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Thermodynamic analysis of ammonia–water power/chilling cogeneration cycle with low-grade waste heat

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HIGHLIGHTS

- A modified Kalina cycle is proposed for cogeneration from low-grade waste heat.
- A subcooler, throttle and an evaporator are set to complete cooling sub-process.
- The adjustable concentrations make the system with higher efficiency.
- The chilling fraction can be set to fulfill various demands for power or refrigeration.
- Thermal and exergy efficiency of combined cycle can reach up to 16.4% and 48.3%.

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ABSTRACT

An ammonia–water absorption cycle for power and chilling output cogeneration from mid/low-grade waste heat was analyzed and optimized, which is a modified Kalina cycle adding an evaporator and a subcooler to realize the chilling effect. The cycle achieves higher efficiency by generating chilling output from proper internal recuperation process without consumption of additional heat resource and by realizing heat transfer with suitable ammonia concentrations for variable phase change processes to match both heat source and cooling water. Analysis of the impact of key parameters for the system on the thermal and exergy efficiencies was carried out. The results show that there are matching basic and work concentration pairs for a higher efficiency. The smaller circulation multiple and greater chilling fraction are favorable to the efficiencies but restricted respectively by heat transfer constraint of recuperator and the demand. The calculation example with the turbine inlet parameters set at 195 °C/2.736 MPa and the cooling water inlet temperature set at 25 °C with chilling fraction of 0.5 shows that the thermal efficiency and exergy efficiency reach up to 16.4% and 48.3%, about 24.24% and 8.16% higher than those of an ammonia–water power cycle under identical condition.

1. Introduction

The increasing demand for electric power and air-condition chilling load but short supply of energy has become an urgent issue for industries, environment and daily life. It is essential to utilize energy more efficiently with fewer harmful emissions and explore energy resources such as geothermal or mid/low-grade industrial waste heat for power generation and air-condition chilling.

Kalina cycles [1,2], a bottoming cycle in which ammonia–water is used as the working fluid, has the potential to reclaim power from mid/low-grade waste heat efficiently. Ammonia–water has different characteristics from pure water and other organic working fluids. The most dramatic characteristic is its variable temperature in phase change, which matches the exothermic curve of the heat source as well as the endoergic curve of the cooling water to reduce exergy losses in both boiling and condensing processes by evaporating with richer ammonia composition and condensing with leaner composition through the absorption process.

The thermal performances of some different types of modified Kalina cycles for specific applications were studied, simulated, and compared by many researchers [3–12]. In recent years, some modified Kalina cycles, including the cogeneration cycles, have been proposed [13–17]. Goswami et al. [13–15] proposed a power/

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Nomenclature

Symbols

COP	refrigeration coefficient
e	exergy (kJ/kg)
f	circulation multiple
g	relative steam quality
G	mass flow (kg/s)
h	enthalpy (kJ/kg)
n	chilling fraction
p	pressure (MPa)
q	specific heat (kJ/kg)
s	entropy (kJ/(kg K))
t	temperature (°C)
T	temperature (K)
w	specific work (kJ/kg)
x	concentration (ammonia fraction)
η_{ex}	exergy efficiency
η_{th}	thermal efficiency

Subscript

0	benchmark state
a	chilling water
B	heat resource
b	basic (concentration)
c	cooling water
d	dilute (concentration)
E	evaporator, chilling part
h	high
l	low
m	mid
number	state points of the cycle
T	turbine based
w	work (concentration)

chilling cogeneration cycle that uses exhaust fluid from a turbine to realize chilling effect. However, its chilling effect should be very limited as the turbine exhaust is vapor or wet vapor instead of liquid. Zheng et al. [16] and Zhang et al. [17] proposed respectively two similar ammonia absorption power/refrigeration cogeneration cycles. Nevertheless, these cycles use rich ammonia as refrigerant and adopt the generator-rectifier column which consumes external heat and might be detrimental to the performance and efficiency of the cogeneration cycles.

This study presents a novel ammonia–water absorption power/chilling cogeneration cycle. It uses low-grade industrial waste heat to vaporize the working fluid in the boiler. The chilling effect is actuated by partial evaporation of some work solution, the same concentration as in the turbine, instead of pure ammonia, thus no rectifier is needed. The chilling effect is like the by-product of the power generation cycle and it consumes very little additional heat. A numerical model was built to analyze the thermodynamic performance of the proposed cycle, and a parametric analysis was conducted. Optimum and suitable values for the key parameters (i.e., the circulation multiple f, the work concentration x_w, the basic concentration x_b, the thermal efficiency, and the exergy efficiency) were sensitively studied to evaluate the thermal performance of the system.

2. The ammonia–water power/chilling cogeneration cycle

2.1. Description of the cycle

The power/chilling cogeneration cycle is based on the Kalina cycle, and following modifications were adopted.

1) A preheater (PH) is set for heating the work solution before flowing into the boiler (B), and a water cooler (WC) is added at the liquid outlet of the separator (S) for cooling the dilute solution before entering to the low-p-absorber (A1). And the output water with higher temperature from the water cooler can be used as sanitary hot water as another by-product of the cycle.
2) The work solution at the outlet of the high-pressure pump split into two streams, one for power generation and the other for chilling. The chilling loop consists of an evaporator (E), a throttle valve (V3) and a subcooler (SC).

Fig. 1 shows the proposed ammonia–water power/chilling cogeneration cycle, with following four sub-processes:

1) The power sub-process: The work solution (11) from high pressure pump is preheated (12) by rich ammonia vapor (4″) from separator (S) in the preheater (PH) and flows into the boiler (B). The high-pressure and high-temperature ammonia–water vapor (15) from the boiler (B) expands in the turbine (T) to generate power.
2) The absorption sub-processes: The low-p-absorber produces the saturated basic solution (1), and then it is pumped to the mid pressure (2), while the mid-p-absorber produce the saturated work solution (9), and then certain part of the work solution (10) is pumped to the boiler with high pressure (11). To simplify the calculation, the state point 8 or 19 is assumed to illustrate the mixture state before absorption in the corresponding absorber.
3) The desorption or separation sub-process: Heated by the turbine exhaust vapor (16), part of the basic solution (2a) is heated to the two-phase-flow state (4) and then is separated in the separator (S) into two streams: the rich ammonia vapor (4″) and the dilute solution (4′). The stream (4″) is cooled in preheater by work solution and then enters the mid-p-absorber, while the stream (4′) is cooled in the water cooler (WC) and then throttled before enters low-p-absorber and sprays on the tube bundle. The heat transfer process in recuperator can be divided into sub-cooling part and partial evaporating part, and the state point 3 just stands for the saturation point of cold stream, while the state point 17 stands for the corresponding point of hot stream.
4) The chilling sub-process: The stream 9 is divided into two parts: one (10) goes into the boiler (B) and turbine (T) as the power generating fluids after being pumped to high-pressure (11); the other (20) goes through the subcooler (SC) and then is throttled in V3 (22) and enters the evaporator (E) to absorb the air-conditioning chilling output. The partial vaporized two-phase flow from evaporator goes through subcooler to the low-p-absorber.

The valve V1 is used for throttling dilute solution from mid-pressure to low-pressure. The valve V2 is used for controlling the basic solution flow percentage in recuperator (R) and mid-p-absorber