is analyzed. Following conclusions are made:

- The theoretical model can be utilized to predict the performance of the dehumidifier, which is verified by experimental data in the literature.
- The studied internally-cooled liquid desiccant dehumidifier have the capability to process air to

required state, but the field-distributions are not uniform, which can be improved by changing flow form.

- The moisture removal rate in internally-cooled dehumidifier is 20% higher than that of the adiabatic one at the same operating condition.

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