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Thermodynamic analysis of a novel air-cooled non-adiabatic absorption refrigeration cycle driven by low grade energy

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ABSTRACT

An air-cooled type absorption refrigeration cycle using ammonia–lithium nitrate and ammonia–sodium thiocyanate solutions as working fluids are thermodynamically studied in this paper. In the case of many occasions especially small cooling capacity occasion where water cooling is restricted or inconvenient, application of conventional adiabatic absorbers in air-cooled type absorption refrigeration system has been studied by many investigators. Comparing to the adiabatic absorber, a novel air-cooled non-adiabatic absorber is applied to the absorption refrigeration system in this study to improve system performance. It is shown that, system performance has a significant improvement when temperatures of rich ammonia solution at the outlet of absorber decrease under the effect of the heat dissipation capacity of the non-adiabatic absorber. Another advantage is that heat load of the system heat exchangers including generator, solution heat exchanger and air-cooler, decreases with the solution temperature decrease at the outlet of the absorber under the same system cooling capacity condition, which brings benefits to the system cost reduction. Variation of system performance and other system operation parameters with generator temperature, absorption temperature and absorption efficiency has been carried out. Effects of the self-circulation flow rate of the absorber have been studied. A datasheet of system operation parameters has been proposed.

1. Introduction

Low grade energy such as solar energy [1], biomass energy, geothermal energy [2] and industrial waste heat energy [3] can be directly utilized in absorption refrigerators. Small capacity and air-cooled type absorption refrigerators have attracted increasingly worldwide interest in recent years. However, up to now no small capacity absorption refrigeration alternatives are available for traditional vapor compression refrigeration systems. Researchers focus on this area in order to improve the system efficiency and to make it possible for practical application. Among those available research results [4], the ammonia–LiNO3 and ammonia–NaSCN absorption refrigeration cycles are considered to be the most possible ones for application in small capacity refrigeration units. The ammonia–LiNO3 and ammonia–NaSCN absorption refrigeration systems can also provide cooling capacity at evaporating temperature of $T_e < 0$ d operate normally without a rectifier for refrigerant purification comparing to the water–LiBr systems and ammonia–water systems, respectively. The superiorities of the air-cooled type absorption refrigerators are due to their wide applicable occasions and simple structures comparing to the water-cooled ones. There is a technology obstacle on system performance improvement for air-cooled type units and much research [5,6] has been devoted on the application and performance improvement of the air-cooled type absorption refrigeration cycles. 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. Under these situations, without water, air-cooled type absorption refrigeration units applying adiabatic absorbers have been extensively studied in recent years. The absorption efficiency of adiabatic absorber is low due to the temperature rise caused by absorption heat, hence, applying high efficiency absorbers in the air-cooled type absorption refrigeration units will be the key factor for the system performance improvement.

Thermodynamic analyses of ammonia/LiNO3 and ammonia/NaSCN absorption refrigeration cycle are based on the working fluids thermophysical property data or correlations, however, up to now no authoritative data are available. Most research work in this area was carried out based on experimental data and regression correlations presented by investigators. For vapor pressure of ammonia/NaSCN solutions, Blytas and Daniels [7] presented

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Nomenclature

COP	coefficient of performance
P	pressure, kPa
T	temperature, K or °C
C_p	specific heat at constant pressure, kJ kg^{-1} K^{-1}
w	mass concentration, kg NH_3/kg solution or kg salt/kg solution
Q_s	integral heat of solution, kJ mol^{-1}
n_0	amount of substance ratio of solvent and solute
M	molar weight, kg mol^{-1}
h	specific enthalpy, kJ kg^{-1}
m	mass flow rate, kg s^{-1}
V	volume flow rate, m^3 h^{-1}
Q	heat transfer rate, kW
η_{AB}	efficiency of absorber
η_{HX}	effectiveness of solution heat exchanger
f	circulation ratio
a	gas-emission scope
NaSCN	sodium thiocyanate
LiNO3	lithium nitrate
NH3	ammonia

Subscript

e	evaporator
g	generator
a	absorber
air	air cooler
k	condenser
$NH3$	ammonia
$NaSCN$	sodium thiocyanate
HX	solution heat exchanger
sat	saturated liquid solution
$salt$	sodium thiocyanate or lithium nitrate
act	actual

experimental results of vapor pressure in ammonia mass concentration range of $0.3 \leqslant w_{NH3} \leqslant 0.73$ temperature range of $-20\,°C \leqslant T \leqslant 90\,°C$. Infante Ferreira [8] regressed these experimental data and gave a correlation equation. Since air-cooled type ammonia–NaSCN systems generally operate at high condensing pressure, the generator temperature may exceed 100 °C and Infante Ferreira's [8] correlation will cause deviations in this situation. Chaudhari et al. [9] presented the latest vapor pressure experimental data of ammonia–NaSCN solutions in a wide range of ammonia mass concentration as well as temperatures, however, the correlation equation coefficients provided by Chaudhari et al. [9] appear to be inaccurate when the calculation results from Chaudhari's correlation are compared to the Chaudhari's experimental data. A more accurate correlation needs to be regressed from the experimental data. The specific enthalpy of ammonia/salt solutions can be calculated from integral heat of solution data and heat capacity data. Blytas and Daniels [7] presented ammonia/NaSCN integral heats of solution at 0 °C in ammonia mass concentration range of $0.53 \leqslant w_{NH3} \leqslant 0.97$, Infante Ferreira [8] regressed these experimental data with a high degree polynomial model. The actual mass concentration of ammonia in the generator of an air-cooled type ammonia/NaSCN systems is around 0.4, which is far beyond the experimental data range. There will be significant deviations caused by high degree polynomial model when calculation points are out of the source data range. A more appropriate correlation model should be proposed for integral heat of solution prediction. Chaudhari et al. [9] presented the latest heat capacity experimental of ammonia/NaSCN in the ammonia mass concentration range of $0.5 \leqslant w_{NH3} \leqslant 1.0$ and temperature range of $30\,°C \leqslant T \leqslant 90\,°C$ as well as a correlation equation. Blytas and Daniels [7] and Sargent and Beckman [10] presented ammonia/NaSCN solution heat capacity data in temperature range of $0°C \leqslant T \leqslant 25\,°C$ and $30\,°C \leqslant T \leqslant 110\,°C$, respectively. Infante Ferreira's [8] correlation does not coincide well with all these experimental data.

For the thermophysical properties of ammonia/LiNO3 solutions, many available results can be found. Blytas et al. [11] presented vapor pressure of ammonia/LiNO3 in ammonia mass concentration range of $0.33 \leqslant w_{NH3} \leqslant 1.0$. Aggarwal and Agarwal [12] experimentally extended the thermophysical property data to a temperature range of −25–156 °C. Libotean et al. [13,14] presented the latest thermophysical property experimental data and correlation equations of ammonia/LiNO3 solution in a temperature range of $293.15\,K \leqslant T \leqslant 353.15\,K$. Contrast selection should be carried out to make sure the correlation equations are applicable for thermodynamic analysis of air-cooled type ammonia/LiNO3 absorption refrigeration systems.

System performance evaluations on ammonia/NaSCN and ammonia/LiNO3 absorption refrigeration systems had been carried out in the past decades. Sargent and Beckman [10] theoretically studied the NH3/H2O and NH3/NaSCN systems and concluded that NH3/NaSCN system was superiority both in performance and structure compare with that of NH3/H2O system. Sun [15] compared the performance of NH3/H2O, NH3/LiNO3 and NH3/NaSCN absorption refrigeration system and concluded that the working pairs of NH3/LiNO3 and NH3/NaSCN were available alternatives for NH3/H2O systems, another conclusion from Sun was that the performance of NH3/salts system was better than that of NH3/H2O system. Best et al. [16–18] carried out the thermodynamic design data analysis of ammonia/LiNO3 absorption refrigeration systems, detailed system performance parameters were obtained and compared under various operating conditions. Antonopoulos [19] predicted the hour-by-hour performance of solar-driven NH3/LiNO3 and NH3/NaSCN absorption heat pumps using local climatological data, and the results showed that both NH3/LiNO3 and NH3/NaSCN systems were suitable for use in Athens.

Recently, thermodynamic analyses of ammonia/NaSCN and ammonia/LiNO3 absorption refrigeration systems have been intensified. Zhu and Gu [20] studied a absorption refrigeration system using NH3/NaSCN as working solution and found that the COP of NH3/NaSCN system is about 10 percent higher than the ones for the NH3/H2O system working at the same conditions. Abdulateef et al. [21] analyzed the NH3/H2O, NH3/NaSCN and NH3/LiNO3 absorption refrigeration cycles, and comparison of system COP values vs generator temperature, evaporator temperature, condenser temperature and absorber temperature of the three cycles were illustrated. Rivera and Rivera [22] developed a mathematical model to simulate the NH3/LiNO3 system operation performance with local meteorological data, refrigeration efficiency in different seasons was exhibited and compared. Moreno-Quintanar et al. [23] experimentally and comparatively studied a solar-driven intermittent absorption ice producer working with NH3/LiNO3 and NH3/LiNO3/H2O mixtures, the results showed that the high viscosity and low thermal conductivity of NH3/LiNO3 solutions was a disadvantage of the refrigeration system. Farshi et al. [24] recently studied and compared the NH3/LiNO3 and NH3/NaSCN cycle thermodynamically using both the first and second law, operation