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First law analysis of a novel double effect air-cooled non-adiabatic ammonia/salt absorption refrigeration cycle

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ABSTRACT

This paper thermodynamically analyzes an air-cooled type double effect absorption refrigeration system using ammonia/lithium nitrate and ammonia/sodium thiocyanate solutions as working pairs and driven by high temperature heat source such as waste heat energy, innovatively, an air-cooled type non-adiabatic absorber is implemented in the system to improve the cycle performance. Comparing to the single effect absorption refrigeration system, the double effect system is designed not only to directly and efficiently utilize high temperature waste heat energy for cycle performance improvement, but also to greatly extend the application occasion to high ambient temperature condition. Parametric analysis of the present system show that COP of the double effect system is 30–60% higher than the single effect system under air cooling working condition and the high pressure generating temperature of the double effect system can be extended to as high as 220 °C. Influences of high pressure generator temperature, low pressure generator temperature, absorber outlet solution temperature as well as other system working parameters on cycle performance are numerically simulated and parametric optimization is provided in the present model. Cycle performance comparison of $NH_3/LiNO_3$ system with $NH_3/NaSCN$ system has been carried out. According to the simulation results, COP of $NH_3/NaSCN$ system is found to be 10–15% higher than that of $NH_3/LiNO_3$ system in evaporating temperature range of $-10\,^{\circ}C < T_e < 5\,^{\circ}C$. However in low evaporating temperature conditions, $T_e \leqslant -10\,^{\circ}C$, $NH_3/LiNO_3$ systems are found to be more competitive than that of $NH_3/NaSCN$ system. The main concern of the present study is that implementation of non-adiabatic absorbers in air-cooled type double effect ammonia/salt absorption refrigeration systems is essential, and only under non-adiabatic absorption conditions can the double effect ammonia/salt system realize miniaturization.

1. Introduction

Comparing to the traditional H_2O–LiBr absorption refrigeration system, besides the unique advantages in renewable energy (solar energy [1], biomass energy [2,3] and geothermal energy [4]) utilization and waste heat energy recovery [5], ammonia-based working fluid absorption refrigeration attracts increasingly worldwide interest in recent years due to its low evaporating temperature and the lack of problems under vacuum conditions. Miniaturization is essential for application extension of the absorption refrigeration systems and air-cooled absorption will be the key technology for the absorption systems to realize miniaturization. $NH_3/NaSCN$ and $NH_3/LiNO_3$ absorption refrigeration cycles are considered to be the most potential ones for application in air-cooled type small capacity refrigeration units. Another aspect, for the refrigerant, despite its low toxicity, ammonia is known to be an environment-friendly natural refrigerant with zero ODP and low GWP values. For the absorbent, according to Farshi et al. [6], $LiNO_3$ and NaSCN are respectively a slightly toxic and moderately toxic material, both $LiNO_3$ and NaSCN are noncombustible and stable. If appropriate protective measures are taken, the working fluids as well as the system are considered to be safe.

The energy efficiency of traditional air-cooled type absorption refrigeration cycle is low due to the limited absorption capability of the adiabatic absorber used by the air-cooled system. The traditional non-adiabatic absorber such as the falling film absorbers, commonly cooled by water, are of higher absorption capacity than the adiabatic ones, however in many application occasions especially small cooling capacity application occasion, water cooling is restricted or inconvenient. Hence, applying high efficiency absorbers in the air-cooled type absorption refrigeration units will be the key factors for the system performance improvement.

Application of absorption refrigeration cycles in high temperature heat source such as waste heat energy recovery has been

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Nomenclature

P	pressure, kPa
T	temperature, K or °C
w	mass concentration, kg NH_3/kg solution or kg salt/kg solution
C_p	specific heat at constant pressure, kJ/(kg K)
h	specific enthalpy, kJ/kg
m	mass flow rate, kgs^{-1}
Q	heat flow rate, kW
f	Circulation ratio
a	gas-emission scope
$\Delta T_{HPG.LPG}$	difference of condensing temperature of ammonia generated by high pressure generator and the generating temperature of solution in low pressure generator, °C
$Q_{LPG.recover}$	energy recovered by low pressure generator, kW
COP	coefficient of performance
W_{SP}	power of the solution pump, kW

Greek symbols

η_{HX}	solution heat exchanger effectiveness
η_{AB}	absorber effectiveness
ρ	density, kg/m^3

Subscript

NH_3	ammonia
salt	sodium thiocyanate or lithium nitrate
sat	saturated
l	liquid
HPG	high pressure generator
LPG	low pressure generator
HX1	solution heat exchanger 1
HX2	solution heat exchanger 2
AB	absorber
max	maximum
e	evaporator
air	air cooler
k	condenser
subcool	subcooling
superheat	superheat
hot	hot end of the heat exchanger
cold	cold end of the heat exchanger

discussed by some investigators [7–9]. Under many circumstances, industrial waste heat energy is provided in the form of high temperature exhaust gas or steam. For example, temperature of the exhaust gas from an electric power generating gas turbine can be as high as 508 °C [8], waste heat released by an internal combustion engine will be at a temperature ranging from 420 °C to 535 °C [10]. When used to driven the single effect system, such high temperature heat source will easily cause over high generating temperature and thereby the risk of crystallization rises [11] under air cooling conditions. Besides that, large temperature difference between heat source and the solution in the generator increases the irreversible loss of the total waste heat recovery process. To overcome these drawbacks of the air-cooled type single effect ammonia/salt absorption system, an air-cooled type double effect ammonia/salt absorption refrigeration system is proposed by the present paper.

Thermodynamic analyses and performance evaluations of single effect ammonia/salt absorption refrigeration cycles were early carried out by many researchers [12–21], recently, studies focusing on this field have been intensified. Táboas et al. [22] thermodynamically analyzed and compared system performance of an single effect absorption refrigeration cycle using NH_3–H_2O, NH_3–$LiNO_3$ and NH_3–($LiNO_3$ + H_2O) as working fluids and driven by waste heat energy of jacket water in diesel engines of fishing ships. NH_3–$LiNO_3$ solution is known to be very viscous which reduces efficiency of the absorber and heat exchangers of the system. Addition of water in the binary NH_3–$LiNO_3$ mixture for the purpose of heat and mass transfer enhancement of heat exchangers and absorber was proposed by Ehmke [23] and Bokelmann [24] and recently evaluated by Táboas et al. [22]. The NH_3–($LiNO_3$ + H_2O) absorption system can operates without a rectifier and the system performance of which approximates to that of NH_3–$LiNO_3$ system, and Táboas concluded that the NH_3–($LiNO_3$ + H_2O) absorption system was adapted for use in fishing ships. However, the problems of temperature glide and water accumulation in the evaporator of the NH_3–($LiNO_3$ + H_2O) system still need to be solved before practical application. Passive intensification techniques of adding carbon nanotubes (CNTs) in the NH_3–$LiNO_3$ solution has been studied by some investigators [25–27]. With a small CNTs mass concentration in the NH_3–$LiNO_3$ solution, thermal conductivity of NH_3–$LiNO_3$ solution increase 6.0% to 7.5% and heat transfer coefficients of which increases around 39%.

Regarding the recently experimental study of ammonia/salt refrigeration cycles, Hernández-Magallanes et al. [28] reported experimental results of a single effect NH_3–$LiNO_3$ absorption refrigeration system which was adapted to be used for food conservation and air conditioning. The system coefficient of performance obtained by Hernández-Magallanes' experiment was as high as 0.7 under water cooling condition when the heat source with a temperature ranging from 85 °C to 105 °C was used to drive the system. Almost at the same time, an air-cooled type NH_3–$LiNO_3$ absorption cooling prototype was designed and built by Llamas-Guillén et al. [29]. The coefficient of performance obtained by Llamas-Guillén's prototype was around 0.3–0.4 when the system operated at ambient temperature ranging from 25 °C to 35 °C with the evaporator temperature below 10 °C. Llamas-Guillén's prototype turned out to be reliable and stable and encountered no risk of crystallization. In addition, both water-cooled and air-cooled pre-industrial prototypes of NH_3–$LiNO_3$ absorption chillers were built and experimentally studied by Zamora et al. [30]. For Zamora's air-cooled prototype, 64% of the nominal cooling capacity at 35 °C was still able to be provided by the system at an ambient temperature of 41 °C, this result indicated that the NH_3–$LiNO_3$ absorption refrigeration system was well adapted for practical application under air cooled condition.

For the double effect ammonia/salt absorption refrigeration system. System performance assessment and comparison of single effect, half effect, double effect in series and triple effect absorption refrigeration cycle with NH_3–$LiNO_3$ solution was carried out by Domínguez et al. [31], coefficient of performance of a double effect NH_3–$LiNO_3$ absorption system obtained by Domínguez was as high as 1.12 with a generator temperature higher than 140 °C, which was much higher than that of a single effect system. Thermodynamic analysis of a solar driven double effect NH_3/$LiNO_3$ absorption refrigeration cycle for sub-zero temperatures had been carried out by Vasilescu and Ferreira [32], in Vasilescu's study, even driven by solar energy, the working parameters of the double effect system are acceptable.