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Feasibility of a hybrid photovoltaic/thermal and liquid desiccant system for deep dehumidification

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ABSTRACT

Air dehumidification is widely applied in the civilian and industrial use, however, conventional vapor compression air-conditioning system consumes substantial power. Using renewable energy in the air handling process has potential to further reduce the power consumption, meanwhile ease the carbon emission. This paper proposes a novel liquid desiccant system integrated with a concentrated photovoltaic/thermal collector for deep dehumidification. The generated electric power drives a vapor compression chiller for cooling the desiccant solution for a two-stage dehumidification, and the released heat from the collector is used for the desiccant regeneration. Simulation studies indicated the proposed system has a superior power saving ability of 55.65% comparing with the conventional one, besides the equivalent power generation efficiency reaches 8.7% in the base design condition. A comparative driven force analysis showed the two-stage dehumidification has a better match of driven force compared with the single-stage liquid desiccant dehumidification, thus leading to a reduced irreversible loss of 65.43%. Sensitivity analysis indicated that the dehumidification temperature has a decisive effect on the system performance. The exergy efficiency has a maximum value of 13% as the dehumidification temperature is 22.3 °C. The economic studies showed that the investment on the concentrated photovoltaic/thermal collector account for the largest share of the total initial investment, and has a significant effect on the payback period. The payback period would be reduced further if the benefit of the clean development mechanism (*CDM*) is considered.

1. Introduction

Conventional vapor compression air-conditioning systems (VCS) are extremely mature technologies which are widely applied in the building ventilating and industrial sectors. To reduce the power consumption of the VCS, the hybrid liquid desiccant air-conditioning systems were proposed, in which the liquid desiccant cycle treats the latent heat, leading to the reduced cooling load and power consumption of the vapor compression chiller. Zhang et al. [1] proposed a compression-absorption refrigeration air-conditioning system integrated with a liquid desiccant dehumidification unit. Assisted by a compressor, the condensation heat of the absorption refrigeration cycle can be used for the generation of the weak desiccant solution in the liquid desiccant dehumidification cycle. The absorption refrigeration cycle and the liquid desiccant cycle treat the sensible and latent heat, respectively. Su et al. [2] found the dehumidification potential of the outlet saline solution from the absorber of the conventional absorption refrigeration cycle, and proposed a new hybrid air-conditioning system, in which this stream of solution is used for liquid desiccant dehumidification, and the sensible heat is treated by the absorption refrigeration cycle.

Hybrid heat pump and liquid desiccant systems received much concern in recent years, and are appropriate to use in the building ventilating. Chen et al. [3,4] conducted the experimental and theoretical researches of a hybrid air-conditioning system coupled with liquid desiccant dehumidification. The condensation heat from the vapor compression cycle is used for desiccant generation, and the cold energy is for cooling the desiccant solution and the air. Because of the higher condensation temperature, the heat pump consumes large amount of electric power. The liquid desiccant systems integrated with the direct evaporative cooler (DEC), the indirect evaporative cooler (IEC) or the dew point indirect evaporative cooler (DP-IEC) are called stand-alone systems [5], in which the low-temperature heat is mainly consumed for desiccant regeneration, and only a small portion of electric power is used to drive fans and pumps. These hybrid liquid desiccant systems integrated with evaporative cooling technologies are suitable application in the general building ventilating, and could meet most application standards, but could hardly realize the deep dehumidification in some industrial applications [6].

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Nomenclature

A	area, m^2
BOP	balance of the plant
C	concentration ratio
COP	coefficient of performance
$C_{O\&M}$	operation and maintenance cost
DF	driven force
DNI	direct normal irradiation, W/m^2
d	humidity ratio, g/kg
E	exergy, kW
ED	exergy destruction, kW
FF	fill factor
f	inflation rate
H	enthalpy, kW
H_{op}	annual operation time, h
I	annual solar radiation, $kW\,h/(m^2{\cdot}a)$
i	interest rate
i'	nominal interest rate
J_{SC}	short circuit current density, A/m^2
M	mass, kg
m	mass flow rate, kg/s
NCF	net cash flow
NPV	total net present value
NTU_m	number of mass transfer units
PBP	payback period
PSR	power saving ratio
P_{el}	output electric power
P_{in}	absorbed heat of PV/T
Q	heat transfer rate, kW
R	thermal resistance, k/W
SM	solar multiple
S	entropy, kW
TPC	total plant cost
T	temperature, K
t	temperature, °C
V_{oc}	open-circuit voltage, V
W	electric power, kW
y	mass concentration, %
η_e	power efficiency of PV/T, %
η_{ex}	exergy efficiency, %
η_{eq}	equivalent power-generation efficiency, %

Subscripts

0	ambient condition
a	air
ld	liquid desiccant system
ref	reference system
s	desiccant solution

To improve the performance of the liquid desiccant air-conditioning system, multi-stage dehumidification systems with different system flow are developed. Improved heat pump driven two-stage liquid desiccant air dehumidification systems were developed [7]. The dehumidification and regeneration temperatures of the desiccant solutions in each stage could be increased and decreased significantly, respectively, compared with those of the one-stage hybrid system. This means that the condensation temperature of the vapor compression chillers can be decreased at a higher evaporation temperature, and the *COP* of the vapor compression chiller could therefore be improved. Though the moisture-absorption rate can be raised significantly in the improved heat pump driven multi-stage liquid desiccant systems, but substantial electric power is still consumed in the compressor.

To further reduce the power consumption, some other stand-alone multi-stage systems were proposed and assessed. Xiong et al. [8,9] proposed a two-stage liquid desiccant system using a relatively cheap desiccant for pre-dehumidification and a relatively expensive one for normal dehumidification. However, because of the temperature limitation of the local cooling water, the moisture-absorption ability of the cooled desiccant is low. Kumar et al. [5] compared the performance of the conventional single stage and multi-stage liquid desiccant dehumidification systems. In the multi stage system, one stream of desiccant solution cooled by cooling water flows into several dehumidifiers, in series, to absorb the moisture of air streams in parallel. The multi-stage liquid desiccant system can take full advantage of the moisture-absorption ability, but the humidity ratio of the process air rises stage by stage because of the decrease of the partial vapor pressure in the desiccant solution, thus could not realize the deep dehumidification. McNevin et al. [10] preliminarily simulated a multi-stage liquid desiccant system with flow in series of both the process air and liquid desiccant. But no discussions were given about the advantages of the multistage liquid desiccant dehumidification from the perspective of the driven force matching. Su et al. [11] proposed a two-stage liquid desiccant dehumidification system by the cascade utilization of low-temperature heat for industrial applications. The waste heat is used in a cascade manner. The higher-temperature heat is used to generate a strong desiccant solution, which will be used in the preliminary dehumidifier. The lower-temperature heat is used to drive a single-effect absorption refrigerator and provide cooling energy to the deep dehumidifier. The study found that the driven force matching in the dehumidification process grew better comparing with the conventional VCS.

In general, the multi-stage liquid desiccant system integrated with the heat pump still needs electric power with high energy quality. The stand-alone multi-stage liquid desiccant systems with the cooling water only gain the limited moisture-absorption ability, and could not meet the rigorous requirements of some industrial applications. Currently, using renewable energy in the liquid desiccant system were reported only about the desiccant regeneration, including the solar thermal regeneration [12,13] and the photovoltaic–electrodialysis regeneration [14,15]. Seeking a new and efficient method to use renewable energy is urgent to remove the dependence on the electric power, meanwhile, realize a deep dehumidification. The hybrid photovoltaic/thermal solar collectors are a promising solution to reach a high solar utilization efficiency above 80% by converting the solar energy to the electricity and the available thermal energy. Pierrick et al. [16] developed a glass covered water-based PV/T prototype for power and hot water supply, and a dynamic model was also given to precisely predict its performance. Santoli et al. [17] proposed a different hybrid photovoltaic thermal solar system for power and hot water production, in which the PV/T thermal output is adopted as the cold temperature heat sink of the heat pump. The thermal heat output from the PV/T collector is suitable for integration with other technologies for various functions. Since the liquid desiccant cycle can use power and low-temperature heat for air dehumidification, there is a large potential to efficiently utilize solar energy by integrating the liquid desiccant dehumidification cycle with the photovoltaic/thermal collector.

The paper proposes a hybrid photovoltaic/thermal and liquid desiccant system for deep dehumidification. The generated electric power drives a vapor compression chiller for cooling the desiccant solution for a two-stage dehumidification, and the concentrated solar heat is used for desiccant regeneration. The detailed modeling processes of the liquid desiccant cycle and the photovoltaic/thermal collector are given. The thermal performance of the proposed system is analyzed under the base case condition. The comparison of the driven force matching among the conventional VCS, single stage liquid desiccant system and the proposed system are discussed. Finally, a parametric analysis and an