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A two-stage liquid desiccant dehumidification system by the cascade utilization of low-temperature heat for industrial applications

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HIGHLIGHTS

- A liquid-desiccant dehumidification system is raised for industrial applications.
- The low-temperature heat is efficiently used in a cascaded way.
- The new system can save 92.29% power comparing to the conventional system.
- The ratio of saving power to absorbed heat can reach 7.35% in proposed system.
- A driving force analysis and an economic and environmental analysis is given.

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ABSTRACT

Cooling dehumidification driven by power is widely used in industrial processes to obtain dry air, but the main drawback is its large power consumption. In these processes, large amounts of low-temperature waste heat are released to the environment directly, so there is a great energy-saving potential to recover low-temperature waste heat and generate dry air. A new two-stage liquid desiccant dehumidification system with the cascade utilization of low-temperature heat is proposed. 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 first-stage dehumidifier. The lower-temperature heat is used to drive a single-effect absorption refrigerator and provide cooling energy to the second-stage dehumidifier. Simulation results showed that the proposed system can reduce electricity consumption by 92.29% compared with the conventional cooling dehumidification system driven by power. The ratio of electricity savings to absorbed heat can reach 7.35%. The advantage of the cascade utilization of the low-temperature heat was further illuminated by studying the driving force in the dehumidifiers, and a preliminary economic and environmental analysis was performed. The increased initial investment can be recovered in only 3.39 years. Approximately 11,028 tons of standard coal are saved per year, and a reduction of 27,488 tons CO_2 can also be realized per year. Finally, a parametric sensitivity analysis was conducted to optimize the system performance. This study may provide a new method to perform dehumidification by efficiently using a low-temperature heat source.

1. Introduction

Air dehumidification technology is widely applied in industrial systems in the metallurgy, machinery, textile, paper-making, and foodstuff sectors as well as other sectors, and the demand for industrial air dehumidification is increasing rapidly. Vapor compression air-conditioning systems (VCS) are currently widely applied in the industrial sectors, but they consume large amounts of electrical power due to the low evaporating temperature. Industrial units are also major emission sources of CO_2, representing approximately 61.4% of the total emissions in 2013 according to the estimate of the International Energy Agency (IEA) [1]. For developing countries, the share of industrial carbon emissions is much higher than the global average level, such as approximately 80.1% for China [2]. However, many industrial processes, such as those in steelworks, produce large amounts of underutilized or exhaust heat during manufacturing runs. This mid- and low-temperature heat is dissipated to the ambient atmosphere, which

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Nomenclature

a	mass flow ratio of desiccant solution and air
COP	coefficient of performance
$c_{p,cold}$	specific heat at constant pressure of fluid on the cold side, J/(kg K)
$c_{p,hot}$	specific heat at constant pressure of fluid on the hot side, J/(kg K)
DEC	direct evaporative cooler
DP-IEC	dew point indirect evaporative cooler
d	humidity ratio, g/kg
d_e	humidity ratio of humid air in equilibrium with liquid desiccant, g/kg
h	specific enthalpy, kJ/kg
h_e	enthalpy of humid air in equilibrium with liquid desiccant (kJ/kg)
H	height of the cross flow dehumidifier/regenerator, m
HLDACS	hybrid liquid desiccant air-conditioning systems
H_{a1}	total enthalpy of fresh air, kW
H_{a3}	total enthalpy of supply air, kW
IEC	indirect evaporative cooler
L	thickness of cross flow dehumidifier/regenerator, m
LD	liquid desiccant dehumidification system
m	mass flow rate, kg/h
NTU_m	number of mass transfer units
P	absolute pressure, kPa
PSR	powers saving ratio
Q	heat transfer rate, kW
t	temperature, °C
T	temperature, K
VCS	vapor compression system
W	electric power consumption, kW
y	mass concentration

Greek symbols

α	scaling exponent
η_{eq}	equivalent power generation efficiency
ε	heat exchanger efficiency

Subscripts and superscripts

a	air
heat	thermal energy
high	higher temperature heat
in	inlet
ld	proposed system
low	lower temperature heat
out	outlet
p	process air
ref	reference system
s	desiccant solution

clearly causes energy waste and heat island effects. In consideration of a number of factors, such as the industry characteristics, fuel types, energy utilization efficiency and operational tactics, industrial waste heat accounts for 10–50% of the total fuel consumption in various industrial sectors [3]. Therefore, if this industrial waste heat can be efficiently and effectively recovered, it will offer a great potential to both reduce the electric power consumption and ease environmental problems.

Liquid desiccant dehumidification systems are advantageous in reducing the electric power consumption by utilizing low-temperature thermal energy and thus have attracted much attention [4–6]. A conventional one-stage liquid desiccant system with an external heat source has the highest electric power savings but clearly could not meet the required supply air conditions in buildings, let alone the rigorous requirements of the industrial sector [7].

To meet the required supply air conditions, several studies have been performed on hybrid liquid desiccant air-conditioning systems (HLDACS), in which a liquid desiccant system realizes the dehumidification of the air and a compression refrigeration system realizes the cooling of the air. Mucke et al. [7] studied the electric power saving ability of a HLDACS, in which the desiccant dehumidifier of the liquid desiccant system is connected in series with the VCS. The two systems, the VCS and the liquid desiccant system, working independently of each other provide electric power savings of more than 40%, but an external heat source is required for the desiccant regeneration. Dai et al. [8] 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, but an external heat source is also required.

Some studies have been performed on a liquid desiccant air-conditioning system driven totally by a VCS. The condensation heat of the VCS is recovered for the desiccant regeneration, and no external heat source is needed. Chen et al. [9] 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. Bergero et al. [10] studied the electric power saving ability of a HLDACS consisting of a membrane-type LD system and a VCS. The refrigerant in the VCS directly cools or heats the desiccant solution, respectively, in the evaporator and condenser. Yamaguchi et al. [11] 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. Ma et al. [12] put forward a HLDACS integrated with a VCS and solar adsorption chillers, where the condensation heat of the VCS is also used for the regeneration of the dilute desiccant solution. Liu et al. [13,14] improved the thermodynamic performance of this type of HLDACS by adopting direct-contact total heat recovery exchangers to reduce the cooling load of the VCS. To reduce the power consumption further, a new hybrid system of multi-stage dehumidification and multi-stage regeneration with several VCSs was proposed [15]. 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 VCS can be decreased at a higher evaporation temperature, and the *COP* of the VCS could therefore be improved. Su et al. [16] combined a liquid desiccant dehumidification system with a compression-absorption hybrid refrigeration system. The water vapor evaporating from the LiBr-H_2O solution in the generator is pressurized by the compressor, and the condensation heat with higher temperature in the condenser is used for the liquid desiccant regeneration. Though hybrid systems could improve the *COP* of the conventional VCS, substantial high-grade energy is still needed for the compressor.

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