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Theoretical study on a novel ammonia–water cogeneration system with adjustable cooling to power ratios

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HIGHLIGHTS

- A novel ammonia–water cycle for power and cooling cogeneration is proposed.
- The solution of different levels of temperature and concentration are integrated in a cascade way.
- Cooling to power ratios for the combined system can be adjusted.
- Effects of the key thermodynamic parameters on the cycle performance are examined.

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ABSTRACT

A novel ammonia–water cogeneration system with adjustable cooling to power ratios is proposed and investigated. In the combined system, a modified Kalina subcycle and an ammonia absorption cooling subcycle are interconnected by mixers, splitters, absorbers and heat exchangers. The proposed system can adjust its cooling to power ratios from the separate mode without splitting/mixing processes in the two subcycles to the combined operation modes which can produce different ratios of cooling and power. Simulation analysis is conducted to investigate the effects of operation parameter on system performance. The results indicate that the combined system efficiency can reach the maximum values of 37.79% as SR1 (split ratio 1) is equal to 1. Compared with the separate system, the combined efficiency and COP values of the proposed system can increase by 6.6% and 100% with the same heat input, respectively. In addition, the cooling to power ratios of the proposed system can be adjusted in the range of 1.8–3.6 under the given operating conditions.

1. Introduction

Ammonia–water mixtures as binary natural refrigerant are environmentally friendly materials which have excellent thermophysical properties. They are commonly used as working fluids in absorption refrigeration cycles, absorption power cycles, and combined power and cooling cycles. Compared with lithium-bromide absorption chiller, ammonia absorption refrigeration system has broader operation temperature range (approximately −60 °C to 10 °C) and can provide cold for industrial applications when the evaporation temperatures are below 0 °C [1–3]. Moreover, ammonia–water mixtures as binary non-azeotropic mixtures have a low boiling point and variable boiling temperatures during phase change process at constant pressure, which leads to a good thermal match between the hot and cold streams. Besides, compared with pure fluids such as steam, ammonia–water mixtures have the ability to work at lower temperatures and can be used as working fluid in power generation cycles, especially being suitable for utilizing low-and-mid temperature heat source, such as solar energy, industrial process heat, and waste heat from power plants [4,5].

Maloney and Robertson [6] studied the performance of ammonia–water based absorption power cycle and found it had no thermodynamic advantage over the steam-cycle. Kalina [7,8] proposed a novel absorption power cycle which employed ammonia–water mixtures as the working fluid. In this cycle, the conventional condensation process in Maloney and Robertson cycle was replaced by an absorption condensation process. That cycle solves the problem that the turbine back pressure in Maloney and Robertson cycle was higher than that of the steam Rankine cycle since the condensation process takes place at a variable temperature. Similarly to the Rankine cycle, Kalina cycles have many special configurations and designs for application for different types of heat sources [9–16]. Ibrahim and Klein [9] conducted a thermodynamic analysis and

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Nomenclature

h	specific enthalpy (kJ/kg)
m	mass flow rate (kg/s)
mf	mass flow rate (kg/s)
P	pressure (MPa)
Q	heat duty (kW) or quality (–)
R	ratio (–)
T	temperature (K)
W	power output (kW)
X	ammonia mass fraction (kg ammonia/kg mixture)
η	efficiency (%)
Δh	enthalpy drop (kJ/kg)

Abbreviations

ABS	absorber
COP	coefficient of performance
CON	condenser
DE	desorber
EVA	evaporator
GAX	generator–absorber heat exchange
HE	heat exchanger
PREC	precooler
REB	reboiler
REC	rectifier
MX	mixer
SP	splitter
SR	split ratio
SHE	solution heat exchanger
V	valve
1,2,...,35	states on the cycle flow sheet
A_1, A_2, A_3, B_1, B_2, B_3	connections between the two subcycles

Subscripts

i, j, k	state points
in	input
out	output
net	net
E	evaporation
REB	reboiler
REC	rectifier
P	power or pump
C	cooling
C/P	cooling to power
TOT	total
Turb	turbine
GE	generation

concluded that under certain conditions the Kalina cycle produced more power than the one studied by Maloney and Robertson.

As previously mentioned, the absorption cooling cycle and the absorption power cycle both employ ammonia–water mixtures as working fluid, and consequently it is possible to combine the two cycles into one integrated system. Recently, some combined cooling and power systems using ammonia–water mixtures driven by waste heat have been proposed and studied by many researchers. Goswami et al. [17,18] proposed a combined power and refrigeration cycle. In their system, the concentrated ammonia solution separated by a rectifier firstly expanded in the turbine to produce power and then the cold exhaust from turbine continues to produce refrigeration by transferring its sensible heat to the refrigerant. The proposed cycle by Goswami can produce cooling and power in one same cycle, and has the flexibility to produce different combination of power and refrigeration [19–25].

Zheng et al. [26] proposed a combined cycle in which the flash tank in Kalina cycle was replaced by the rectification column to enhance the separation process. The thermal efficiency of 24.2% and the exergy efficiency of 37.3% of the proposed cycle were reported. Liu and Zhang [27] proposed a novel ammonia–water based combined cycle that integrated a Rankine sub-cycle with an ammonia absorption refrigeration sub-cycle. The performance of the cycle was evaluated and the exergy efficiency was found to be 58% for the base case studied. Zhang and Lior [28,29] developed three different combined cycles for refrigeration and power cogeneration using ammonia–water as working fluid. It was found that the energy and exergy efficiencies were 26–28% and 55–60%, respectively, for the base case studied (at a heat input temperature of 450 °C). These cycles [27–29] required high driving temperatures and especially are used to recovery waste heat from the gas turbine plants.

Considering the principle of the cascade utilization of energy, Han and Sun et al. [30,31] proposed the new combined cycles for effective utilization of low-and-mid temperature waste heat. Han et al. [30] developed a combined refrigerator including a compression refrigeration subcycle and a conventional ammonia absorption refrigeration subcycle driven by the mid-temperature waste heat. It showed a better thermal efficiency due to the cascade use of heat input. Sun et al. [31] proposed an ammonia–water based cogeneration system including a Rankine subcycle and an absorption refrigeration subcycle. It was found that the exergy and the equivalent heat-to-power efficiencies reached 42.0% and 18.6%, respectively.

A combined power and cooling cycle based on a double-effect absorption refrigeration system was presented by Ziegler [32]. The unique feature of the proposed cycle was that it could be driven by the low-grade heat such as solar, geothermal and industrial waste heat. Wang et al. [33,34] simplified Zhang's connected cycle in Ref. [29] and developed a new cycle in order to reduce the cost for investment, making it suitable for utilizing the low-temperature heat source. Jawahar et al. [35] proposed a combined power and cooling cycle based on a GAX. The parametric analysis showed that about 20% of internal heat of the proposed cycle could be recovered by using the GAX heat exchanger. Wang et al. [36] developed a novel resorption cycle for the cogeneration of electricity and refrigeration based on ammonia adsorption refrigeration system driven by the low grade heat source. The exergy efficiency of 0.69 and coefficient of performance (COP) of 0.77 in the simulation were reported, respectively.

In the present study, a novel power and cooling cogeneration cycle using ammonia–water mixtures is proposed and investigated. In this cycle, a modified Kalina cycle (named as subcycle1) proposed by Zheng et al. [26] and an ammonia absorption refrigeration cycle with pre-cooler (named as subcycle2) are interconnected by mixers, splitters, absorbers and heat exchangers. The proposed system which simultaneously produces power and cooling in the different cycles can be driven by the flue gases from engine or gas turbine, high temperature fuel cells, and industrial waste heat. The purpose by introducing the splitting/mixing units is to adjust the flow rates when the split ratios varied. The effect of the operation parameters such as turbine back pressure, reboiler temperature, and split ratios (SR1, SR2 and SR3) on the performance of the cycle is conducted.