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Thermodynamic analysis and multi-objective optimization of a novel power/cooling cogeneration system for low-grade heat sources

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ABSTRACT

A novel power/cooling cogeneration system based on an ammonia-water power cycle is proposed and investigated. The cooling capacity of the conventional combined system is much improved since an absorption-ejector refrigeration cycle is introduced. Besides the novel combined system could get more high-grade work at the same time obtain amounts of refrigeration due to the unique coupling mode. A mathematical model of the novel system is developed for system simulations under steady-state conditions. The results show that the thermal efficiency and the exergy efficiency are 21.34% and 38.95%, respectively. Exergy analysis shows that the exergy destruction mainly occurs in the recovery heat exchanger, followed by boiler and rectifier, respectively. Parametric study shows that the absorber temperature, the cycle high pressure, the temperature at boiler outlet and the extracting ratio have significant effects on the system performance. In addition, a multi-objective optimization using NSGA-II method is carried out to obtain the final optimums of the proposed system. The optimization results show that the exergy efficiency and the overall capital cost rate are 37.24% and 0.69408 $/h, respectively, and the thermal efficiency versus the overall capital cost rate are found to be 20.99% and 0.73351 $/h.

1. Introduction

With the over exploitation of fossil fuels in the world, the energy problems, environmental problems and climate changes become more and more serious. Low-grade heat sources mainly include solar energy, geothermal energy, industrial waste heat, which have the characteristics of clean, renewable and low-cost. So the effective utilization of low temperature heat sources is of great significance to ease these global issues. More and more attention has been paid to the development as well as the methods of making full use of these low-grade heat sources [1–4]. Ammonia-water mixture exhibits variable boiling temperatures during the heating process, which could reduce the irreversibility losses compared with the pure working fluids, so there is a good temperature matching between the ammonia-water mixture and the low-temperature heat sources [5,6]. The famous application of ammonia-water as the working fluid is Kalina power cycle [7], and related study showed that the cycle had about 5% higher first law and 15% higher second law efficiencies than the Rankine cycle at the same thermal boundary conditions [8].

In recent years, scholars of various countries have been devoting themselves to the development of new thermal systems suitable for the low-grade heat sources. Hong et al. [9] investigated a Kalina cycle driven by middle-temperature solar energy that used a parabolic trough collector with a variable concentration ratio, and the results showed that a much border direct normal irradiance of 100–1000 W/m^2 achieved a solar-to-power efficiency of 4–20%. Cao et al. [10] made an analysis of a gas turbine and an organic Rankine cycle, in which the organic Rankine cycle was used to recover the waste heat from the turbine exhaust gas. The results also showed that the gas turbine and organic Rankine combined cycle had better thermodynamic performance than the gas turbine and Rankine combined cycle. Fallah et al. [11] carried out an exergy analysis, based on the engineering equation solver (EES), for a Kalina power cycle driven by a low temperature geothermal source. According to the exergy analysis results, the exergy destructions mainly occurred in the condenser and the evaporator, and an improvement in the other devices could improve the system performance. Wang et al. [12] found that the Kalina cycle using sliding condensation pressure method could achieve much better annual average thermal efficiency compared with the cycle adopting the composition tuning method.

Compared with the simple power generation system, the combined power and cooling system not only improves the overall energy

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Nomenclature

A	heat transfer area (m^2)
C	purchased cost ($)
CP	cooling capacity to power ratio
CRF	capital recovery factor
E	exergy (kW)
h	specific enthalpy (kJ/kg)
I	exergy destruction (kW)
j	interest rate (%)
m	mass flow rate (kg/s)
N	annual operational hours (h)
P	pressure (MPa)
P_{high}	cycle high pressure (MPa)
P_{low}	cycle low pressure (MPa)
Q	heat duty (kW) or quality (–)
s	specific entropy (kJ/(kg·K))
T	temperature (K)
U	overall heat-transfer coefficient (W/(m^2·K))
W	power (kW)
x	ammonia mass concentration
α	extracting ratio
μ	entrainment ratio
η	efficiency (%)

Subscripts

abs	absorber
b	boiler
c	cooling
con	condenser
d	diffuser chamber
ej	ejector
eva	evaporator
exg	exergy efficiency
in	input
m	mixing chamber
n	nozzle
net	net
out	output
p	primary flow
r	recovery heat exchanger
rec	rectifier
s	isentropic progress
sf	secondary flow
sur	superheater
t	first law
tot	total
tur	turbine

conversion efficiency but also provides both power and refrigeration to users simultaneously [13]. It's noted that the combined system employing the ammonia-water mixture as the working fluid could achieve cooling capacity easily. Many works have been conducted on the combined system which used ammonia-water mixture as the working fluid. Goswami [14] proposed a new combined cycle, named Goswami cycle, in which the vapor generated by the boiler is experienced a rectification progress to further increase the ammonia concentration, so the turbine exhaust gas can reach a lower temperature, allowing refrigeration to be extracted from it in the refrigeration heat exchanger. Demirkaya et al. [15] studied the effects of the cycle structure on the cycle performances. The results showed that an internal rectification cooling source always produced higher efficiencies compared with the cycle which employed an external rectification cooling source, because the rectifier heat was recovered. The superheating progress also showed a big influence on the temperature of the turbine exhaust gas, and when the ammonia-rich vapor was superheated, the cycle efficiency increased but the cooling output declined. Then the research for the multi-objective optimization of the combined system was studied, and the results showed that there was no conflict between net work output, effective first, and exergy efficiency when the Goswami cycle was the basic cycle [16]. Exergy analysis of Goswami cycle was found that total exergy destruction decreased when the pressure ratio increased and the exergy destruction mainly occurred in the absorber, boiler, and turbine [17]. An initial experimental study was also conducted to verify the expected boiling and absorption process of the Goswami cycle [18].

The specific heat capacity of the turbine exhaust gas is relatively small and the gas only transfers the sensible heat to the chilled water, so the cooling output of the Goswami combined system is small. In addition, when the superheating temperature is higher as well as the turbine efficiency is lower, the combined system may lose the refrigerating ability. Zheng et al. [19] proposed an absorption power/cooling combined cycle based on the Kalina cycle, in which the cooling capacity was much improved by adopting the evaporation refrigeration, thus expanding the application flexibility of the system. Sun et al. [20] proposed a combined system composed by an ammonia Rankine cycle and an absorption refrigeration cycle; also the experimental study was conducted to investigate the cooling capacity produced by the ammonia absorption refrigeration system. The absorption refrigeration cycle was driven by the turbine exhausted gas, so the heat source temperature and the turbine exhausted gas should have higher temperature. Yu et al. [21] proposed a novel combined system which the cooling capacity to power ratios of the system could be adjusted in the range of 1.8–3.6 under the given conditions, but the cycle structure was complicated. Liu and Zhang [22] introduced a splitting/absorption unit to meet the different concentration requirements in the cycle heat addition process and the condensation process, and the exergy efficiency was found to be 58% for the base case studied. Zhang and Lior [23] proposed a novel power/cooling cogeneration system operating in a parallel combined system mode with an ammonia-water power cycle and an absorption refrigeration cycle, with exergy and energy efficiencies of 55.7% and 22.7%, respectively, under the given conditions. Wang et al. [24] investigated a new combined power and ejector-absorption refrigeration cycle, employing ammonia-water mixture as the working fluid, in which an ejector was introduced to improve the cycle performance. Concerning that the basic power cycle and the refrigeration sub-cycle usually operated at different cycle high pressures, the cycle structure was difficult to achieve the proper matching between the turbine inlet pressure and the rectifier pressure.

A genetic algorithm, first presented by Holland [25], employs an iterative method to mimic streamlined principles of biological evolutionary process and detect an optimal solution. Genetic algorithm can search for optimum design in parallel by using numbers of possible points so it is not trapped in a local optimal solution, and it also has the advantage of robust. Thus, it has been used in a wide area of engineering optimizations. Cao et al. [26] investigated a Kalina-based combined cooling and power cycle driven by low-grade heat sources. A performance optimization was conducted by genetic algorithm to obtain the optimum of the cycle exergy efficiency. Kordlar and Mahmoudi [27] proposed a novel combined cooling and power system which was driven by geothermal hot water, and the corresponding optimization results showed that, in the cost optimum case, the total cost around 20.4% and 24.32% was lower than thermal and exergy efficiency. Khani et al. [28] proposed a combined system based on a solid oxide fuel and the genetic algorithm method was used to maximize the exergy efficiency and minimum the sum of the unite costs of products.

In this work, a novel power/cooling cogeneration system combining an ammonia-water power cycle and an absorption-ejector refrigeration

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