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Dynamic Analysis of an Energy Efficiency Dehumidifier for Building Applications

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Abstract—This paper presents a dynamic analysis of an energy efficiency dehumidifier for building applications. This new structured dehumidifier is working with a controllable desiccant concentration, and the dynamic behavior of the heat and mass transfer process inside the dehumidifier becomes rather critical. A model is developed to describe the dynamic behavior of the process air with experimental validation. The numerical results of the dynamic response are clarified to conclude that decreasing the solution inlet temperature has a more significant impact on improving the dehumidification ability than increasing solution mass flow rate. The outcomes provide a comprehensive understanding of the dynamic behavior and the results will benefit the humidity control of the indoor air to improve the living quality of the occupants.

Keywords— LDDS, Dehumidifier, Dynamic modeling, Hybrid model, Performance analysis

I. INTRODUCTION

Recent years, energy efficiency and humidity comfort become two attractive topics in the air-conditioning field. A great amount of efforts has been attracted in providing a good indoor environment quality while reduces the energy consumption. Liquid Desiccant Dehumidification Systems (LDDS) achieve a low humidity level with relatively low energy consumption, employs desiccant solution as working fluids to improve supply air quality, and also has the potential to apply low grade energy, such as solar energy and geothermal energy.[1-3] These merits make LDDS more attractive in developing a green indoor living environment with a satisfied comfortable level.

To improve the energy efficiency, a strong solution buffer is installed with the conventional dehumidifier to remove the constant change of strong and weak solutions between regenerator and dehumidifier. [4] This strong solution buffer supplies strong solution to the dehumidifier to maintain the working concentration and a regulating valve is used to regulate the working concentration in the dehumidifier and consequently the treated air with required humidity ratio. Meanwhile, this new structure separates the 1vs.1 dehumidifier and regenerator pairs, allows a centralized regenerator to provide concentrated solution to multiple dehumidifier in different locations, which is more appropriate in building applications, i.e. to use the heat source intensively and provide

the treated air to distributed places. However, this improvement in structure introduces a mixing process to determine the working concentration, and this process has a significant effect on the heat and mass transfer process between the two working fluids. [5, 6] Thus, a dynamic model of the heat and mass transfer process must be developed to provide an good prediction of the humidity ratio of the out air, which is an important parameter related to living human quality.

So far, the modelling techniques have been focused on steady state models of heat and mass transfer.[7-9] Gandhidasan [10] proposed a simplified finite difference model for LDDS, by which the water mass transfer rate between air and liquid was predicted. The simplified model was proved to be effective through experimental verification. Luo et al. [11] developed a volume of fraction model, in which the properties such as density and viscosity are determined by percentage of air and liquid. A simplified hybrid model without iteration was developed by Wang et al. [12, 13] for system monitoring and optimization, and validated with a high accuracy. Though not many researchers focus on the dynamic modeling of dehumidifier, some studies have been conducted on a series of similar processes. N. Harun [14] et al. proposed a dynamic model for CO₂ scrubbing tower, and discussed the transient responds of each component inside the system in details under the manipulation of both reboiler heat duty and flue gas flow rate.

This study presents a dynamic analysis of the heat and mass transfer process in this buffer integrated dehumidifier. Starting from the mass and energy conservation principles, the dynamic performance analysis is carried out to learn the dynamic behavior of this proposed model. The mass balance of water content in the process air and energy balance between these two phases are described by partial differential equations. The proposed model is implemented in Matlab and validated by experimental data. The temperature and humidity condition of process air is studied by two cases: increasing inlet cooling amount with a fixed mass flow rate of liquid desiccant solution, increasing mass flow rate under a fixed solution inlet temperature. The results from the dynamic analysis provide a quantitative understanding the behavior of transient system performance and will benefit in the concentration and outlet humidity control of this buffer integrated dehumidifier.

II. MODEL DEVELOPMENT

A. The working principle of a buffer integrated dehumidifier

A schematic diagram of the dehumidifier is shown in Fig. 1, where a strong solution buffer and a regulating valve are integrated to provide a stable working concentration for dehumidifiers. In the dehumidifier, the concentrated desiccant solution is sprayed at the top of the dehumidifier while the process air enters from the bottom of the dehumidifier in a counter-flow configuration in the packing column, dry air then exits the system as supply air.

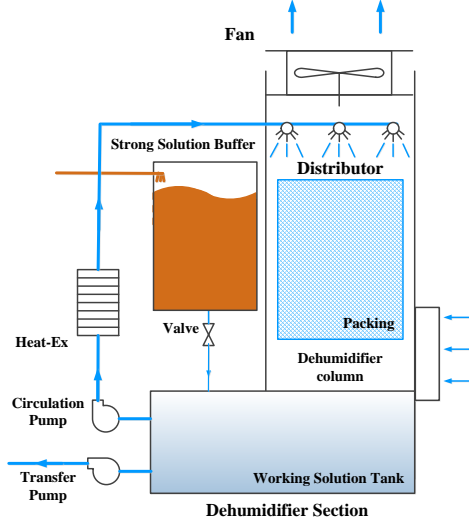


Fig.1 A buffer integrated dehumidifier

B. Model description

The mass conservation equations of water in liquid desiccant solution and process air are explained as Eq.(1). The positive direction of the z-axis is the same as the process air flow direction:[14-16]

$$\frac{\partial X_L}{\partial t} + \frac{\partial(U_L X_L)}{\partial z} - K'_G (p_G - p_L^*) = 0 \quad (1a)$$

$$\frac{\partial X_G}{\partial t} + \frac{\partial(U_G X_G)}{\partial z} + K'_G (p_G - p_L^*) = 0 \quad (1b)$$

where X_L , X_G , U_L , U_G , p_G , p_L^* and K'_G are the water concentration of liquid desiccant solution, moisture content of process air, the velocity of solution in z direction, the velocity of process air in z direction, the water vapor pressure of process air, surface water vapor pressure of liquid desiccant solution and the modified mass transfer coefficient, respectively. The first terms in Eq. (1a) and (1b) represent for concentration temporal variant rate, and the second term describes the convection of the two fluids, and the last terms is the mass transfer rate between two fluids.

The energy balance equations for the solution and process air are: [14-16]

$$\frac{\partial T_L}{\partial t} + \frac{\partial(U_L T_L)}{\partial z} - \alpha_{GL} \cdot \frac{N_{H_2O} \cdot \Delta H}{\rho_L \cdot c_{pL}} - \frac{h \cdot \alpha_{GL}}{\rho_L \cdot c_{pL}} \cdot (T_G - T_L) = 0 \quad (2a)$$

$$\frac{\partial T_G}{\partial t} + \frac{\partial(U_G T_G)}{\partial z} + \frac{h \cdot \alpha_{GL}}{\rho_G \cdot c_{pG}} \cdot (T_G - T_L) = 0 \quad (2b)$$

where T_L , T_G , c_{pL} , c_{pG} and ΔH are the temperature of liquid desiccant solution, temperature of process air, specific heat of liquid desiccant solution, specific heat of process air, and water condensing heat, respectively. The third term in equations (2a) is the heat release by water vapor during condensation. The last terms in equation (2a) and (2b) are the heat transfer rates between the two fluids in the surface due to temperature differences.

To derive a simplified form of this model, the linear assumptions of the spatial information have been made, which implies:

$$X_L = a_{L1}z + a_{L2} \quad (3a)$$

$$X_G = a_{G1}z + a_{G2} \quad (3b)$$

$$T_L = b_{L1}z + b_{L2} \quad (3c)$$

$$T_G = b_{G1}z + b_{G2} \quad (3d)$$

where a_{L1} , a_{L2} , a_{G1} , a_{G2} , b_{L1} , b_{L2} , b_{G1} , b_{G2} are the fitting parameters.

The heat and mass transfer coefficients are obtained from the hybrid models introduced in [12, 13]as:

$$K'_G = \frac{\alpha_{GL} \cdot c_1 (m_L)^{c_3}}{1 + c_2 T_G (m_L)^{c_3} (m_G)^{c_4}} \quad (4a)$$

$$h' = \frac{\alpha_{GL} c_5 m_L^{c_7}}{1 + c_6 (m_L / m_G)^{c_7}} \quad (4b)$$

By submitting Eq. (4) and (3) into Eq. (1) and (2), the final form of the model can be described as:

$$\begin{cases} \dot{X}_{L,out} = -\frac{a_L m_L}{\rho_L S \sin(\theta)} + \frac{\alpha_{GL} c_1 m_L^{c_3} (\dot{p}_{G,in} - \dot{p}_{L,out}^*)}{1 + c_2 \dot{T}_{G,in} (m_L)^{c_3} (m_G)^{c_4}} \\ \dot{X}_{G,out} = -\frac{a_G m_G}{\rho_G S \sin(\theta)} - \frac{\alpha_{GL} c_1 (m_L)^{c_3} (\dot{p}_{G,out} - \dot{p}_{L,in}^*)}{1 + c_2 T_{G,in} (m_L)^{c_3} (m_G)^{c_4}} \\ \dot{T}_{L,out} = -\frac{b_L m_L}{\rho_L S \sin(\theta)} + \frac{\alpha_{GL} \Delta H c_1 (m_L)^{c_3} (\dot{p}_{G,in} - \dot{p}_{L,out}^*)}{\rho_L c_{pL} (1 + c_2 T_{G,in} (m_L)^{c_3} (m_G)^{c_4})} \\ \quad + \frac{\alpha_{GL} c_5 m_L^{c_7} (T_{G,in} - T_{L,out})}{\rho_L c_{pL} (1 + c_6 (m_L / m_G)^{c_7})} \\ \dot{T}_{G,out} = -\frac{b_G m_G (t)}{\rho_G S \sin(\theta)} - \frac{\alpha_{GL} c_5 m_L^{c_7} (T_{G,out} - T_{L,in})}{\rho_G c_{pG} (1 + c_6 (m_L / m_G)^{c_7})} \end{cases} \quad (5)$$

of which $c_1 - c_7$ are the parameters are identified with the experimental data.[17]

III. MODEL VALIDATION

The dynamic model described above is validated by experimental data obtained from the proposed LDDS system as illustrated in Fig. 2. The dehumidifier and the strong solution buffer are installed as Fig.1, with a valve connecting between these two tanks.



Fig. 2 LDDS experimental platform

- 1 – fan; 2 – heat exchanger; 3 – heat pipes; 4 – power cabinet; 5 – data acquisition system; 6 – Solution solution buffer

Lithium chloride (LiCl) is used as the liquid desiccant. The temperature of the desiccant solution is measured by PT-1000, while the temperature and humidity of the air at the are obtained from the measurements of a probe type temperature and humidity ratio transmitter. The volume flow rate of the LiCl solution is evaluated from the measurement magic flow meter, whereas the air flow rate is measured by a blade type flow sensor. The data of the sensors are acquired by the online measurement of a data acquisition system. The concentration of LiCl is obtained by a simplified version of soft-sensors explained in [18].

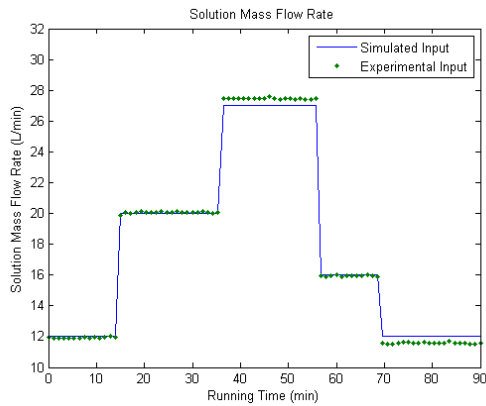


Fig. 3 Inlet solution mass flow rate

To determine the model parameter matrix, 800 groups of experimental data are collected though the step increasing of the inlet solution temperature and solution mass flow rate. The data were collected once per 2 seconds to capture the dynamic property to identify the model parameters. Each group of parameters is estimated by utilizing the method deliberated in the last section. Solution inlet temperature and solution mass

flow rate are manipulated as Fig.3 and Fig.4 to study the dynamic performance of this system during a 90mins experiment. The experiments are carried out in an air-conditioned room with an inlet air of 12 g/kg dry air and 25°C during this experiment, and the validation results are shown as Fig.5 and Fig.6.

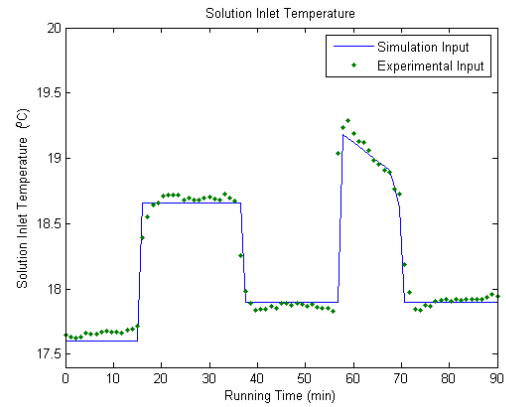


Fig. 4 Solution inlet temperature

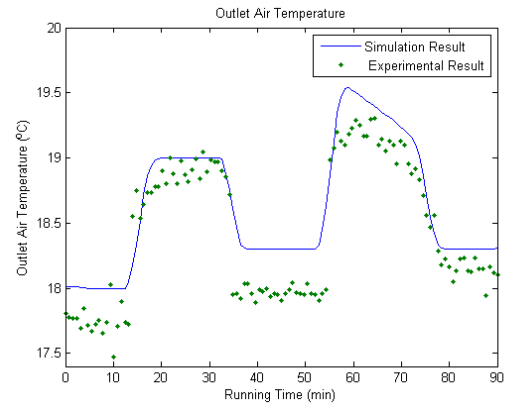


Fig. 5 Outlet Air Temperature Condition

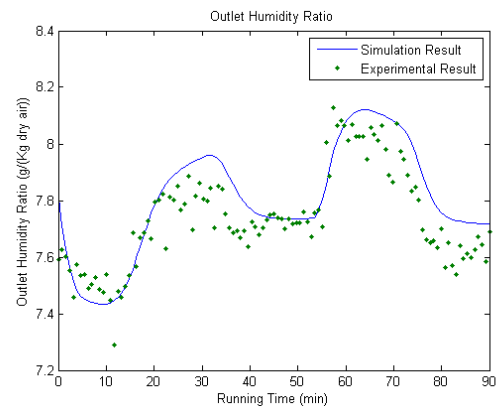


Fig. 6 Outlet Humidity Condition

IV. DYNAMIC ANALYSIS

The dynamic behavior of the heat and mass transfer in dehumidification process is studied by incorporating the variation of the input change of cooling and solution flow rate. Two different cases of simulations are designed to analyze the

dynamic properties of this model. The impact of solution inlet temperature and solution mass flow rate on the outlet process air condition and LiCl solution conditions are discussed in details. The outlet air humidity and temperature condition are covered in these discussions.

The responses of this system on these input modifications are explained in the following parts.

A. Case 1: Increase inlet cooling amount with a fixed mass flow rate of LiCl solution.

The dynamic behavior of this process under different cooling amount supply is discussed in this case. This simulation is performed without regarding the energy lost during the whole process to focus only on the dehumidifier properties. The process air is set as a temperature of linear increase from 28°C to 28.7°C and a constant humidity ratio of 14g/kg dry air, and the initial solution concentration is regulated as 26% while solution mass flow rate is set as 0.7kg/s. Three different initial temperatures of solution are carried out in the simulation, which are 16.2°C, 17.2°C and 18.2°C. A cooling amount of 2.4kw is removed from the original cooling supply at the 10th minute after the simulation starts to run.

Fig.5 and Fig.6 present the simulated and experimented outlet air humidity and temperature of this system under the conditions narrated above. The dehumidification amount decreases 0.6g/kg dry air to respond the step reduction of cooling supply. Prior to the step decrease of cooling amount, the outlet air humidity is about 6.736 g/kg dry air, 7.146 g/kg dry air and 7.581 g/kg dry air and the outlet temperature is about 16.55°C, 17.55°C and 18.55°C under different initial solution temperature (16.2°C, 17.2°C and 18.2°C) at the 4th minute. The outlet humidity values have a more significant variation under a relatively higher temperature range. A slight increase of outlet humidity in the 10 minutes ran due to the concentration lost and the increase of inlet air temperature. The outlet temperature of process air has a more stable value respect to humidity. Three minutes are needed for the outlet humidity and temperature to regain stability.

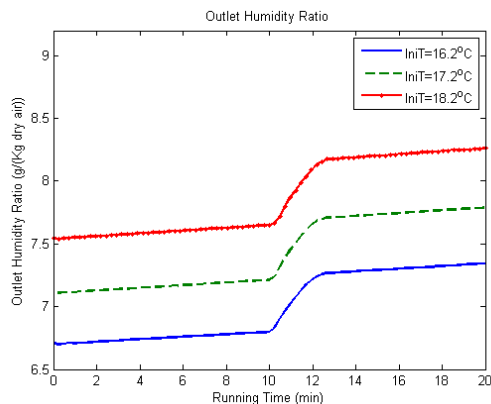


Fig. 7 Case 1: Outlet humidity profile

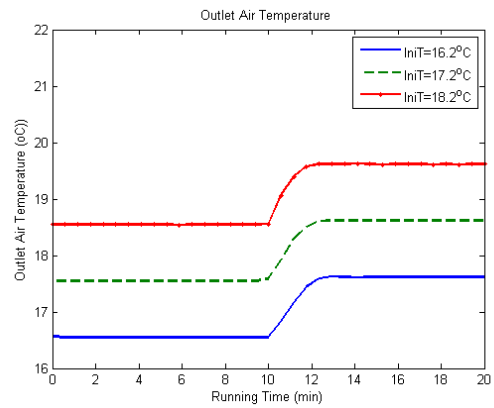


Fig. 8 Case 1: Outlet temperature profile

B. Case 2: Increase the mass flow rate of LiCl solutions with a fixed solution inlet temperature.

This case investigates the dynamic behavior of this process through manipulating LiCl solution flow rate under a fixed solution inlet temperature. The same inlet air condition and solution concentration as Case 1 is preset in this simulation. Three different mass flow rates are simulated while other variables are fixed as the description narrated above. The mass flow rates are set as a constant value of 0.2kg/s, 0.4kg/s, 0.6kg/s, while a step increase of 0.3kg/s is implemented at the 10mins after the simulation starts to run. In case 2, the solution inlet temperature is regulated at 16°C during the whole simulation procedure to analysis the impact of this variable on the system dynamic performance.

The Fig.9 and Fig.10 demonstrate the outlet air humidity and temperature profiles under Case 2. No significant humidity and temperature difference has been observed under this case. The 0.3kg/s step input of mass flow rate results maximal 0.03g/kg dry air decrease of air humidity and 0.05°C decrease of outlet air temperature. From Fig.14, it can be noted that the dehumidification amount is dominated by the effect of solution inlet temperature instead of mass flow rate. At a low mass flow rate, the outlet humidity has a significant transient response and needs shorter time to reach new stability. The outlet humidity has a tendency to increase due to the inlet air temperature and concentration loss of liquid desiccant.

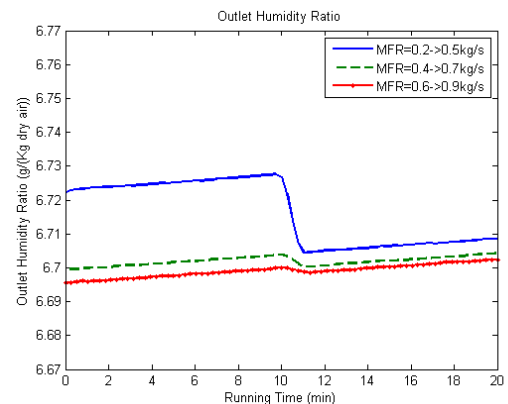


Fig. 9 Case 2: Outlet humidity profile

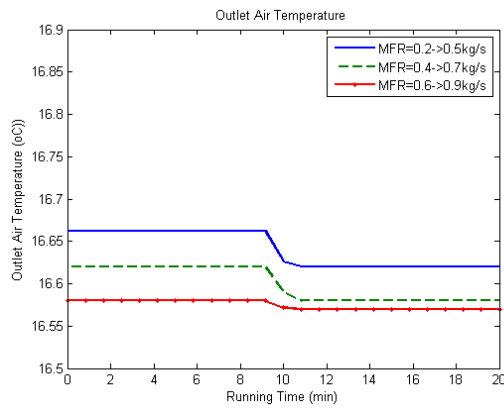


Fig. 10 Case 2: Outlet temperature profile

V. DISCUSSION AND CONCLUSION

From the results obtained from dynamic analysis, the following discussions are performed.

A. Solution Inlet temperature has a stronger impact on outlet air humidity

A step decrease of input cooling amount increases the outlet air humidity and temperature as described in Fig.7 and Fig.8, and the step increment of mass flow rate ultimately causes the inlet temperature to decrease as shown in Fig.9 and Fig.10. From the comparison outlet air humidity between these two cases, the manipulating of mass flow rate does not have any significant effect on the outlet air condition. The maximum mass flow rate modification range produces an insignificant effect on the outlet air condition as in Fig.9 and Fig.10. It can be conducted that solution inlet temperature has a stronger impact on outlet air condition than mass flow rate.

This can be explained from the basic principle of mass transfer. Low solution temperature leads to a decrease on surface water vapor for liquid desiccant, correspondingly increase the water vapor difference between the two fluids, and will increase the dehumidification ability. Enough liquid is needed to form a liquid film on the packing, and the heat and mass transfer happens on this film. If the cooling amount supplied into the packing column is in the form of lower temperature, the temperature of this film will be changed, and then, the mass transfer ability increases. Enough solution amounts are indispensable in forming this film, thus it can be observed from Fig.9 and Fig.10, which under the condition of a low mass flow rate, the system has a more significant response of the outlet humidity and temperature involves the film forming.

B. The outlet air temperature is highly related to the solution inlet temperature

Under the condition of Case 2, the solution inlet temperature is set as a constant value, and the outlet temperature gives out only an insignificant difference about 0.1°C. Under Case 1, the outlet temperature values are all highly related with the solution inlet temperature as shown in Fig.8. The low specific heat of air makes its temperature easily affected by the solution temperature. This indicates the

importance of solution inlet temperature to regulate an appropriated outlet air temperature.

C. Regulation solution inlet temperature produces a stable outlet air condition.

Equal mass flow rate increments do not lead an equal increment on dehumidification amount ascribing to the system nonlinearity as in Fig.9, and thus it is practical to consider this nonlinearity when regulated the outlet humidity or temperature values. The driving force of dehumidifier can be provided by a fixed cooling amount or fixed solution inlet temperature. Under a fixed cooling amount, attribute to the trade-off relationship between solution inlet temperatures and mass flow rate, enlarge solution mass flow rate will not provide confirmed outlet air conditions, as can be observed in Fig.9 and Fig.10. Regulating humidity through mass flow rate will not produce a significant difference under some conditions. By means of regulating the cooling amount under a constant mass flow rate, the system expresses outlet humidity and temperature decrease smoothly as shown in Fig.7 and Fig.8. Regulating the system outlet temperature and humidity by manipulating the cooling amount is a practical choice to give a stable performance.

In conclusion, a dynamic model of dehumidifier in a LDDS system was proposed and validated by experimental data. A Packing column model were built to demonstrate the complicated two phases heat and mass transfer process inside the dehumidifier. The dynamic behavior of this system was studied by manipulating the potential control variables such as in the input cooling amount, solution inlet temperature and solution mass flow rate. The impact of these variables on the outlet air temperature and humidity were analyzed quantitatively through dynamic simulation. The simulation performance further convinces the solution inlet temperature has a stronger impact on the outlet air condition. Regulating the system outlet temperature and humidity by manipulating the input cooling amount is a practical choice to give a stable performance.

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