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New hybrid absorption–compression refrigeration system based on cascade use of mid-temperature waste heat

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HIGHLIGHTS

- A hybrid absorption–compression refrigerator powered by waste heat is proposed.
- The input heat is used in cascade in the two subsystems.
- System COP is 41.9% higher than that of a simple ammonia absorption refrigerator.
- The performance improvement of the new system is confirmed by exergy analysis.

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ABSTRACT

This paper proposes a new hybrid absorption–compression refrigerator powered by mid-temperature waste heat. The system uses an ammonia–water binary mixture as working fluid. It consists of a heat-driven compression refrigeration subsystem and an absorption refrigeration subsystem. These refrigeration subsystems share the same condenser and evaporator. Mid-temperature waste heat is first used in the power and compression refrigeration subsystem to compress ammonia vapor from the evaporator to the condenser. Then the low-temperature waste heat is used in the absorption refrigeration subsystem to preheat the strong solution before entering the rectifier. The exhaust vapor from the ammonia–steam turbine is introduced into the rectifier of the absorption refrigeration subsystem to generate pure ammonia. The new system exhibits superior performance because of the cascade use of waste heat in the two subsystems. With the same waste heat input, the proposed system generates 46.7% more cooling energy than does a conventional ammonia–water absorption refrigerator. The system can serve as an efficient approach to producing cooling with waste heat.

1. Introduction

Energy efficiency has received heightened interest with the increasing attention paid to climate change and environmental pollution. The current practice is burning large amounts of fossil fuels to provide process heating, and then releasing mid-temperature flue gas, as waste, into the environment. Energy efficiency can be improved by using an absorption–refrigeration system (ARS) to convert waste heat into useful cooling energy [1,2]. The application of ARSs reduces the electricity consumption of conventional vapor compression refrigerators, but such traditional compression systems still dominate the market. Promoting the use of ARSs necessitates the improvement of system performance [3,4].

In ARSs, two working fluids are used as refrigerant and absorbent. Water–lithium bromide (H_2O–LiBr) and ammonia–water (NH_3–H_2O) are commercially available throughout the world. ARSs that use H_2O–LiBr as working fluid are employed in air-conditioning and chilling applications. Researchers have proposed multiple-effect absorption refrigeration cycles, such as double- and triple-effect absorption refrigeration cycles, to improve ARS performance [4]. ARSs that use NH_3–H_2O as working fluid are generally employed in large industrial applications that require low temperatures for process cooling because the freezing point of NH_3 is −77 °C. The first NH_3–H_2O ARS was introduced by Ferdinand Carre in 1859 [4]. The coefficient of performance (COP) of a conventional single-stage NH_3–H_2O ARS is approximately 0.5 [5–7]. The generator/absorber heat exchanger (GAX) cycle was proposed by Altenkirch and Tenckhoff to enhance the ARSs' performance [4,5]. Heat transfer processes were investigated based on pinch-point analysis methodology, and

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Nomenclature

E	exergy (kW)
h	specific enthalpy (kJ kg^{-1})
m	mass flow rate (kg h^{-1})
p	pressure (bar)
Q	heat duty (kW)
s	specific entropy (kJ kg^{-1} K^{-1})
t	temperature (°C)
T	temperature (K)
W	power (kW)
x	ammonia mass concentration
η_{ex}	exergy efficiency (%)

Abbreviations

ABS	absorber
ARS	absorption refrigeration system
C	cooling
CON	condenser
COP	coefficient of performance
EVA	evaporator
f	flue gas
GAX	generator/absorber heat exchanger
HE	heat exchanger
HP	high-pressure pump
HRVG	heat recovery vapor generator
LP	low-pressure pump
MIX	mixer
NCOM	NH_3 compressor
PC	partial condenser
REB	reboiler
REC	rectifier
SHE	subcooling heat exchanger
TUR	turbine

some absorption heat was effectively used to reduce the required heat input to the generator [8]. Zheng et al. [9] reported that the first and second law efficiencies of the GAX cycle are 31% and 78% higher than those of the single-effect ARS, respectively. Kang et al. [10] developed an advanced GAX cycle for the use of waste heat, so that the outlet temperature of the generator can be reduced to 172 °C, with a COP higher than that of a standard GAX cycle.

Various components, such as an ejector or compressor, were installed in the absorber inlet to overcome the limitations presented by the low absorber temperatures in ARSs [5,11]. Kang et al. [12] performed a parametric study on four different advanced hybrid GAX cycles that achieve high COPs and low evaporator or generator temperatures, as well as produce hot water. Ramesh Kumar and Udayakumar [13] compared the performance levels of a GAX with and without a compressor in the absorber inlet for air-conditioning applications. They found that the former achieves an average of 30% higher COP than does the latter. Zhao et al. [14] studied two combined absorption–compression refrigeration cycles using both the work and heat output from an engine. Balamuru et al. [15] used NH_3–H_2O–NaOH mixture as working fluid to help remove ammonia from the liquid solution. They concluded that salting out decreases the operating temperature of the generator while improving cycle performance.

Given the considerations above, this study aims to (1) propose a new absorption–compression hybrid refrigeration system to use the sensible heat of flue gas more efficiently; (2) investigate the thermodynamic performance of the hybrid refrigeration system; (3) identify the advantages of the hybrid system.

2. Description of the proposed hybrid and reference systems

2.1. Proposed hybrid system

Fig. 1 shows the flowchart of the hybrid absorption–compression refrigeration system. It consists of a heat-driven compression refrigeration subsystem and an absorption refrigeration subsystem, which are integrated by an absorber (ABS) and a rectifier (REC).

High-temperature flue gas (25) successively goes into a heat recovery vapor generator (HRVG) and a heat exchanger (HE3) to heat the working fluids of the compression refrigeration subsystem. The strong solution (1) that comes from the absorber is split into two streams. Stream 2 is pressurized by a high-pressure pump (HP) and preheated in a heat exchanger (HE1). It then flows into the HRVG, where it is converted into superheated vapor (5). The high-temperature and high-pressure vapor (mixture of ammonia and steam) expands through a turbine (TUR), and the exhaust vapor of the turbine (6) is ducted directly to the bottom of the rectifier. The turbine directly drives an ammonia compressor (NCOM) to compress a portion of ammonia vapor (23) from the evaporator (EVA) to the condenser (CON). In the absorption refrigeration subsystem, the strong solution from the absorber (7) is pumped and then successively preheated in heat exchangers (HE2 and HE3). It then goes into the rectifier with the exhaust vapor of the turbine to generate pure ammonia and weak solution (11). A portion of the ammonia vapor is condensed into liquid state in a partial condenser (PC) and refluxed into the rectifier. After condensation, the liquid refrigerant (17) is subcooled in a subcooling heat exchanger (SHE) and sequentially throttled by a valve (V1) before it evaporates for refrigeration in the evaporator. The low-temperature and low-pressure ammonia vapor (20) from the evaporator is sent to the absorber and the ammonia compressor after it cools the liquid ammonia in the subcooling heat exchanger (SHE). After the cooling process in the heat exchangers (HE1 and HE2), the weak solution stream (13) is throttled to a low pressure by a valve (V2) and then ducted to the absorber, where the ammonia vapor is absorbed (22). The high-pressure (HP) and low-pressure (LP) pumps are also driven by the turbine.

2.2. Reference system

A basic NH_3–H_2O ARS is set as the reference system. Fig. 2 shows the system layout. High-temperature flue gas is introduced into a reboiler (REB) of a rectifier to generate pure ammonia vapor. The ammonia vapor is sequentially converted into a liquid refrigerant in a condenser, subcooled in a subcooling heat exchanger, and throttled by a valve before it evaporates for refrigeration in the evaporator. The low-pressure ammonia vapor is then absorbed by a stream of weak solution generated in the reboiler. The strong solution at the outlet of the absorber is pumped into the rectifier after being heated in a heat exchanger (HE).

3. System evaluation

3.1. Evaluation criteria

COP and exergy efficiency are used as the criteria for evaluating system performance. COP is defined as the cooling capacity output (Q_C) divided by the sum of the heat absorbed by the refrigerator from the flue gas (Q_h) and power input (W_P):