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Thermodynamic performance optimization of the absorption-generation process in an absorption refrigeration cycle

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ABSTRACT

The absorption refrigeration cycle is a basic cycle that establishes the systems for utilizing mid-low temperature heat sources. A new thermal compressor model with a key parameter of boost pressure ratio is proposed to optimize the absorption-generation process. The ultimate generation pressure and boost pressure ratio are used to represent the potential and operating conditions of the thermal compressor, respectively. Using the proposed thermal compressor model, the operation mechanism and requirements of the absorption refrigeration system and absorption-compression refrigeration system are elucidated. Furthermore, the two typical heat conversion systems are optimized based on the thermal compressor model. The optimum boost pressure ratios of the absorption refrigeration system and the absorption-compression refrigeration system are 0.5 and 0.75, respectively. For the absorption refrigeration system, the optimum generation temperature is 125.31 °C at the cooling water temperature of 30 °C, which is obtained by simple thermodynamic calculation. The optimized thermodynamic performance of the absorption-compression refrigeration system is 16.7% higher than that of the conventional absorption refrigeration system when the generation temperature is 100 °C. The thermal compressor model proposed in this paper is an effective method for simplifying the optimization of the thermodynamic systems involving an absorption-generation process.

1. Introduction

Energy-efficient and renewable energy technologies are being developed to reduce the world's dependency on fossil fuels and relieve environmental problems, such as global warming and air pollution. The majority of thermal energy exists in the form of mid-low temperature heat sources [1]. There are various surplus heat sources in industrial fields, such as steelworks, cement plants, food processing factories and engine exhaust gas [2]. Moreover, solar energy and geothermal energy are generally between 100 °C and 400 °C [3]. Taking full advantage of mid-low temperature heat sources is of great importance for reducing the burning of fossil fuels. Absorption refrigeration is one of the promising technologies that can be driven by surplus heat, solar energy and so on [4]. Furthermore, absorption refrigeration typically uses environmentally friendly working fluids without global warming penitential or ozone depletion potential [5].

Absorption refrigeration was first proposed in 1777 [6]. Water-sulfuric acid was adopted as the working pair at that time. In 1859, French scientist Ferdinand Carre invented the first continuous-mode absorption refrigeration unit using an ammonia-water solution. A US patent was issued for this machine in 1860 for ice making and food storage [7]. In 1911, Altenkirch and Tenckhoff introduced an absorption refrigeration cycle with a generator/absorber heat exchanger (GAX), in which heat from the absorber can be transferred to the generator to reduce the generation heat load [8]. In 1945, an American company named Carrier invented the first lithium bromide/water absorption refrigerator [9]. A few years later, the double-effect absorption refrigeration cycle was introduced [10,11]. The most common working fluids for absorption refrigeration cycles are water-lithium bromide ($H_2O/LiBr$) solution and ammonia-water (NH_3/H_2O) solution. $H_2O/LiBr$ absorption chillers are widely used for their high coefficient of performance. The ammonia-water absorption refrigerator is popular due to no danger of crystallization and its ice-making ability. Although various configurations of the absorption refrigeration cycle (ARC) have been developed so far [4], the simple cycle is still the most practical and popular one because of operation and economy.

When the temperature of a heat source is too low to drive a conventional absorption refrigeration system or when the evaporation

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Nomenclature

COP	coefficient of performance, –
F, *g*	function
f	circulation ratio, –
h	specific enthalpy, kJ g^{-1}
m	mass flow rate, g s^{-1}
p	pressure, bar
Q	heat transfer rate, kW
q	specific heat consumption, kJ g^{-1}
R	reflux ratio
T	temperature, K
t	temperature, °C
w	mechanical work per unit mass, kJ g^{-1}
x	solute mole fraction in liquid phase, –

Abbreviations

ABS	absorber
ACRS	absorption-compression refrigeration system
ARC	absorption refrigeration cycle
COMP	compressor
CON	condenser
EVA	evaporator
GAX	generator/absorber heat exchanger
MVCRC	mechanical vapor-compression refrigeration cycle
P	pump
PC	partial condenser
REB	reboiler
REC	rectifier
SHX	solution heat exchanger
SUBC	subcooler
TV	throttling valve

Greek symbols

ε	compression ratio, –
σ_P	boost pressure ratio, –
ω	heat-driven coefficient of performance, -

Subscripts

A	absorption
C	condensation, compression
CW	cooling water
E	evaporation
eq	equivalent
G	generation
H	high temperature
L	liquid
min	minimum
P	pressure
S	strong solution
sat	saturation
tol	total
ult	ultimate
V	vapor
W	weak solution, work

temperature is too low to be reached efficiently, absorption-compression refrigeration systems are an effective option. Fernández-Seara et al. [12] studied a cascade refrigeration system with a CO_2 mechanical compression system for the low temperature stage and an NH_3/H_2O absorption system for the high temperature stage to generate cooling energy at −30 °C to −50 °C. Jain et al. [13,14] developed a thermodynamic model for cascaded vapor compression-absorption systems, which consist of a vapor compression system with R22 or R410a as the refrigerant and a single-effect H_2O/LiBr absorption system. When the working fluids of the absorption refrigeration cycle and mechanical compression refrigeration cycle are the same, an open-style absorption refrigeration system can be developed by adding a compressor to a traditional absorption refrigeration system. Kang et al. [15] analyzed four different types of open-style absorption-compression refrigeration cycles (this cycle is called the GAX hybrid cycle in the literature). The results showed that with a compressor placed between the condenser and the desorber, the maximum desorption temperature can be reduced by approximately 30 °C when the condensation pressure is the same as that in the standard cycle.

All types of absorption refrigeration systems mentioned above can be considered the integration of several simple single-stage absorption refrigeration cycles or based on the basic cycle and adding one or two components. The absorption-compression refrigeration system has been often analyzed as the coupling configuration of an absorption refrigeration subcycle and a mechanical compression refrigeration subcycle [16,17]. The mechanical compression refrigeration cycle is relatively simple, and the only key component is the mechanical compressor. Comparatively speaking, the absorption refrigeration cycle is much more complicated and should therefore receive more attention.

The coefficient of performance (COP) of an ARC is determined by the operating temperature levels and the thermodynamic irreversibility in the transport processes [6]. Numerous papers have studied the influence of temperature levels on the COP of ARCs to optimize their thermodynamic performance. Essentially, the optimization mainly focuses on the absorption-generation process in the ARC [18]. Karamangil et al. [19] examined the effects of operating temperatures, the effectiveness of heat exchangers and the selection of the working fluid on absorption refrigeration systems. The results showed that the COP increases rapidly with increasing generation temperature from a low value at first, levels off and then gradually decreases as the generation temperature increases further. The results agree with the studies of Sun [20] and Saravanan and Maiya [21] and the experimental results of Aphornratana and Sriveerakul [22]. The results obtained by Fernández-Seara et al. [12] in the analysis of an absorption-compression cascade refrigeration system showed that the intermediate temperature level is an important design parameter that causes the opposite effect on the COP of absorption and compression cycles, and the cascade system COP reaches a maximum when the intermediate temperature is varied. Meng et al. [23] studied an absorption refrigeration system with a working fluid pair of R134a and DMF and found an optimum compressor outlet pressure (i.e., the absorption pressure) region under specified working conditions.

In this paper, the absorption-generation process is extracted from the absorption refrigeration cycle, and a new "thermal compressor" model with the key parameter of "boost pressure ratio" is proposed. The characteristics of the thermal compressor are elucidated for its application. The absorption refrigeration system and absorption-compression refrigeration system are two of the most typical systems that contain the thermal compressor model. Using the proposed model, the operating mechanisms and principles of absorption refrigeration and absorption-compression refrigeration systems are studied quantitatively. Furthermore, the thermodynamic performances of the two systems are optimized using a simple method based on the proposed model.