Applied Thermal Engineering 128 (2018) 795–804

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Feasibility of a two-stage liquid desiccant dehumidification system driven by low-temperature heat and power

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HIGHLIGHTS

- A new two-stage liquid-desiccant dehumidification system is raised.
- The new system can save 30.63% power comparing to the conventional system.
- The comparative exergy analysis is conducted for proposed and reference systems.
- Power saving mechanism is revealed by driven force analysis.
- The power and heat is efficiently used in a cascaded way.

ARTICLE INFO

Article history:
Received 31 May 2017
Revised 8 September 2017
Accepted 10 September 2017
Available online 12 September 2017

Keywords:
Low-temperature heat utilization
Liquid desiccant dehumidification
Power saving
Exergy analysis
Vapor partial pressure

ABSTRACT

Liquid-desiccant dehumidification technology is a promising way to take advantage of low-grade energy to dry air for air conditioning and industrial applications. This paper proposed a two-stage liquid-desiccant dehumidification system driven by low-temperature heat and electric power, which is integrated with a vapor compression refrigeration system that performs deep dehumidification. Air moisture is preliminarily removed by the desiccant solution at environmental temperature in a first-stage dehumidifier and then deeply removed by the desiccant solution cooled to 18 °C by a vapor compression refrigerator. Simulation results show that the new system can decrease power consumption by 30.63% compared with a conventional cooling dehumidification system. The equivalent power-generation efficiency of the proposed system can reach 2.91%. Finally, the power-saving mechanism of the proposed system was illuminated by conducting the exergy analysis and the study of the surface vapor partial-pressure difference in the liquid desiccant dehumidifiers.

1. Introduction

Currently, building energy consumption has already reached approximately 20–50% of the total energy consumption of the world [1]. Air-conditioning systems account for approximately 50–70% of building energy consumption, and dehumidification loads make up approximately 30–40% of HVAC [2]. In a conventional HVAC system, moisture in air is removed by condensation; humid air must be cooled to below its dew-point temperature, which requires the temperature of cooling energy to be as low as 7 °C. Due to the low refrigeration temperature (1–5 °C) of the vapor-compression refrigeration process, a conventional vapor compression air-conditioning system (VCS) requires substantial power. Exploring new dehumidification methods to reduce power consumption has significant research value and very large application potential.

Liquid-desiccant dehumidification technology, utilizing the special moisture absorption characteristics of a saline solution and can remove moisture at higher temperature, are advantageous in reducing the electric power consumption by utilizing low-temperature thermal energy and thus have attracted much attention [3–5]. A single one-stage liquid desiccant system has high electric power savings potential and can meet most of application requirement. However, the solution temperature at the inlet of dehumidifier is usually lower than the ambient temperature, and a refrigerator is necessary to produce cooling energy.

To meet the required supply air conditions and also reduce the power consumption of the conventional VCS, heat pump liquid desiccant dehumidification can be a promising way, in which the condensation heat is used for liquid desiccant regeneration and

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http://dx.doi.org/10.1016/j.applthermaleng.2017.09.048
1359-4311/

Nomenclature

d	humidity ratio, g/kg
E	exergy, kW
h	specific enthalpy, kJ/(kg K)
Q	heat transfer rate, kW
R	gas constant, 8.314 kJ/kmol
s	specific entropy, kJ/(kg K)
t	temperature, °C
T	temperature, K
u	chemical potential, kJ/kg
W	electric power, kW
y	mass concentration, %
η_{ex}	exergy efficiency, %

Subscripts and superscripts

0	restricted dead state
a	air
C	cooling
e	evaporator
eq	equivalent power generation
heat	thermal energy
ld	the proposed system
out	output
ref	the reference system
s	solute
w	water
*	ultimate dead state

the produced cooling energy is used for directly cooling or indirectly cooling of air. Earlier studies mainly focused on reducing the power consumption of the heat pump by adding direct-contact total heat recovery exchangers [1,6] or adopting multi-stage dehumidification with several heat pumps to improve their evaporating temperature and decrease the condensation temperature [7]. Currently the studies on heat pump driven and membrane-based liquid desiccant air dehumidification systems have been conducted mainly for preventing liquid desiccant droplets from crossing over into the process air and achieving high energy efficiencies [8–10]. Abdel-Salam et al. [11,12] proposed a novel capacity matching index, which can be used to quantify the capacity matching for the heat pump liquid desiccant systems. In addition, Chen et al. [13] developed a new HLDACS, in which the chilled water of the VCS is used to cool the liquid desiccant (LiCl-H_2O solution) and the process air already dehumidified in the liquid desiccant dehumidification cycle; the condensation of the heat of the VCS is used for desiccant regeneration. Yamaguchi et al. [14] proposed a HLDACS that integrates a dehumidifier and evaporator as well as a regenerator and condenser, so that the process air is simultaneously dehumidified and cooled in the dehumidifier, and the regeneration air is simultaneously humidified and heated in the regenerator. Mucke et al. [15] indicates that the system which combines the evaporator and absorber as well as the condenser and regenerator in one unit each shows only electric power savings of about 10% under a particular climate. In these mentioned systems, in order to meet the requirement of liquid desiccant regeneration, the condensation temperature is always higher compared to conventional one, leading to a relatively low *COP* though the evaporating temperature can be increased to some extent.

Hybrid liquid desiccant air-conditioning systems (HLDACS) which simultaneously consumes power for VCS and the external heat for liquid desiccant regeneration, have been studied but not much in recent years. Mucke et al. [15] studied the electric power saving ability of a typical HLDACS, in which the liquid desiccant removes the moisture of air, and the VCS decrease the temperature of air, providing an electric power saving ratio of more than 40%. Dai et al. [16], in the early days, proposed a HLDACS consisting of a VCS with a normal condensation temperature and an evaporative cooler. The electric power consumption of the VCS is further reduced because of the supplementation of the evaporative cooler. In the two systems, an external heat source is required for liquid desiccant regeneration. Su et al. [3] proposed a liquid desiccant dehumidification system integrated with a compression-absorption refrigeration system. The compressed steam condenses in the condenser, and the releasing heat drives liquid desiccant cycle for treating the latent load, and the cooling energy produced in evaporator is used to treat the sensible load. The mentioned HLDACS, both consuming heat and power, only adopts one-stage liquid desiccant dehumidification to meet the general requirement of air humidity ratio.

The current multi-stage dehumidification configurations in the open literature could be divided into two types. One is that the moisture of the process air is absorbed, in series, in several dehumidifiers by the liquid desiccant in different cycles [2,7,17,18]. Xiong et al. [2,18] proposed a two-stage liquid desiccant system using a relatively cheap desiccant for pre-dehumidification and a relatively expensive one for normal dehumidification. However, due to the temperature limitation of the local cooling water, the moisture-absorption ability of the cooled desiccant is still low. Using multi-stage liquid desiccant dehumidification for a higher moisture load has potential to further reduce the power consumption of the VCS. Liu et al. [7] proposed a two-stage heat-pump-driven liquid desiccant system to improve the *COP* of heat pumps, while substantial electric power is still consumed. To reduce the humidity ratio of the air after cooled in evaporative cooler, Al-Sulaiman [17] adopts two totally the same desiccant in two solution cycles for removing the moisture of the process air successively. The other type is that one stream of desiccant solution flows into several dehumidifiers, in series, to absorb the moisture of different air streams [19]. This system can take full advantage of the moisture-absorption ability, but could not realize the deep dehumidification either. In current research on multi-stage dehumidification configurations, one of streams, for example air, flows through dehumidifiers in passing series and the other one enters dehumidifiers in parallel. There is great potential to improve the performance of the whole system by set both streams flow through dehumidifiers in series. However, little literatures focused on this topic. Moreover, when applied in the special applications with the strict requirement of dehumidification, almost no studies indicated the advantages of the multistage liquid desiccant dehumidification from the perspective of the driven force matching.

In this paper, a new two-stage liquid-desiccant system driven by low-temperature heat and power is proposed to perform the deep dehumidification. Adopting commercially established technologies including vapor compression refrigerators and liquid desiccant dehumidification devices, the system achieves the cascade use of moisture removal ability of liquid desiccant, meanwhile, exhibits an enhanced power-saving efficiency and heat utilization efficiency. By conducting the driven force analysis and exergy analysis, the power-saving mechanism has been discussed in detail.