Energy Conversion and Management 172 (2018) 391–401

Contents lists available at ScienceDirect

Energy Conversion and Management

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

A high-temperature hybrid absorption-compression heat pump for waste heat recovery

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ARTICLE INFO

Keywords:
Absorption-compression
Heat pump
Mixture working fluid
Cascade utilization
Low-grade waste heat

ABSTRACT

An absorption-compression heat pump is a promising way to recover low-temperature waste heat efficiently in industrial applications. In this paper, an advanced ammonia-water absorption-compression heat pump is proposed to recover the sensible heat of flue gas below 150 °C to generate saturated steam at 0.5 MPa (151.8 °C). The sensible heat is cascade utilized in the hybrid heat pump system. The high-temperature waste heat is recovered to generate pure ammonia vapor in the rectifier, and the low-temperature heat is used to evaporate the ammonia liquid. In the ammonia vapor compression process, the gas compression process is combined with a liquid compression process, leading to the clear decrease in power consumption. The simulation results indicate that the coefficient of performance and exergy efficiency of the proposed system reaches 5.49 and 27.62%, which is almost two times and 4.69% higher than that of the reference system, respectively. Subsequently, a sensitivity analysis is conducted to optimizing the key parameters, and the optimums values are obtained. Finally, an economic analysis is adopted to evaluate the economic performance of the proposed system. The payback period of the proposed system is 6.26 years compared to the reference system. This study may provide a new way to produce saturated steam by efficiently using the low-temperature waste heat.

1. Introduction

Nowadays, approximately 50% of industrial energy input is lost as waste heat [1], in which low-temperature (< 220 °C) waste heat accounts for approximately 60%. Meanwhile, steam is used extensively in industrial processes, such as chemical process [2] and food processing industry [3]. Saturated steam at the pressure of 0.41 MPa was used to dry Asian noodles [4]. The first autoclaved phosphogypsum (PG) for making the building materials was prepared with lower-pressure steam at 0.12 MPa while the second autoclaved PG was prepared with higher-pressure steam at 0.8 MPa [5]. It is estimated 30% of manufacturing industry energy consumption is used to steam generation [6]. Steam is usually generated by boilers or heat recovery steam generators (HRSG). However, the HRSG can only recover high-temperature waste heat, and low-temperature heat emit directly [7]. Generating industrial steam by recovering waste heat has great potential to reduce industrial energy consumption. Adsorption and absorption systems are the main technologies for low-temperature waste recovery. Usually adsorption systems are used to produce cooling energy [8]. However, absorption system can continuously generate heat besides cooling energy. Heat pump technology has proved promising and efficient for low-grade waste heat utilization [9]. Absorption heat pumps can increase the quantity of the heat by converting both high and low temperature heat supplied to the generator and evaporator into supplied water [10]. Liu et al. [11] developed a heat pump for heating and domestic hot water (50 °C) by recovering the waste heat of gas engine. The results indicated that the total heating capacity increase by 54.5%. Garimella [12] analyzed the single-effect AHP to provide conditioning and 54 °C hot water by recovering heat from a waste gas of 120 °C. The results reported that the system can produce 1.275 MW cooling and 3.573 MW heat with 2.26 MW waste heat input. Le et al. [13] investigated absorption heat pumps (AHP) to produce hot air of 50–100 °C for mobile wood chip drying. The results demonstrated that two-stage AHP must be used when the set point temperature of drying air is over 60 °C. Jeong et al. [14] carried out a numerical model to predict the transient performance of an absorption heat pump. This heat pump can produce heat water at a temperature of 69.4 °C by waste heat recovery. The results pointed out that a higher solution flow rate leads to a higher heating capacity but a lower COP. The absorption heat pump have a great advantage in increasing the quantity of the heat, and the

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https://doi.org/10.1016/j.enconman.2018.07.027
Received 2 March 2018; Received in revised form 6 July 2018; Accepted 8 July 2018
0196-8904/

Nomenclature

Abbreviations

ABS	absorber
AHEX	ammonia heat exchanger
AHPS	absorption heat pump subsystem
AP	ammonia pump
BOP	balance of the system, $
CHPS	compression heat pump subsystem
CIV	cash inflow value, $
COM	compressor
CON	condenser
COP	coefficient of performance
COV	cash outflow value, $
DES	desorber
EVA	evaporator
HRSG	heat recover steam generator
IHEX	internal heat exchanger
INC	the initial investment cost, $
LVS	liquid-vapour separator
MIX	mixer
NCF	the net cash flow value, $
NPV	the total net present value, $
OMC	the operation and maintenance cost, $
PBP	payback period, years
PC	partial condenser
REB	reboiler
REC	rectifier
SFP	steam splitter
SHEX	solution heat exchanger
SP	solution pump
TPC	the total cost, $
VAL	valve
VHEX	vapor heat exchanger
WHEX	water heat exchanger
WP	water pump

Symbols

a	year
E	exergy, kW
f	the inflation rate, %
h	specific enthalpy, kJ/kg
i	the interest rate, %
m	mass flow, kg/h
Q	heat, kW
s	specific entropy, kJ/kg K^{-1}
T	temperature, °C
W	power, kW
x	mass fraction, %
X	capacity
γ	the cost function exponent

generation temperature needed to be much higher than that of the supplied water. However, in some cases, the temperature of hot water demanded are higher than that of the waste heat. Such as, steam of temperature more than 150 °C is deadly demand in industries [15] and many existing waste heat are lower than that. Absorption-compression heat pump was developed for waste heat temperature upgrading use [16], in which the evaporator and the condenser of the vapor-compression cycle are replaced by a generator and an absorber.

The desorption and absorption processes in an absorption-compression heat pump are non-isentropic compared to the isentropic processes in a vapor compression heat pump, which means that the heat transfer entropy generation is decreased and the energy efficiency is increased. Brunin et al. [17] evaluated the working domains of some compression heat pumps (CHP) and a absorption-compression heat pump (ACHP). The results showed that the ACHP using NH_3-H_2O as working fluids can cover the whole working domain of the high temperature (80–120 °C) heat pumps with performance levels comparable. The absorption-compression heat pumps using NH_3–NaSCN solutions was studied in Tarique et al. [18], and the results indicated that the initial investment and running costs of the compressors were reduced greatly compared to that of the pure ammonia cycle. A single-stage absorption-compression heat pump using ternary working fluid was studied by Bourouis et al. [19]. The results presented that the ACHP system with ternary working fluid can upgrade thermal wastes at 80 °C up to temperatures between 120 and 150 °C. Meanwhile, there was an optimal pressure ratio under fixed thermal waste, upgrading temperature and desorber pressure.

Farshi et al. [20] connected two ACHP subsystems by a cascade heat exchanger for higher temperature lifts and compared the cascaded absorption-compression heat pump with several kinds of conventional heat pumps. The results indicated that the proposed cascaded system had advantages in compression ratio, temperature lifts and primary energy ratio. Zhou and Radermacher [21] substituted a solution heat exchanger in a single-stage absorption-compression heat pump with an internal desorbed/absorber heat exchanger. This system produced heating and cooling water at temperatures of 49 °C and 9 °C, respectively. In order to develop the experimental correlations of the heat transfer coefficient for ACHP application, Jung et al. [22] analyzed a hybrid absorption-compression heat pump with a brazing-type plate heat exchanger, which could process hot water above 80 °C. It is concluded that the aspect ratio had a positive effect on the heat transfer coefficient. In studies by Nordtvedt [23] and Kim et al. [24], a two-stage reciprocating ammonia compressor was introduced in the absorption-compression heat pump system. The system was designed to use hot water approximately 50 °C to simultaneously produce hot water above 90 °C and cooling water below 20 °C. To provide heat for even higher temperature process, Jensen et al. [25] evaluated the work domains of an absorption-compression heat pump when high-pressure NH_3 and a trans critical CO_2 compressor were used in the hybrid system, which can deliver heat supply at a temperature of 135 °C with economic benefits compared with gas combustion. The simulation results indicated that the heat supply temperature above 150 °C could be obtained when the compressor discharge temperature constraints were relaxed.

The temperature of heat generated by heat pumps is lower than 150 °C in the previous literatures, the main barrier of the absorption-compression heat pump is the limitation of the compressor discharge temperature [26]. Considering the negative effect of high discharge temperature on the compressor performance and reliability, Wu et al. [9] controlled the highest discharge temperature below 100 °C. A reciprocating piston compressor was used in the experimental work of the ACHP by Wu et al. [27] and the highest compressor discharge temperature was limited at 150 °C. Chamoun et al. [28] developed a new twin screw compressor for new high temperature heat pump use and pointed out the need for water injection to avoid compressor failure at a maximum temperature of 160 °C and improve its efficiency. The discharge temperature for the unmodified compressors is set to 170 °C in the study of Jonas et al. [29]. To reduce wear and excess degradation, the compressor discharge temperatures were limited to 180 °C in several papers [30] according to Nekså et al. [26].

By now, the temperature of heat generated by the heat pumps is lower than 150 °C and little system can generate steam. The aim of this