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Thermodynamic analysis of a biomass-fired Kalina cycle with regenerative heater

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ABSTRACT

The biomass fuel is a renewable energy resource, which is viewed as a promising alternative to fossil energy. This paper investigates a biomass-fired Kalina cycle with a regenerative heater which is generally utilized to heat the feedwater and to increase the efficiency in coal-fired steam power plant. The mathematical model of the biomass-fired Kalina cycle with a regenerative heater is established to conduct numerical simulation. A parametric analysis is conducted to examine the effects of some key thermodynamic parameters on the system performance. Furthermore, a parametric optimization is carried out by genetic algorithm to obtain the optimum performance of system. The results demonstrate that there exists an optimum extraction pressure and its corresponding maximum fraction of flow extracted from turbine to maximize the net power output and system efficiency. In addition, a higher turbine inlet pressure or turbine inlet temperature leads to higher net power output and system efficiency. And net power output and system efficiency increases as separator temperature rises. The optimization result of the biomass-fired Kalina cycle with/without regenerative heater indicates the system is more efficient when regenerative heater is added.

1. Introduction

Fossil fuel consumption accounts for most of total energy consumption nowadays. And population and economic growth lead to a greater demand for energy, which pose a global threat to sustainable development. Owing to the burning of fossil fuel, a great number of pollutants and greenhouse gases are emitted into atmosphere. Consequently, energy crisis and environment pollution have been the most serious issues people faced. Renewable energy including solar energy, wind energy, geothermal energy and biomass is an alternative to fossil energy. Biomass is generally a mixture of hemicellulose, cellulose, lignin and minor amounts of other organics. Comprehensively, biomass comprises all the living matter present on Earth [1]. Biomass-fired systems have been the subject of much research. New techniques have been devised for the utilization of biomass for energy production, including thermochemical conversion (combustion, gasification, pyrolysis, liquefaction, hydrothermal upgrading), biochemical conversion and extraction of vegetable oils. Combustion can be utilized for power and/or heat generation on a large-scale, which is widely applied [2]. In the US, there are more than 1000 biomass-fired plants typically ranging from 10 to 25 MW. Two thirds of these plants are owned by paper and wood product industries for their own use [3]. And some researchers have combined biomass boiler or burner with novel power cycle. Liu et al. [4] examined a 2 kW biomass-fired CHP (Combined Heat and Power) system with ORC (organic Rankine cycle). They selected three organic working fluids and performed a thermodynamic assessment of the system. Pouria Ahmadi et al. [5] proposed a new multi-generation system based on biomass combustion and organic Rankine cycle. They also conducted a parametric study to assess the impact of several key parameters on the energy and exergy efficiencies of the system. Al-Sulaiman et al. [6] carried out energy and exergy analyses of a biomass trigeneration system using an organic Rankine cycle. Their study revealed the fuel utilization efficiency increased from 12% for electrical power to 88% for trigeneration. Bhattacharya et al. [7] studied a BIGCC (Biomass Integrated Gasification Combined Cycle). They used biomass as a supplementary fuel and examined the effect of the amount of fuel burned in the supplementary firing chamber on the thermal and exergetic efficiencies. However, owing to the high cost of construction and systematic complexity, IGCC system is not economically viable for large-scale utilization at present.

In 1984, Alexander Kalina [8] came up with a new thermodynamic power cycle, namely, Kalina cycle which utilizes ammonia-

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Nomenclature

B	biomass consumption, kg·s^{-1}
b	biomass consumption rate, kg (kW·h)$^{-1}$
d	Ammonia-water mixture consumption rate per kilowatt, kg (kW·h)$^{-1}$
E	exergy, kJ
e	specific exergy, kJ·kg^{-1}
HCV	higher calorific value, kJ·kg^{-1}
h	specific enthalpy, kJ·kg^{-1}
I	exergy destruction, kJ
NCV	net calorific value, kJ·kg^{-1}
M	mass fraction, %
m	mass flow rate, kg·s^{-1}
P	pressure, MPa
Q	heat consumption rate, kJ·s^{-1}
q	heat consumption rate per kilowatt, kJ (kW·h)$^{-1}$
s	specific entropy, kJ (kg·K)$^{-1}$
T	temperature, K
t	temperature, °C
W	power, kW
w	mass fraction of water in biomass fuel
x	ammonia mass fraction
Greek letters	
α	fraction of flow extracted from turbine
η	efficiency
φ	ratio of specific exergy to NCV

Subscript	
air	air
abs	absorber
amb	ambient
b	basic
bio	biomass
B	boiler
cond	condenser
dry	dry basis
exh	exhaust
ext	extracted steam
fp	feed pump
g	gas
in	inlet
max	maximum
NET	net
out	outlet
p	ammonia-poor solution
$p1$	condensate pump 1
$p2$	condensate pump 2
r	ammonia-rich vapor
sys	system
T	turbine
w	ammonia-water working solution

water mixture as working fluid to generate power. By using two fluids with different boiling points, the ammonia-water mixture evaporates and condenses over a range of temperatures rather than at a single, fixed temperature, which enables the Kalina cycle to accomplish better performance owing to better thermal match achieved in evaporator and condenser.

A volume of research has been done on Kalina cycle. Marston [9] conducted a parametric analysis for Kalina cycle. He carried out an optimization for a simplified form of Kalina cycle and developed a method of balancing the cycle. Rogdakis [10] considered thermodynamic analysis and the parametric study of a Kalina Power Unit. Nag and Gupta [11] conducted an exergy analysis of Kalina cycle. Arslan [12] evaluated the exergoeconomic performances of Kalina cycle system 34. And the optimum design KCS-34 plant was determined on the basis of the exergetic and life-cycle-cost concepts.

Because of Kalina cycle being superior to steam power cycle, Kalina cycle is used as a bottoming cycle to recover waste heat from gas turbine, diesel engine or industrial production. Marston et al. [13] compared the performance of a triple-pressure steam cycle with a single-stage Kalina cycle and an optimized three-stage Kalina cycle as the bottoming sections of a gas turbine combined cycle power plant. They found both Kalina cycles were more efficient than the triple-pressure steam cycle. Ibrahim and Kovach [14] investigated a Kalina cycle which utilized the exhaust from a gas turbine. The effects of the ammonia mass fraction at the turbine inlet on the cycle efficiency were studied. The results indicated that the Kalina cycle was 10–20% more efficient than a Rankine cycle with the same the boundary conditions. He et al. [15] studied a combined thermodynamic cycle used for waste heat recovery of internal combustion engine. The combined thermodynamic cycle consists of two cycles: the organic Rankine cycle, for recovering the waste heat of lubricant and high-temperature exhaust gas, and the Kalina cycle, for recovering the waste heat of low-temperature cooling water. They found the combined cycle could recover more waste heat compared with the traditional cycle configuration. Bombarda et al. [16] conducted a comparison between the thermodynamic performances of Kalina cycle and an ORC cycle which were adopted to recover waste heat from Diesel engines. The results showed that a net electric power of 1615 kW and of 1603 kW respectively for the Kalina and for the ORC cycle was calculated. However, the Kalina cycle required a very high maximum pressure in order to obtain high thermodynamic performances in this case. Wang et al. [17] conducted the exergy analyses and parametric optimizations for different cogeneration power plants in cement industry. They compared single flash steam cycle, dual-pressure steam cycle, organic Rankine cycle and Kalina cycle and concluded that the Kalina cycle could achieve the best performance in cement plant. Singh and Kaushik [18] conducted a computer simulation of Kalina cycle coupled with a coal-fired steam power plant with the aim of examining the possibility of exploiting low-temperature heat of exhaust gases for conversion into electricity. They developed a numerical model to find the optimum operating conditions for the Kalina cycle. Ogriseck [19] studied an integration of the Kalina cycle process in a combined heat and power plant for improvement of efficiency. The calculations showed that the net efficiency of an integrated Kalina plant was between 12.3% and 17.1% depending on the cooling water temperature and the ammonia content in the basic solution.

In addition to the application in bottom cycle to recover waste heat, Kalina cycle is expected to play a more significant role in the area of renewable energy utilization. Because renewable energy has advantages in reducing fossil fuel consumption and alleviating environmental problems [20], many researchers have explored Kalina cycle utilizing renewable energy resources such as solar energy and geothermal heat sources. Wang et al. [20] examined a solar-driven Kalina cycle and conducted a parametric analysis to examine the effects of some key thermodynamic parameters on the system performance. Lolos and Rofdakis [21] investigated a Kalina cycle using low-temperature heat sources provided by flat solar

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