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Research paper

Energy and exergy investigation of a hybrid refrigeration system activated by mid/low-temperature heat source

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HIGHLIGHTS

- Proposed an ammonia–water hybrid refrigeration system activated by flue gas.
- The flue gas heat is utilized in cascade to generate refrigerant vapor.
- The compressor is driven by the power generated by the turbine in the system.
- Energy and exergy analyses illustrate the energy utilization and exergy distribution of the system.
- Investigated the effects of key parameters on the system performance.

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ABSTRACT

This study proposes a hybrid refrigeration system activated by mid/low-temperature sensible heat source with ammonia–water (NH_3–H_2O) binary mixture as working fluid. The heat source is utilized in cascade in the hybrid system. This heat source is used to generate a superheated NH_3–H_2O mixture vapor, which is used successively in the power generation and compression subsystem and in the absorption and rectification subsystem to produce refrigerant vapor. Energy and exergy analysis results show that the Coefficient Of Performance, System Coefficient Of Performance, and exergy efficiency of the proposed system in the base case are 0.722, 0.485, and 23.1%, respectively. Effects of turbine inlet pressure, turbine outlet pressure, and solution concentration in the power generation subsystem on system performance are examined. This study provides a new refrigeration method to effectively utilize mid/low-temperature sensible heat.

1. Introduction

Heat-activated Absorption Refrigeration Systems (ARSs) have received increasing attention and are considered a promising refrigeration technology because of their benefits in both energy and environment. ARSs can be driven by mid/low-temperature heat sources, such as engine flue gas, solar energy, geothermal energy and nuclear energy, with very small electricity consumption. Compared with vapor compression cycles, absorption systems can decrease primary energy consumption significantly [1–3]. ARSs that use ammonia–water (NH_3–H_2O) as working fluid are generally used in industrial applications that require a cooling energy below 0 °C, such as in food storage and oil refining, because the freezing temperature of NH_3 is -77 °C.

The first NH_3–H_2O ARS was invented by Ferdinand Carré in 1859 [4]. The Coefficient Of Performance (COP) of a conventional single-stage NH_3–H_2O ARS is approximately 0.5 [5–7]. Edwin and Sekhar investigated that the feasibility of using local available energy to operate the NH_3–H_2O absorption cooling system for the food preservation in India [8]. The system efficiency and the economic performance of the cooling facility with different energy sources were analyzed. Results show that the use of biomass is beneficial to the thermodynamic performance, while the use of biagas is more economical than other sources. Altenkirch and Tenckhoff proposed the Generator/Absorber heat eXchanger (GAX) cycle to enhance the performance of ARS [3,5]. Hanna et al. optimized the heat transfer processes of a GAX with the use of a pinch-point analysis methodology [9]. Zheng et al. reported that the COP and the exergy

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Nomenclature

A	energy level
ABS	absorber
ARS	Absorption Refrigeration System
COM	compressor
CON1	condenser 1
CON2	condenser 2
COP	Coefficient Of Performance
CW	cooling water
E	exergy, kW
E_D	exergy destruction and loss, kW
EUD	Energy-Utilization Diagram methodolody
EVA	evaporator
GAX	Generator/Absorber heat eXchanger
H	enthalpy, kW
h	specific enthalpy, kJ kg^{-1}
HP	high-pressure pump
HRVG	heat recovery vapor generator
LP	low-pressure pump
m	mass flow rate, kg h^{-1}
p	pressure, bar
Q	energy, kW
REB	reboiler of the rectifier
REC	rectifier
R_P	compression ratio
r_D	exergy destruction ratio
S	entropy, kJ K^{-1}
SCOP	System Coefficient Of Performance
SHEX	solution heat exchanger
SPL1	splitter 1
SPL2	splitter 2
SUBC	subcooler
s	specific entropy, kJ kg^{-1} K^{-1}
T	temperature, K
TUR	turbine
t	temperature, °C
V1	throttle valve 1
V2	throttle valve 2
VHEX	vapor heat exchanger
W	power, kW
x	ammonia mass concentration
η_{COM}	isentropic efficiency of the compressor
η_{ex}	exergy efficiency

Subscripts

0	ambient state
1, 2, …, 24, G1, G2	stream number in the system
C	cooling
f	fuel
j	component number
in	input
out	output

efficiency of a GAX cycle are higher than a single-effect ARS by 32% and 78%, respectively [10]. Kang et al. developed an advanced GAX cycle to utilize low-temperature heat, in which the generator outlet temperature could be reduced to 172 °C with a higher COP than that of a standard GAX cycle [11]. Jawahar and Saravanan developed an experimental setup of air-cooled modified GAX system [12]. Test results showed that 15 kW of internal heat was recovered; a fuel COP of 0.61 was obtained at generator and evaporator temperatures of 120 °C and 2 °C, respectively, as well as a maximum cooling capacity of 9.5 kW. Gómez et al. constructed a GAX cooling system with rated capacity of 10.6 kW, in which the thermal oil was used as heat source [13]. The experimental results were also used to validate the theoretical research results. The internal heat recovery rate can reach about 55% with respect to the total heat supplied to the generator. García-Arellano et al. pointed out that the dynamic response of the GAX system is very important to the system performance [14]. They carried out a dynamic analysis of the evaporator in a GAX cooling system, and concluded that the application of transfer functions is a significant method in the dynamic analysis of the GAX cooling system.

Researchers also introduced some components into the system, such as a compressor and an ejector, to improve performance [5,15–17]. Kang et al. developed four different advanced hybrid GAX cycles with different compressor locations in the system to achieve a high COP, a low evaporator temperature, a low generator temperature, and hot water production, respectively [16]. Ramesh Kumar and Udayakumar compared the performance levels of a hybrid GAX cycle with a compressor at the absorber inlet and a conventional GAX cycle for air-conditioning applications [17]. They found that the hybrid GAX cycle has an average COP that is 30% higher than the conventional GAX cycle. Mehr et al. investigated the thermodynamic and economic performance of a standard GAX absorption cycle and a hybrid GAX absorption cycle [18]. Results show that the hybrid GAX cycle has a better thermodynamic performance and a higher unit product cost. The cost of unit product for the hybrid GAX cycle is 13.45% higher than that of the standard GAX cycle.

Some absorption heat is utilized effectively in a GAX cycle to reduce the required heat input to the generator. Most studies to date on this topic have focused on the recovery and utilization of inner waste heat of the refrigeration cycle. Few have considered that the utilization of the heat source is unreasonable when this heat source is mid-temperature sensible heat (e.g., flue gas from engine, industrial gas turbine or helium turbine in the high-temperature gas-cooled nuclear reactor cycle). The heat source temperature is much higher than the required temperature in the generator, and the large temperature difference between the heat source (~400 °C) and the working solution (~150 °C) leads to major exergy destruction in the generator or reboiler. In this regard, improving the performance of a refrigeration system further through the development of a new method to efficiently use the flue gas has considerable potential.

The authors have made a large amount of research on the NH_3–H_2O based thermodynamic systems both theoretically and experimentally [19–22]. In this study, a new hybrid refrigeration system with NH_3–H_2O working pairs is developed to efficiently use the mid-temperature flue gas. The thermodynamic performance of the proposed system is investigated in detail from both energy and exergy aspects. Effects of turbine inlet pressure, turbine outlet pressure, and solution concentration in the power generation subsystem on system performance are also examined.

2. Configuration of the proposed hybrid refrigeration system

Fig. 1(a) shows the configuration of the proposed hybrid refrigeration system. The thermodynamic process of the hybrid