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Study on an internally-cooled liquid desiccant dehumidifier with CFD model ☆

Yimo Luo [a], Yi Chen [b,*], Hongxing Yang [b], Yuanhao Wang [a,*]

[a] Faculty of Science and Technology, Technological and Higher Education Institute of Hong Kong, Hong Kong
[b] Renewable Energy Research Group (RERG), Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong

HIGHLIGHTS

- A model for internally-cooled counterflow dehumidifier was developed based on CFD.
- High temperature desiccant worsened the performance by decreasing the contact time.
- *Le* number was greater than unity for dehumidification process.
- It was more efficient to set higher heat-flux density at the upper part.
- It was necessary to consider variational properties of solution and air.

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ABSTRACT

The liquid desiccant air conditioning system is considered as a possible substitute of the traditional air conditioner mainly due to its characteristics of energy saving. The dehumidifier is a key component of the system therefore was chosen as the research object. It was found the present models conducted the simulation with lots of assumptions, especially ignoring the effect of flow behavior. Besides, most studies focused on the inlet and outlet parameter changes rather than the interior condition of the dehumidifier. To fill the research gap, a model for an adiabatic dehumidifier was established with CFD technology in authors' previous study. On the basis of it, a model was further developed in present work for internally-cooled liquid desiccant dehumidifier. The interior heat and mass transfer processes were then simulated with the model, followed by the detailed performance investigation. Analysis was conducted to investigate the influence of some factors, including inlet desiccant temperature, desiccant flow rate and two types of internally cooling, and variable physical properties. The advantage of present study lied in its more in-depth analysis of interior condition of the dehumidifier. Besides, the study also demonstrated the necessity of considering the variable properties of desiccant solution during the simulation.

1. Introduction

The indoor environment has drawn increasing concerns as people spend most of their time in the buildings [1]. At present, the pleasant indoor environment still depends greatly on a large number of fossil fuels consumption, resulting energy crisis and serious environmental problems [2]. Therefore, it becomes more and more urgent to improve the energy utilization efficiencies [3–5] or resort to the utilization of renewable energy [6–8].

Studies show that there are mainly four factors which play great role in determining human comfort degree, i.e., temperature, relative humidity, pressure, air velocity [9]. According to ASHRAE standard 62-2001, the relative humidity needs to be kept in the range of 40–60% to meet the requirements of human comfort [10]. In the traditional air conditioner, the condensation dehumidification is employed for removing the excessive moisture from the air, and it takes up about 30–50% of the total energy consumption [11]. Then some liquid desiccants, such as lithium bromide (LiBr), lithium chloride (LiCl), calcium chloride ($CaCl_2$), were proposed for air dehumidification [12]. By introducing the liquid desiccant dehumidification into air conditioning, it is named the liquid desiccant air conditioning system, which can realize the separate control of temperature and humidity. Like the traditional air conditioner, the sensible heat of the air is removed by the cooling

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* Corresponding authors.
E-mail addresses: chen.yi@connect.polyu.hk (Y. Chen), wangyuanhao@vtc.edu.hk (Y. Wang).

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Nomenclature

A	contact area (m^2)
Ca	Capillary number (dimensionless)
C_p	specific heat at constant pressure ($J\,kg^{-1}\,K^{-1}$)
D	diffusion coefficient ($m^2\,s^{-1}$)
E	energy per unit mass ($J\,kg^{-1}$)
$\boldsymbol{F}$	source term in the momentum equation ($N\,m^{-3}$)
F_{ST}	source term due to surface tension ($N\,m^{-3}$)
$\boldsymbol{g}$	acceleration due to gravity ($m\,s^{-2}$)
h	sensible enthalpy ($J\,kg^{-1}$)
h_m	local mass transfer coefficient ($kg\,m^{-2}\,s^{-1}$)
H_{lg}	latent heat of evaporation ($J\,kg^{-1}$)
H	heat flux ($W\,m^{-2}$)
J	mass flux ($kg\,m^{-3}\,s^{-1}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$),
K	local overall mass transfer coefficient ($kg\,m^{-2}\,s^{-1}$)
l	liquid flow distance (m)
L	characteristic length (m)
m	the number of the species (dimensionless)
n	the number of the phases (dimensionless)
$\hat{n}$	the divergence of the unit normal (dimensionless)
P	pressure (Pa)
Q_m	mass flow rate per unit length ($kg\,m^{-1}\,s^{-1}$)
Q_V	volume flow rate of the unit width ($m^3\,m^{-1}\,s^{-1}$)
Re	Reynolds number (dimensionless)
S_E	source term in the energy equation ($W\,m^{-3}$)
S_{lg}	mass transfer source at the phase interface ($kg\,m^{-3}$)
S_C	heat exchange with cooling media ($W\,m^{-3}$)
t	time (s)
t_c	contact time (s)
T	temperature (K)
$\boldsymbol{u}$, u	velocity vector ($m\,s^{-1}$)
u_{surf}	the surface velocity of the liquid film ($m\,s^{-1}$)
We	Weber number (dimensionless)
$W_{g,b}$, $W_{g,e}$	the humidity ratio of the bulk air and the equilibrium air humidity ratio to the desiccant solution ($kg\,kg^{-1}$)
x, y	coordinate axis (dimensionless)
x_s	mass fraction of LiCl in the solution (dimensionless)
$x_{k,q}$	mass fraction of the species k in the qth phase (dimensionless)

Greek characters

α	the volume fraction of phases (dimensionless)
μ	dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)
σ	surface tension coefficient ($N\,m^{-1}$)
κ	curvature of free surface (dimensionless)
$\Gamma_{k,q}$	diffusion coefficient of the species k in the qth phase ($m^2\,s^{-1}$)
λ	thermal conductivity coefficient ($W\,m^{-1}\,K^{-1}$)
ψ	concentration difference ratio (dimensionless)
δ	film thickness (m)
υ	kinetic viscosity ($m^2\,s^{-1}$)

Subscripts

a	air
eff	effective
g	gas phase
i, j	signal of coordinate axis
in	inlet
k	the kth species
l	liquid phase
q	the qth phase
s	solution
T	turbulence
w	wall

coil. However, the latent heat is controlled by removing the moisture from the air with liquid desiccant. As it needs not to reduce the air temperature to the dew-point temperature, the evaporative temperature of the cooler is increased so as the cooler COP in the liquid desiccant air conditioning system is higher than that of the traditional air conditioner [13]. Therefore, compared with conventional vapor compression, a desiccant air conditioning system can save up to 40% energy [14,15]. In addition, the dehumidification process is able to be driven by a relatively low regeneration temperature, i.e., between 60 and 75 °C. Thus, the low-grade thermal energy resources are capable of regeneration, such as geothermal energy, solar energy, and waste heat [16]. Moreover, it can avoid moisture condensation and reduce the wet surfaces which are the breeding ground for bacteria and mildew [17]. As a result, the liquid desiccant air conditioning system is considered as a possible substitute of the traditional air conditioner.

In the liquid desiccant air conditioning system, the dehumidifier is a key component, where the moist air is dehumidified. Lots of studies have been conducted to improve its performance by experiment [18,19]. In terms of simulation, it was summarized three models had been developed for adiabatic dehumidifiers [20], i.e., finite difference model [21,22], effectiveness NTU (ε-NTU) model [23] and some simplified solutions [24]. For the three different models, the finite difference model is used most often for its accuracy. However, it involves complicated iterative process, so it is only suitable for dehumidifier or regenerator design or operation optimization. Besides, some simplifications should be made to start the calculation. Compared with the finite difference model, two more assumptions are required for the ε-NTU model. Therefore, it is less accurate yet potential for saving computing time. In the simplified solutions, some more additive assumptions are made to be applicable for certain operation conditions. For example, the analytical solution of Ren et al. [25] is only suitable for the case where the solution flow rate and concentration change slightly as it assumed that the variation of the equilibrium humidity ratio of solution depended only on the change of the solution temperature. The complicated iteration could be avoided, so the simplified solutions have high efficiency of calculation. When it comes to internally-cooled dehumidifier, there are also three types of models developed on the basis of finite difference model [20]. They are models without considering liquid film thickness [26], models considering uniform liquid film thickness [27], and models considering variable liquid film thickness [28]. In the first model, the effect of velocity field on heat and mass transfer is ignored even though velocity, mass and energy are coupled. In the models considering uniform liquid film thickness, the film thickness and velocity field are kept unchanged in the process of calculation. It is found this model usually under-predict the dehumidification performance. The third model takes into consideration the influence of ever-changing velocity field, resulting in more accurate simulation. Based on the review, it is concluded that to simplify the heat and mass transfer process, lots of common assumptions had been made in present models, such as ignoring the influence of velocity, assuming the heat and mass transfer process to be steady state, and so forth. But it has been found the flow behaviors have strong effect on the performance of various heat and mass transfer devices and the

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