THEORETICAL ANALYSIS AND SIMULATION OF HYBRID SOLID AND LIQUID DEHUMIDIFIER SYSTEM

Yuan Weixing, Associate Professor, Department of Man-Machine-Environmental Engineering, Beijing University of Aeronautics and Astronautics, Beijing, China

Li Yunxiang PhD Candidate, School of Automation, Northwestern Polytechnical University, Xi'an, China

Wang Chenjie, Master Students, Department of Man-Machine-Environmental Engineering, Beijing University of Aeronautics and Astronautics, Beijing, China

Abstract: A waste heat driven hybrid solid dehumidifier and liquid dehumidifier system is proposed. This new type of dehumidification system can be efficiently driven by low temperature heat source such as solar energy and achieve high dehumidification performance, due to its unique serial dehumidification and regeneration process. The humid process airflow is first dehumidified by liquid dehumidifier and then by solid one, at the same time, regeneration air first regenerates solid dehumidifier and then the liquid one. This is because the liquid dehumidifier is more efficient to dehumidify high RH air with relative low temperature regeneration heat, while the solid dehumidifier can dehumidify lower RH air with higher temperature regeneration heat. Theoretical analysis and performance simulation of the hybrid dehumidifier system is carried out with varied process air conditions and regeneration temperatures. The results show that this new hybrid dehumidifier system is promising for dehumidification performance improvement and high grade energy saving. It can be efficiently driven by waste heat as low as 70℃ with a satisfactory dehumidification performance. The ratio of dehumidification between liquid and solid dehumidifier should vary according to regeneration temperature and process air conditions.

Key Words: waste heat, hybrid, dehumidifier, simulation

1 INTRODUCTION

One of the great practical engineering interests is the removal of water moisture from humid air using heat driven solid or liquid desiccants. There are two types of such corresponding dehumidifier, the solid one and the liquid one. Each type of the dehumidifier has its own merits and weak points. For example, with high temperature regeneration heat source usually above 100℃, which means electricity or natural gas has to be used for regeneration, the solid dehumidifier could have a higher degree of dehumidification, ability to absorb moisture from high temperature streams. For liquid dehumidifier, one the contrary, low temperature heat source below 70℃ can be used for regeneration, but it is hard to obtain low humidity ratio for the process humid air.

The solid desiccant rotary wheel, namely rotary dehumidifier is a competitive drying facility, and can be applied to drying and air conditioning industries. Since the introduction of this technology, much research on the solid desiccant dehumidifiers has been accomplished (Nia 2006).

On one hand, the research work is focused on heat and mass transfer process of the dehumidifier in order to find possible methods to increase the performance of it. Maclaine-Cross and Banks (Maclaine-Cross and Banks 1972) developed an analogy method for predicting the coupled heat and mass transfer process in desiccant dehumidifier wheel. Zheng and Worek （Zheng and Worek 1993） discussed the effect of rotary speed on the performance of the desiccant wheel by numerical simulation using an implicit finite differential method. Dai et al. (Dai and Wang 1993) used a finite difference model to analyze and explain the "concentration" wave, "thermal" wave and middle zone point in the desiccant wheel in detail, and the rules to improve the performance of dehumidification were discussed using psychrometric charts. Zhang and Niu （Zhang and Niu 2002） presented a two-dimensional coupled heat and mass transfer model which takes into account the heat conduction, the surface and gas diffusion in both axial and radial directions and compared the performances of desiccant wheels as dehumidifier and enthalpy recovery. Yuan and Liu (Yuan and Liu 2007) proposed a simplified dimensionless mathematical model for performance simulation and optimization of the desiccant wheel.

On the other hand, researches on the desiccant wheel is also focused on the development of advanced desiccant materials that give improved sorption capacity, better moisture and heat diffusion rates, as well as favorable equilibrium isotherms, of which an ideal Type 1M isotherm shape (Modified Langmuir Type 1) was proposed by Collier et al. (Collier 1986). Improved performance of desiccant systems will lower their initial and operating costs, and make them a more attractive alternative to existing vapor compression systems. At present, commercially available desiccants include silica gel, activated alumina, natural and synthetic zeolites, titanium silicate, calcium chloride, lithium chloride, and synthetic polymers. New composite materials based on silica gel – calcium chloride have become an attractive alternative to the existing silica gel or calcium chloride desiccants. The comprehensive experimental study of the physicochemical properties and some application researches of the composite adsorbent have been reported by Aristov et al. , also by Liu and Wang, and by X.J. Zhang et al. (Zhang 2005).

Liquid dehumidifier may yield not only air dehumidification but may also improve indoor air quality by more efficient humidity control. The performance of liquid desiccant dehumidifiers is dependent on the type of desiccant material, the operating parameters and the absorber internal geometry (type of packing). The absorber is the central part of all liquid desiccant dehumidifiers. Four basic configurations are encountered: a spray chamber, a sprayed coil arrangement, a packed tower and an indirect evaporative cooling (IEC) plate heat exchanger.

Numerous models have been predicted by different researchers to express the heat and mass transfer processes for liquid dehumidifier. Models for heat and mass transfer in counter flow and cross flow dehumidifiers are summarized by Liu and Jiang (Liu and Jiang 2007). The models can be classified as simplified models and complicated models. In simplified models, the assumption of slug flows of air and desiccant, which are separated by the heat and mass transfer surface, is usually adopted. Such models have been adopted for adiabatic counter flow dehumidifiers and for internally cooled counter flow and cross flow dehumidifiers, respectively. In complicated models, the velocity field within the dehumidifier is first gained by solving the combined continuity and momentum equations, and then, the temperature and concentration fields are obtained by solving the energy and mass balance equations. Complicated models consume much time and require large computational memory.

From researches on solid and liquid dehumidifiers described above, there are two ways to improve the performance of dehumidifiers: the first is to better understand the detailed heat and mass transfer process within the dehumidifier concerning working conditions and structure parameters; the second is to find and develop advanced solid and liquid desiccant materials.

In this paper, we take a third way, that is to take full use of merits and overcome weak points of separate solid and liquid dehumidifier, thus a hybrid solid and liquid dehumidifier system is proposed to improve overall dehumidification performance of the system and numerical studied of it is carried out.

2 DESCRIPTION AND MODELLING OF HYBRID SOLID AND LIQUID DEHUMIDIFIER SYSTEM

A hybrid solid and liquid dehumidifier system consists of a solid desiccant dehumidifier and a liquid desiccant one. Its schematic diagram is shown in Fig. 1 (Yuan et al. 2009).

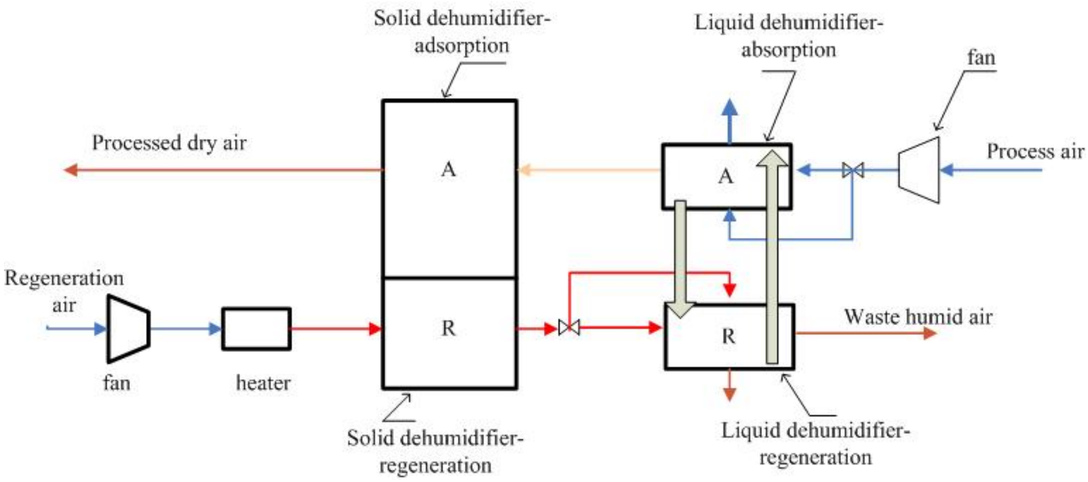

Figure 1: Schematic Diagram of Hybrid Dehumidifier

2.1 Concept of Hybrid Dehumidification System

In the hybrid solid and liquid dehumidifier system, the humid process air is first dehumidified by an IEC liquid dehumidifier, the humidity ratio of the air is reduced and its temperature is slightly increased due to IEC, which is valuable for further dehumidification. Then the process air is further dehumidified by the solid dehumidifier with an isenthalpic process, with its humidity ratio decreased and temperature increased. For regeneration, the high temperature regeneration air first enters the solid dehumidifier to regenerate it, though the temperature of the outlet regeneration air is lowered and humidity ratio increased, the temperature is still high enough thus the relative humidity of the regeneration air is still low enough to regenerate the liquid dehumidifier, so the two dehumidifiers could be regenerated one by one by the same regeneration air flow at gradually lower temperature levels. In this way, the hybrid dehumidifier system could reduce the humidity ratio of humid process air step by step; at the same time, the high temperature regeneration heat could be fully used step by step. Thus, an improved performance of the hybrid dehumidifier system could be expected compared to either the solid dehumidifier or the liquid one.

In order to make a performance simulation of the hybrid dehumidifier system, mathematic models of both solid dehumidifier and liquid dehumidifier are given as below. In this paper, desiccant wheel is used as solid dehumidifier and IEC plate heat exchanger is used as liquid dehumidifier.

2.2 Simulation Models of Solid Dehumidifier

To calculate the performance of desiccant wheel, a simplified model (Yuan and Liu 2007) is adopted. The governing equations include mass conservation equations of air flow and desiccant, energy conservation equations of air flow and desiccant and supplementary equations as following.

Mass conservation equation of air flow：

$$\frac{1}{u_a}\frac{\partial Y}{\partial \tau}+\frac{\partial Y}{\partial x}=\frac{NTU_m}{Dx}\cdot(Y_{ad}-Y) \quad (1)$$

Energy conservation equation of air flow：

$$\frac{1}{u_a}\frac{\partial t_a}{\partial \tau}+\frac{\partial t_a}{\partial x}=NTU_h\cdot(t_{ad}-t_a) \quad (2)$$

Mass conservation equation of desiccant：

$$\frac{\partial W}{\partial \tau}-\beta\cdot NTU_m\cdot(Y-Y_{ad})=0 \quad (3)$$

Energy conservation equation of desiccant：

$$\frac{\partial t_{ad}}{\partial \tau}=\gamma\cdot NTU_h\cdot(t_a-t_{ad})+\chi\cdot NTU_m\cdot(Y-Y_{ad}) \quad (4)$$

Where Y is humidity ratio (kg/kg), t is temperature (℃), W is water content in desiccant (kg/kg).
Supplementary equations include Humidity ratio equation of humid air with respect of relative humidity and temperature, adsorption properties of solid desiccant.

2.3 Simulation Models of Liquid Dehumidifier

In this paper, the IEC plate heat exchanger is used as liquid dehumidifier, like the solid desiccant wheel, the governing equations also include mass conservation equations of air flow and desiccant, energy conservation equations of air flow and desiccant and supplementary equations as following (Liu, 2003).
Mass conservation equation of primary process air：

$$\frac{dY_p}{dx}=\frac{NTU_{mp}}{L_x}\cdot(Y_{sp}-Y_p) \quad (5)$$

Energy conservation equation of primary process air：

$$\frac{dt_{ap}}{dx}=\frac{NTU_{hp}}{L_x}\cdot(t_s-t_{ap}) \quad (6)$$

Mass conservation equation of liquid desiccant：

$$m_{ap}\frac{dY_p}{dx}-\frac{dm_s}{dx}=0 \quad (7)$$

Energy conservation equation of liquid desiccant：

$$m_{ap}\frac{dh_{ap}}{dx}-\frac{dm_s h_s}{dx}+Q_{s-w}=0 \quad (8)$$

Mass conservation equation of secondary evaporative cooling air：

$$\frac{dY_c}{dx}=\frac{NTU_{mc}}{L_x}\cdot(Y_{sc}-Y_c) \quad (9)$$

Energy conservation equation of secondary evaporative cooling air：

$$\frac{dt_{ac}}{dx} = \frac{NTU_{hc}}{L_x} \cdot (t_w - t_{ac}) \tag{10}$$

Mass conservation equation of evaporative water at secondary channel：

$$m_{ac}\frac{dY_c}{dx} - \frac{dm_w}{dx} = 0 \tag{11}$$

Energy conservation equation of evaporative water at secondary channel：

$$m_{ac}\frac{dh_{ac}}{dx} - \frac{dm_w h_w}{dx} - Q_{s-w} = 0 \tag{12}$$

Overall energy conservation equation of the dehumidifier：

$$m_{ap}\frac{dh_{ap}}{dx} - \frac{dm_s h_s}{dx} + m_{ac}\frac{dh_{ac}}{dx} - \frac{dm_w h_w}{dx} = 0 \tag{13}$$

Where Y is humidity ratio (kg/kg), t is temperature (℃), m is mass flow rate (kg/s), h is enthalpy (kJ/kg).

Supplementary equations include humidity ratio of air at surface of liquid desiccant, enthalpy of air at surface of liquid desiccant, mass flow-rate of liquid desiccant, humidity ratio of air at surface of evaporative cooling water, enthalpy of air at surface of evaporative cooling water.

The IEC plate liquid dehumidifier governing equations set consists of 14 separate equations, and there are 14 separate variables inside, thus it is a closed equations set to have a set of solutions.

2.4 Hybrid Dehumidifier System Simulation

Based on the mathematical models of solid desiccant wheel and IEC plate liquid dehumidifier, a simulation study of the hybrid dehumidifier system is done numerically. For the desiccant wheel, it is under a continuous periodic working condition, while for the IEC plate liquid dehumidifier, the liquid desiccant moves between absorption and regeneration part periodically. The hybrid dehumidifier system in this paper is a combination of desiccant wheel and IEC plate liquid dehumidifier, thus the simulation is the combination of desiccant wheel simulation and IEC plate liquid dehumidifier simulation. For a separate simulation of desiccant wheel and IEC plate liquid dehumidifier, the inlet conditions of process air and regeneration air are both needed, while in the hybrid dehumidifier system, the inlet conditions of process air for the desiccant wheel and inlet conditions of regeneration air for the liquid dehumidifier are both unknown, thus assumptions of the values are given at the beginning, then calculation iterations are essential to reach the final convergence results.

3 SIMULATION RESULTS AND DISCUSSIONS

Inlet conditions of process air and regeneration air are given for the simulations in this paper listed in Table 1 as below.

Table 1 Inlet conditions of process air and regeneration air

	Temperature(℃)	Humidity Ratio(g/kg)	Mass flow rate(kg/h)
Process air	35	21	450
Regeneration air	70	21	450

With the same inlet conditions above, the outlet air results of the three kinds of dehumidifiers are listed in Table 2 as below.

Table 2 Outlet conditions of process air

	Temperature (℃)	Humidity Ratio (g/kg)	Relative Humidity	Dehumidification effectiveness
Desiccant wheel	58.12	14.9	12.82%	29%
IEC plate liquid dehumidifier	32.64	13.67	43.65%	34.9%
Hybrid dehumidifier	54.90	8.1	8.2%	61.4%

From the simulation results we could find that under the same inlet conditions, where a low regeneration temperature of 70℃ is used, the hybrid dehumidifier system gets the best performance among the three dehumidifiers, its dehumidification effectiveness (ratio of inlet and outlet humidity ratio difference to inlet humidity ratio) is almost twice higher than desiccant wheel and IEC plate liquid dehumidifier, which means the hybrid dehumidifier system could be a promising system for dehumidification under low regeneration temperature.

4 CONCLUSIONS

In order to improve the performance of dehumidifiers, currently there are usually two ways, one is to make detailed study of the heat and mass transfer process within the dehumidifier to find possible methods to enhance the heat and mass transfer rate; the other is to find and produce advanced desiccant materials that have better properties than that of the current dehumidifier. In this paper, we propose a new concept of hybrid solid and liquid dehumidifier system, which has merits of both higher dehumidification effectiveness and lower regeneration temperature. Simulation results show that the dehumidification effectiveness could be twice better than current dehumidifier under the same working conditions, that is to say this hybrid dehumidifier system is a good way to develop better dehumidifiers at current conditions.

5 REFERENCES

Collier RK, Cale TS, Lavan Z 1986, “Advanced desiccant material assessment”, Gas Research Institute Report GRI-86/0182.

Dai YJ, RZ Wang, H.F. Zhang 2001, “Parameter analysis to improve rotary desiccant dehumidification using a mathematical model”, International Journal of Thermal Science, Vol. 40, pp. 400–408.

Liu X.H., Y.Jiang 2007, “Heat and mass transfer model of cross flow liquid desiccant air dehumidifier”, Energy Conversion and Management, Vol.48, pp.546－554

Liu X.R. 2003, “Theoretical and numerical research on solid and liquid dehumidifiers”, MS Thesis, BUAA, China (in Chinese)

Maclaine-Cross I.L., P.J. Banks 1972, “Coupled heat and mass transfer in regenerators—prediction using an analogy with heat transfer”, International Journal of Heat and Mass Transfer Vol. 15, pp. 1225–1242.

Nia F. E. et al. 2006, “Modeling and simulation of desiccant wheel for air conditioning”, Energy and Buildings Vol. 38, pp. 1230–1239

Yuan WX, Liu XR, 2007, “Numerical simulation and analysis of a new simple model on desiccant wheel”, ACTA ENERGIAE SOLARIS SINICA, Vol. 28 (3), pp. 296-300 (in Chinese)

Yuan WX, et al., 2009, “Hybrid liquid and solid dehumidifier and its dehumidification methods”, Chinese Patent, ZL 200810119998.1 (in Chinese)

Zheng W, WM Worek 1993, “Numerical simulation of combined heat and mass transfer process in a rotary dehumidifier”, Numerical Heat Transfer Part A Vol. 23, pp. 211–232

Zhang LZ, JL Niu 2002, “Performance comparisons of desiccant wheels for air dehumidification and enthalpy recovery”, Applied Thermal Engineering, Vol. 22, pp. 1347–1367.

Zhang XJ et al. 2005, “Parametric study on the silica gel–calcium chloride composite desiccant rotary wheel employing fractal BET adsorption”, Int. J. Energy Res.; Vol. 29, pp.37 – 51