Applied Energy 228 (2018) 12–20

Contents lists available at ScienceDirect

Applied Energy

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

# Model-based optimization for a heat pump driven and hollow fiber membrane hybrid two-stage liquid desiccant air dehumidification system

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

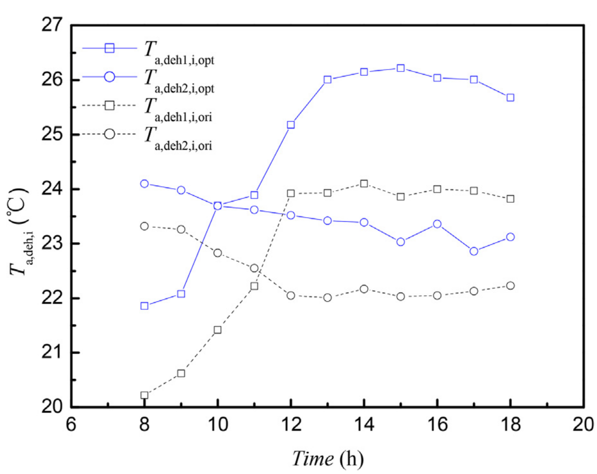
[a] School of Chemistry and Chemical Engineering, South China University of Technology, Guangzhou 510640, China
[b] Heat Pump Engineering and Technology Development Center of Guangdong Universities, Shunde Polytechnic, Foshan 528333, China
[c] School of Energy Science and Engineering, Central South University, Changsha 410083, China

## HIGHLIGHTS

- Model-based optimization strategy of the two-stage system is developed.
- Adjusting air temperature to the membrane modules can satisfy the load variations.
- Total energy saving potential is about 20% under the hot and humid weather.
- Energy reduction of the compressor has a great contribution to total energy saving.

## GRAPHICAL ABSTRACT

Original and optimal air temperatures on the inlet of dehumidifiers during the daytime in a typical summer day (Aug 5) of Guangzhou.




## ARTICLE INFO

*Keywords:*
Heat pump
Hollow fiber membrane
Two-stage
Genetic algorithm
Optimization strategy

## ABSTRACT

Heat pump driven liquid desiccant dehumidification systems using hollow fiber membrane contactors have emerged as a promising and energy-efficient approach to air dehumidification. This paper reports on an optimization strategy for a two-stage system, which based on a set of heat and mass transfer models. The optimization problem was solved by a genetic algorithm to minimize the energy consumption. An experimental rig was built and experimental data were collected to validate the model-based operating strategy. The strategy implies that an hourly optimal regulation is proposed to control inlet temperatures on the inlet of membrane modules can be hourly regulated under hot and humid weather conditions. It appears that energy consumption is reduced by more than 20% to satisfy the indoor air humidity demand and the energy saving potential is more significant for the high moisture load. Slight variations of optimal energy input can stabilize electric power supply. Energy consumption of the compressor dominates the overall energy consumption and has the greatest potential to improve energy efficiency due to small differences between evaporating and condensing temperatures. The presented optimization strategy can be widely used as a real-time operation guide to monitor and control the systems under hot and humid weather conditions.

* Corresponding author.
*E-mail address:* nzhang@scut.edu.cn (N. Zhang).

https://doi.org/10.1016/j.apenergy.2018.06.058
Received 30 January 2018; Received in revised form 5 June 2018; Accepted 8 June 2018

**Nomenclature**

| | |
|---|---|
| $D_{mem}$ | diffusivity of membrane ($m^2$/s) |
| $f$ | function of independent variables |
| $h$ | specific enthalpy (kJ/kg) |
| $m$ | mass ratio (kg/s) |
| $M$ | dehumidification rate (kg/h) |
| $NTU$ | Number of Transfer Units |
| $Q$ | energy consumption (kW·h) |
| $T$ | temperature (°C) |
| $V$ | volumetric flow rate ($m^3$/s) |
| $W$ | power consumption (W) |
| $X$ | solution concentration |
| $\Delta T_{sh}$ | superheating (°C) |
| $\Delta x$ | absolute error |
| $\Delta y/y$ | relative error |

*Greek letters*

| | |
|---|---|
| $\omega$ | humidity ratio (kg moisture/kg air) |
| $\lambda$ | thermal conductivity (kW/(m°C)) |

*Subscripts*

| | |
|---|---|
| a | air |
| aux | auxiliary |
| 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 | inlet |
| max | maximum |
| min | minimum |
| o | outlet |
| opt | optimal |
| ori | non-optimal |
| pump | pump |
| r | refrigerant |
| reg, reg1, reg2 | regeneration, regenerator 1 and regenerator 2 |
| req | required |
| s | solution |
| set | setting value |
| tot | total |

*Abbreviation*

| | |
|---|---|
| HPMTLDAD | heat pump driven membrane-based two-stage liquid desiccant air dehumidification |

## 1. Introduction

The critical importance of moisture removal in hot and humid areas has heightened the urgent need for developing energy-efficient dehumidification technology used in air-conditioning systems [1–3]. Of particular interest and complexity is the liquid desiccant dehumidification technology [4,5], which is a key step to achieve independent control of indoor temperature and humidity [4–6]. Liquid desiccants have high water-adsorption capacity and lead to better dehumidification system performance [3,5]. Liquid dehumidification can use low-grade heat such as solar energy because of relatively low temperature for concentrating liquid solutions, a technology that leads to high-efficiency energy uses [7]. Therefore, liquid desiccant air dehumidification systems have received significant attention [1–8].

Conventional liquid desiccant air dehumidification equipment (e.g., packed bed columns) involves direct air-liquid contacting processes [4,9] in which liquid desiccant droplets may be entrained into rooms by air stream and contaminate the indoor environment. To solve this problem, researchers have proposed to employ hollow fiber membrane-based contactors that comprise a bunch of hollow fiber membranes formed into shell-and-tube shape. Liquid solution flows in the tube side while process air flows across the fibers in the shell side [10]. Because of selective permeation of the porous membrane, only water vapor can be selectively absorbed through the membrane by the liquid solution. Generally, the liquid desiccant is pre-cooled before air dehumidification and pre-heat before solution regeneration to maintain appropriate driving force for moisture transfer through the membrane. The simultaneous requirement of cooling and heating inspired researchers to combine a heat pump with the membrane-based liquid desiccant dehumidification system [11,12]. The heat-pump-based systems can simultaneously use the cooling capacity from an evaporator and the heating effect from a condenser, achieving high air dehumidification capability with less energy consumption.

In practice, the temperature of solution is still high due to the released absorption heat, and the dehumidification capacity may be deteriorated. To solve the problem, the authors have proposed a heat pump driven membrane-based two-stage liquid desiccant air dehumidification (HPMTLDAD) system [13], in which solution is re-cooled and re-heated to keep the high driving force for moisture transfer in the second stage air dehumidification and solution regeneration processes. A heat pump cools and heats the air stream instead of the liquid desiccant, and the air is used as the heat-transfer medium between the heat pump and the liquid desiccant to eliminate the desiccant solution corrosion to metal heat exchangers. Previous studies have showed that the performance of HPMTLDAD is superior to that of the single stage system [7,13], but the information about optimal regulation of this system is still quite limited. The weather conditions and the loads commonly change with time, which makes the parameters of the system vary accordingly. This variation can cause the mismatch between the energy consumptions of membrane and the heat pump, and unnecessary waste of energy [13]. Commonly, HPMTLDAD systems are empirically operated to match time-dependent moisture loads, and there is much room for improving system performance.

Recently, optimum control of liquid desiccant dehumidification has received considerable scholarly attention [14–26]. Some researchers paid attention on the optimum control of specific components, e.g., direct air-liquid contact dehumidifiers [14–16]. Operational parameters are key factors for dehumidification efficiency and the performance of packed bed tower was improved by regulations of solution temperature [17] and concentration [18]. The structure and operation of plate membrane dehumidifiers were also optimized [19]. Apart from dehumidification modules, control strategies have been applied in different