Applied Energy 179 (2016) 727–737

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Performance study of a heat pump driven and hollow fiber membrane-based two-stage liquid desiccant air dehumidification system

Ning Zhang [a], Shao-You Yin [b], Li-Zhi Zhang [a,c,*]

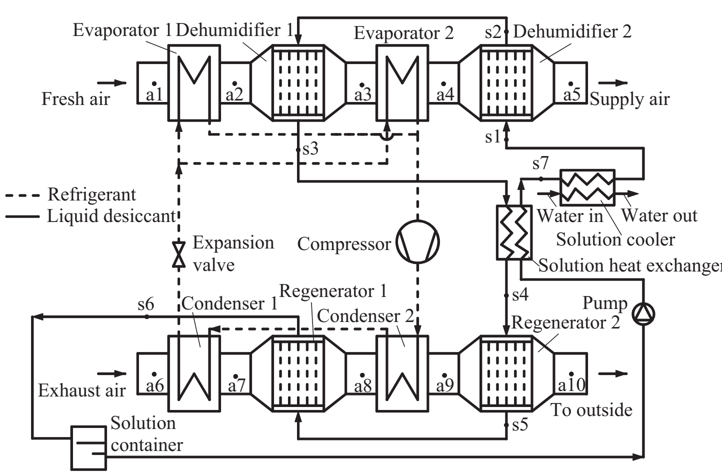
[a] Key Laboratory of Enhanced Heat Transfer and Energy Conservation of Education Ministry, School of Chemistry and Chemical Engineering, South China University of Technology, Guangzhou 510640, China
[b] Heat Pump Engineering and Technology Development Center of Guangdong Universities, Shunde Polytechnic, Foshan 528333, China
[c] State Key Laboratory of Subtropical Building Science, South China University of Technology, Guangzhou 510640, China

HIGHLIGHTS

- A two-stage hollow fiber membrane based air dehumidification is proposed.
- It is heat pump driven liquid desiccant system.
- Performance is improved 20% upon single stage system.
- The optimal first to second stage dehumidification area ratio is 1.4.

GRAPHICAL ABSTRACT

A heat pump driven, hollow fiber membrane-based two-stage liquid desiccant air dehumidification system.



ARTICLE INFO

Article history:
Received 5 April 2016
Received in revised form 21 June 2016
Accepted 11 July 2016

Keywords:
Heat pump
Hollow fiber membrane
Liquid desiccant
Two-stage
System performance

ABSTRACT

A novel compression heat pump driven and hollow fiber membrane-based two-stage liquid desiccant air dehumidification system is presented. The liquid desiccant droplets are prevented from crossing over into the process air by the semi-permeable membranes. The isoenthalpic processes are changed to quasi-isothermal processes by the two-stage dehumidification processes. The system is set up and a model is proposed for simulation. Heat and mass capacities in the system, including the membrane modules, the condenser, the evaporator and the heat exchangers are modeled in detail. The model is also validated experimentally. Compared with a single-stage dehumidification system, the two-stage system has a lower solution concentration exiting from the dehumidifier and a lower condensing temperature. Thus, a better thermodynamic system performance is realized and the *COP* can be increased by about 20% under the typical hot and humid conditions in Southern China. The allocations of heat and mass transfer areas in the system are also investigated. It is found that the optimal regeneration to dehumidification

* Corresponding author at: Key Laboratory of Enhanced Heat Transfer and Energy Conservation of Education Ministry, School of Chemistry and Chemical Engineering, South China University of Technology, Guangzhou 510640, China.
E-mail address: lzzhang@scut.edu.cn (L.-Z. Zhang).

http://dx.doi.org/10.1016/j.apenergy.2016.07.037
0306-2619/

Nomenclature

A	area (m^2)
b_{wat}	slope of air saturation curve
c	specific heat (kJ/(kg °C))
c_p	specific heat at constant pressure (kJ/(kg °C))
COP	coefficient of performance of the system
d	diameter (m)
D_{vm}	diffusivity of membrane (m^2/s)
EER	energy efficiency ratio of heat pump
h	heat transfer coefficient (kW/(m^2 °C))
h_v	latent heat of phase change (kJ/kg)
H	specific enthalpy (kJ/kg)
k	mass transfer coefficient (m/s)
Le	Lewis number
m	mass flow rate (kg/s)
M	dehumidification rate (kg/h)
NTU	Number of Transfer Units
P	perimeter (m)
Q	heat transfer capacity (kW)
T	temperature (°C)
V	volumetric flow rate (m^3/s)
W	power consumption (W)
x, y	spatial coordinate (m)
x_0, y_0	width and length of dehumidifier (m)
X	solution concentration
ΔT_{sh}	superheating (°C)

Greek letters

ρ	density (kg/m^3)
ω	humidity ratio (kg moisture/kg air)
λ	thermal conductivity (kW/(m °C))
δ	thickness (m)

Subscripts

a	air
cal	calculated
com	compressor
cond, cond1, cond2	condenser, condenser 1 and condenser 2
deh, deh1, deh2	dehumidification, dehumidifier 1 and dehumidifier 2
ev	expansion valve
eva, eva1, eva2	evaporator, evaporator 1 and evaporator 2
fan	fan
i	inside, inlet
Lat	latent heat
mean	mean
o	outside, outlet
pump	pump
r	refrigerant
reg1, reg2	regenerator 1 and regenerator 2
s	liquid desiccant
sen	sensible heat
sat	saturate
sta1, sta2	stage 1 and stage 2
tot	total
w	wall, water
wat	water film

area ratio is 1.33. The optimal first to second stage dehumidification area ratio is 1.4; and the optimal first to second stage regeneration area ratio is 1.286.

1. Introduction

Energy consumption by air-conditioning represents a large portion of the entire building energy consumption, especially in hot and humid climate like South China [1–4]. Energy-saving technologies like liquid desiccant air dehumidification systems have been developing rapidly [1,5,6], due to the large dehumidification capability of hygroscopic solution, and the ability of waste energy recovery and the energy storage potentials [7–10].

The packed-bed columns [6] are usually used as the equipments for liquid desiccant air dehumidification. The concentrated solution and the fresh air are contacted directly in these equipments to remove moisture from the fresh air. However, small corrosive liquid droplets may be carried over to rooms by the process air during this process. It is harmful to indoor environment and human health. To solve this problem, semi-permeable membranes are used to separate the liquid droplets from the air stream [11]. According to this concept, a bundle of hollow fiber membranes is packed in a shell to form a shell-and-tube like contactor. Liquid desiccant flows in tube side and air stream flows across the fibers in shell side [12,13]. The membrane permits water vapor to permeate, but it prohibits liquid solution and other gases from crossing-over. To let the whole system operate, a heat pump is combined with the membrane-based dehumidification system to cool and heat the solution for dehumidification and regeneration respectively [14]. However, the obtained *COP* (Coefficient of Performance) of the system is about 0.9, which is not as high as expected. The reason behind is that the dehumidification capability is sacrificed by the temperature rise from absorption heat released in such isoenthalpic dehumidification processes. How to prohibit the temperature rise of solution in dehumidification is a major objective in optimizing systems.

As a solution, a two-stage system can alleviate temperature rise in some degree by inter-cooling of liquid solution in dehumidification. Thermodynamically, it is more perfect. It has gained considerable attention recently because of this high thermodynamic perfect degree [15–19]. According to this concept, both the cooling-dehumidification and the heating-regeneration processes are divided into two stages in the system. Hence, the temperature and concentration differences between the air and the solution in exchangers can be lowered and the heat and mass transfer efficiencies are higher [17]. A two-stage solar liquid-desiccant system is proposed [18]. The performance of the system is better than the conventional one and the energy storage capacity is improved. The exergy losses of the system can also be significantly reduced by increasing desiccant concentration variance between the dehumidification and the regeneration [19].

Apart from the treatment of liquid desiccant, it is an efficient method to cool and heat the air by a heat pump. Theoretically, it is more efficient to cool and heat the solution than the air [20]. However, heat exchangers are usually made of metals, such as copper. Direct heating of LiCl solution, which is highly corrosive,