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A new open absorption heat pump for latent heat recovery from moist gas

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ABSTRACT

Conventional drying processes discharge high humidity gas to the atmosphere. The exhaust gas contains large amount of energy. The direct discharging would result in relatively large energy waste. In order to improve the thermal efficiency of drying process, in this paper, a new open absorption heat pump system was proposed, which aims at recovering the latent heat from exhausted moist gas and producing steam for reutilization. The working principle was discussed in detail and thermodynamic models were established to analyze the performance of the new system. The new system can work under both single-stage and double-stage modes. Simulation results showed that the new system could utilize a heat source with lower generation temperature compared with that utilized by a traditional open absorption system. The temperature range of heat source for the double-stage mode is 130–160 °C, and that for the single-stage mode is 160–175 °C. The new system also eliminates the limitation of traditional close absorption system, whose evaporation temperature has to be lower than the dew point temperature of discharged moist gas to recover the latent heat of water steam. Simulation results also indicated an improved COP_h of the new system compared with that of double-stage close absorption heat pump system. The COP_h of the new system varied from 1.52 to 1.97 and the efficiency of heat recovery varied from 15.1% to 54.8% when the temperature of heat source varied from 135 °C to 175 °C and saturated steam of 100 °C was produced.

1. Introduction

Increased energy consumption and greenhouse gas emissions have led to the concerns of the improvement of thermodynamic efficiency of integrated industrial processes. Drying process is widely applied in industries such as pulp and paper manufacturing, wood manufacturing and food processing industry and is one of the most energy-intensive unit operations. It was reported that the energy consumption of drying processes accounted for 9–25% of national energy consumption in the developed countries [1]. Furthermore, during the drying process, more than 70% of the energy consumed is exhausted to the environment in the form of moist gas [1–6]. This consequently results in a low energy efficiency of the drying process, which is typically in the range of 20–40% [5]. Because of the low thermodynamic-efficiency and high energy-consumption, there is a very large improving space for the drying process.

In order to improve the thermodynamic efficiency, researchers have devoted cumulative efforts to recover the latent heat in the discharged moist gas by using the heat integration approaches. Heat exchanger is the most commonly used equipment for heat recovery, which has advantages of low investment and easy operation. In the research of Laurijssen et al. [7], waste heat in the exhaust gas was recovered by using heat exchanger to pre-heat the incoming air and the process water, leading to 15% decrease of the energy consumption in multi-cylinder paper drying sections. However, using heat exchanger to directly recovering the latent heat in the moist gas only could produce hot air with the temperature lower than the dew point of the moist gas.

The traditional heat pump system, including both mechanical heat pump system and absorption heat pump system, has emerged as one of the widely accepted technologies integrated with the drying processes. Anderson et al. [8] estimated that the mechanical

Abbreviations: AHP, absorption heat pump; A, absorber; A1, primary absorber; A2, secondary absorber; CAHP, close absorption heat pump; COP_h, coefficient of performance of heat pump; CR, circulation ratio; G, generator; G1, primary generator; G2, secondary generator; NOAHP, new open absorption heat pump; OAHP, open cycle absorption heat pump; SHX, solution heat exchanger.

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Nomenclature

d	absolute humidity (kg per kg dry air)
h	enthalpy (kJ/kg)
m	mass flow rate (kg/s)
p	water vapor partial pressure (kPa)
Q	heat transfer rate (kW)
t	temperature (°C)
x	solution concentration (wt.)
ζ	efficiency of heat recovery
λ	liquid–gas ratio

Subscripts

a1	primary absorber
a2	secondary absorber
a	absorber
c	condenser
envir	environment
eva	evaporation
g1	primary generator
g2	secondary generator
ge	generation
hg	high-pressure generator
hp	heat pump
in	input
max	maximum
mg	moist gas
out	output
recovered	recovered from the moist gas

heat pump system, which was coupled with common drying schemes used in Swedish sawmills, could decrease heat demand by 5.6 TW h/year at the cost of increased electricity demand by 1 TW h/year. Bakhtiari et al. [9] investigated the optimal integration of absorption heat pumps in a kraft pulping process using Pinch Analysis method. Ahmadi et al. [10,11] optimized an irreversible absorption heat pump system based on a new thermo-ecological criterion. Qu et al. [12] proposed three new configurations of absorption heat pump to recover latent heat in flue gas from natural gas boiler. The simulation results suggested 5–10% improvement in boiler efficiency. Lostec et al. [13] developed a model of wood chip drying process coupled with absorption heat pumps to conduct thermal and economic analysis. Researches [8–15] demonstrated that absorption heat pumps could effectively recover the latent heat of moist gas since the evaporation temperature could be much lower than the dew point temperature of the moist gas. However, the low evaporation temperature reduced the COP_h of heat pump systems at the same time.

To overcome the limitation of traditional close absorption system, whose evaporation temperature should be lower than the dew point temperature of discharged moist gas to recover the latent heat of water vapor, Westerlund et al. [16–18] proposed an open cycle absorption heat pump (OAHP) system to recover the latent heat from the moist gas. As shown in Fig. 1, the OAHP system consists mainly of three parts, absorber, generator and condenser. The moist gas contacts directly with the absorbent in the absorber. Water vapor in the moist gas is absorbed by the absorbent due to the water vapor partial pressure difference between moist gas and absorbents, giving off the latent heat of vapor to directly heat the moist gas, which could be reused by the drying process. Therefore, the latent heat of vapor could be recovered with

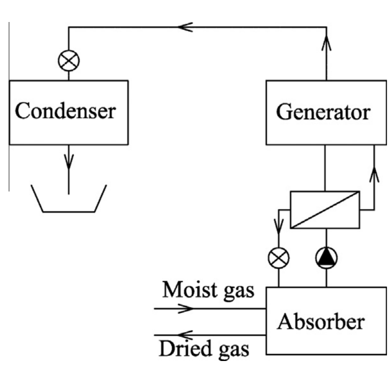

Fig. 1. Schematic diagram of traditional OAHP system [16].

the temperature much higher than the dew point temperature of moist gas. In the research of Wang and Zhang et al. [19,20], the discharged gas was heated from 70 °C to 125 °C in the absorber of the OAHP system and used to produce steam at 120 °C. Anderson et al. [8] demonstrated that the OAHP system could decrease energy consumption by 67.4% for sawmill drying process.

Although the OAHP system performs well at recovering the latent heat of moist gas, to produce high temperature hot air or steam for drying process using the OAHP system would require an even higher generating temperature, which limits its application [16–21]. Consequently, a new OAHP system (NOAHP) is proposed in this paper, which could be operated at double-stage mode to utilize low temperature heat source for generator or single-stage mode to improve system energy efficiency when high temperature heat source for generator is available.

In order to validate the feasibility of the NOAHP system, thermodynamic model was established to analyze the system performance based on the properties of chose absorbent and the mass and energy balance of each component. The performance of the NOAHP system was also compared to that of traditional open absorption and traditional close absorption heat pump system.

2. The description of the NOAHP system

2.1. The working process of the NOAHP system

Fig. 2 shows the schematic of the new open absorption heat pump (NOAHP) system. It consists of two generators (primary and secondary generator G1, G2), two absorbers (primary and secondary absorber A1, A2), condenser and solution heat exchanger (SHX).

The working process of the NOAHP system is described as follows.

Firstly, the open absorption process, which occurs in A1, is a main feature of the new system. It is also the main difference between an open absorption cycle and a close absorption cycle. The water vapor flows into the absorber A1 from outside in terms of moisture in the moist gas and is discharged to outside in terms of condensate at condenser (or directly outputted from generator G1 as hot steam), instead of circulating in the system. This is a main reason why the system is called open cycle absorption. In A1, the moist gas contacts directly with strong solution and the moisture in the moist gas is absorbed when the water vapor partial pressure of the strong solution is lower than that of the moist gas. Latent heat given off during the absorption process is transported to water in the heat exchanger, which is installed in A1.