Energy Conversion and Management 117 (2016) 335–342

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Thermodynamic analysis of a new combined cooling and power system using ammonia–water mixture

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ARTICLE INFO

Article history:
Received 23 September 2015
Accepted 8 March 2016

Keywords:
Combined cooling and power system
Ammonia–water
Exergy destruction analysis
Thermodynamic analysis

ABSTRACT

In order to achieve both power and cooling supply for users, a new combined cooling and power system using ammonia–water mixture is proposed to utilizing low grade heat sources, such as industrial waste heat, solar energy and geothermal energy. The proposed system combines a Kalina cycle and an ammonia–water absorption refrigeration cycle, in which the ammonia–water turbine exhaust is delivered to a separator to extract purer ammonia vapor. The purer ammonia vapor enters an evaporator to generate refrigeration output after being condensed and throttled. Mathematical models are established to simulate the combined system under steady-state conditions. Exergy destruction analysis is conducted to display the exergy destruction distribution in the system qualitatively and the results show that the major exergy destruction occurs in the heat exchangers. Finally a thermodynamic sensitivity analysis is performed and reveals that with an increase in the pressure of separator I or the ammonia mass fraction of basic solution, thermal efficiency and exergy efficiency of the system increase, whereas with an increase in the temperature of separator I, the ammonia–water turbine back pressure or the condenser II pressure, thermal efficiency and exergy efficiency of the system drop.

1. Introduction

With the consumption of traditional fossil energy in the world, more and more attention has been paid to the development and utilization of the low grade heat source and the renewable energy such as industrial waste heat, geothermal resource and solar energy. Among the various utilization methods, the combined cooling and power system exhibits high energy transfer efficiency, which makes it promising to provide both power and refrigeration output for users simultaneously. With respect to system working fluid, ammonia–water mixture is an excellent choice because its variable-temperature phase change offers a better temperature match in the heat exchangers compared to pure working fluids. In addition, it can also achieve a lower refrigeration temperature for users.

Many studies have been conducted on the combined cooling and power system using ammonia–water as working fluid. Goswami [1,2] proposed a new combined cooling and power system to produce both power and refrigeration output simultaneously with only one heat source using ammonia–water as the working fluid. The proposed system substituted an ammonia–water turbine for a condenser and a valve in ammonia–water absorption refrigeration cycle, achieving an innovative combination of a Rankine cycle and an absorption refrigeration cycle. Later, Goswami et al. [3,4] modified the proposed combined system (called Goswami cycle) by adding a superheater between the condenser/rectifier and turbine to increase the turbine inlet temperature and produce more power output. Padilla et al. [5] also examined the effects of boiler pressures, ammonia concentrations, isentropic turbine efficiencies and heat source temperature on the net work, amount of cooling and effective efficiencies of Goswami cycle. The results showed the turbine performance had significant effect on the net work and cooling outputs of Goswami cycle. Kim et al. [6] also investigated the effects of several important parameters on the performance of Goswami cycle. The results showed that with an increase in turbine inlet pressure, the system net work decreases, whereas the specific cooling capacity, total utilization work and thermal efficiency of the system had a maximal value respectively. Hasan et al. [7], Vidal et al. [8] and Fontalvo et al. [9] employed the exergy analysis method to evaluate the exergy destructions in the Goswami cycle.

By the parametric sensitive analysis, the thermodynamic parameters exhibit significant effects on the performance of Goswami cycle. Therefore, the parameter optimization is necessary and important to maximize the performance of the Goswami cycle.

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http://dx.doi.org/10.1016/j.enconman.2016.03.019
0196-8904/

Nomenclature

E	exergy, kJ
h	specific enthalpy, kJ kg^{-1}
m	mass flow rate, kg s^{-1}
P	pressure, kPa
Q	quantity of heat, kW
s	specific entropy, kJ kg^{-1} K^{-1}
T	temperature, °C
W	power, kW
X	ammonia mass fraction, %
Greek symbol	
H	efficiency
Subscripts	
arv	ammonia-rich vapor
bs	ammonia–water basic solution
cw	cooling water
exg	exergy
g	gas
in	inlet
out	outlet
p	pump
ref	refrigeration
s	isentropic
tb	turbine
thm	thermal
wf	working fluid
wls	weak liquid solution
0	reference condition

Lu and Goswami [10,11] optimized the Goswami cycle for maximizing the second law efficiency, power output, and refrigeration output using Generalized Reduced Gradient Algorithm and examined the effect of the ambient temperature on the system performance. Pouraghaie et al. [12] and Demirkaya et al. [13] conducted a multi-objective optimization of the Goswami cycle using Non-dominated Sorting Genetic Algorithm-II (NSGA-II). Since the thermodynamic optimization was not sufficient for system design, some researchers paid more attention on the economic analysis of the combined system. Zare et al. [14] conducted a thermo-economic analysis of the Goswami cycle, and optimized it using genetic algorithm from the viewpoints of both thermodynamics and economics.

In order to validate the feasibility of the Goswami cycle, based on the theoretical investigation [15], Tamm et al. [16,17] constructed an experimental system, and compared the experimental results with the theoretical simulation. The experimental results from test data consisted well with the theoretical simulation. Vapor generation and absorption condensation processes exhibited expected trends, but deviated from ideal and equilibrium modeling.

In order to improve the performance of Goswami cycle, some researchers modified the system configuration. Martin and Goswami [18] and Sadrameli and Goswami [19] used external rectification cooling source to condense the ammonia–water vapor in the rectifier instead of internal rectification cooling source. An effective COP was defined and used as an objective function to optimize the cooling production. Vijayaraghavan and Goswami [20] also made a little modification on the basic Goswami cycle, in which the condensed liquid in the rectifier was throttled back into the absorber. The resource utilization efficiency of the modified combined system was limited by two conflicting factors. One factor was that a low turbine outlet pressure was preferred to increase the power output. In addition, it would also help to achieve a low temperature at the turbine outlet, leading to an increase of refrigeration output. The other factor was that the absorber pressure should be high enough to guarantee a high ammonia concentration solution which leaving the absorber to generate more vapor in boiler. They also [21] implemented a method to decouple the absorber pressure from the turbine outlet pressure to improve the optimum resource utilization efficiency based on the distillation method.

The Goswami cycle produced a relatively small cooling capacity since the turbine exhaust passed through a heat exchanger (cooler) transferring only sensible heat. In order to produce more cooling capacity, the working fluid should go through a phase change in the cooler. Some researchers modified the Kalina cycle to achieve cooling production by adding related components such as evaporator, valve, etc. Zheng et al. [22] proposed a novel combined power/cooling cycle based on the Kalina cycle. The flash tank in Kalina cycle was replaced by a rectifier which could obtain a higher concentration ammonia–water vapor for refrigeration. A condenser and an evaporator were added between the rectifier and the second absorber. The cycle was able to provide both power and refrigeration with these modifications. Based on the Zheng's cycle, Yu et al. [23] interconnected it with an ammonia absorption refrigeration cycle with pre-cooler to form a novel power and cooling cogeneration cycle, which could adjust cooling to power ratios from the separate mode without splitting/mixing processes. Later, Jing and Zheng [24] also proposed a new combined cooling and power system by coupling a Kalina cycle and a double-effect ammonia–water absorption refrigeration cycle. They examined the effect of cycle coupling-configuration on energy cascade utilization and revealed the energy efficiency improvement mechanism of the new cycle. Hua et al. [25] added an evaporator and a subcooler to a Kalina cycle to form an ammonia–water cooling and power system for using mid/low-grade waste heat. Srinivas and his co-researchers [26,27] developed a combined power and cooling system by coupling a Kalina cycle system with an ammonia–water absorption refrigeration system, which characterized that a controlling facility was employed to assign the amount of power and cooling to meet variable demands. Then they [28] also proposed another new combined power and cooling system based on Kalina cycle, in which the ammonia–water turbine exhaust was condensed to saturated liquid and depressurized to a lower pressure and then entered an evaporator to produce cooling effect.

In addition, many researchers devoted to the study about various types of combined cooling and power systems using ammonia–water working fluid. Liu and Zhang [29] proposed a novel ammonia–water system for both power and refrigeration output by introducing a splitting/absorption unit and combining a Rankine cycle with an absorption refrigeration cycle. The system could be driven by industrial waste heat or a gas turbine flue gas. Zhang and Lior [30] also proposed a new ammonia–water system operating in a parallel combined system mode with an ammonia–water Rankine cycle and an absorption refrigeration cycle. They evaluated it by both energy and exergy efficiencies. Later, they [31] summarized some general principles for integration of refrigeration and power systems to achieve better energy and exergy efficiencies based on the reduction of exergy destruction. Wang et al. [32] proposed a new configuration of ammonia–water combined power and cooling system based on the combination of an ammonia–water Rankine cycle and an absorption refrigeration cycle.