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Parametric analysis and optimization of a Kalina cycle driven by solar energy

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HIGHLIGHTS

► A thermal storage system is introduced to provide stable power output.
► A modified system efficiency is defined to evaluate the system performance.
► The effects of thermodynamic parameters on the performance are examined.
► Parametric optimization is conducted to find the optimum performance by GA.

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ABSTRACT

A solar-driven Kalina cycle is examined to utilize solar energy effectively due to using ammonia–water's varied temperature vaporizing characteristic. In order to ensure a continuous and stable operation for the system, a thermal storage system is introduced to store the collected solar energy and provide stable power when solar radiation is insufficient. A mathematical model is developed to simulate the solar-driven Kalina cycle under steady-state conditions, and a modified system efficiency is defined to evaluate the system performance over a period of time. A parametric analysis is conducted to examine the effects of some key thermodynamic parameters on the system performance. The solar-driven Kalina cycle is also optimized with the modified system efficiency as an objective function by means of genetic algorithm under the given conditions. Results indicate that there exists an optimal turbine inlet pressure under given conditions to maximize the net power output and the modified system efficiency. The net power output and the modified system efficiency are less sensitive to a change in the turbine inlet temperature. An optimal basic solution ammonia fraction can be identified that yields maximum net power output and modified system efficiency. The optimized modified system efficiency is 8.54% under the given conditions.

1. Introduction

The Kalina cycle, which utilizes ammonia–water as its working fluid, was originally conceived by Alexander Kalina [1]. The ammonia–water has the advantage of variable-temperature evaporation and condensation at subcritical pressures in contrast to a pure fluid that evaporates and condenses at constant temperature, and could provide a better performance due to better thermal match achieved in the condenser and evaporator. Kalina cycle uses unique DCSS (Distiller Condenser Sub-System) to achieve ammonia–water condensation process at low condensing pressure by changing the ammonia–water mass fraction.

Due to the superior to steam power cycle, many studies have been found to investigate Kalina cycle. El-Sayed and Tribus [2] made a theoretical comparison between the Kalina cycle and Rankine cycle. The configurations developed by them were very much complicated because several heat exchangers had more than two steams. Marston [3] considered the parametric analysis of the Kalina cycle. He developed a method of balancing the Kalina cycle and identified the key parameters for optimizing the Kalina cycle. Rogdakis [4] developed correlations describing the optimum operation of the Kalina cycle. In addition, Nag and Gupta [5] studied exergy analysis of the Kalina cycle.

Because of the advantage of recovering sensible heat source, Kalina cycle is generally used as a bottoming cycle to enhance energy conversion efficiency by recovering waste heat from gas turbine, diesel engine or industrial production such as cement line [6,7]. Marston [8] compared the performance of Kalina cycle with a triple-pressure steam cycle as the bottoming sections of a gas turbine combined cycle power plant. Jonsson et al. [9,10] examined the Kalina cycle as the bottoming cycle with gas engines and gas

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Nomenclature

A	area, m^2
b	width of absorber, m
C	concentration ratio of CPC
c_p	specific heat, kJ kg^{-1} K^{-1}
D	diameter, m
F'	collector efficiency factor
F_R	heat removal factor
h	enthalpy, kJ kg^{-1}
I	hourly radiation, W m^{-2}
k	heat transferring coefficient, W m^{-2} K^{-1}
L	length, m
$\dot{m}$	mass flow rate, kg s^{-1}
N	number of tubes
p	pressure, bar
Q	heat rate, kW
R	tilt factor for radiation
s	entropy, kJ kg^{-1} K^{-1}
S	incident solar flux, W m^{-2}
T	temperature, °C
U	loss coefficient, W m^{-2} k^{-1}; heat transfer coefficient, W m^{-2} k^{-1}
V	volume, m^3
W	power, kW; Width, m
x	ammonia mass fraction

Greek letters

α	absorptivity of the absorber surface
η	efficiency
ρ	reflectivity of the concentrator surface; density, kg m^{-3}
τ	transmissivity of the cover

Subscripts

0	environment
b	beam
C	condenser
d	diffuse
fi	inlet of solar collector
fo	outlet of solar collector
i	inlet
l	uniform; loss
lo	loss
P	pump
s	isentropic process
sys	system
T	turbine
u	useful

diesel engines as prime movers to recover waste heat available from the exhaust gas. Bombarda et al. [11] conducted a thermodynamic comparison between Kalina cycle and ORC as the bottoming cycle to recover waste heat from diesel engines. Results showed the net electric power of Kalina cycle was a little larger than that of ORC under the reasonable design parameters and the same logarithmic mean temperature difference in the heat recovery exchanger.

With the rapid industrialization and social growth, the demand for energy is growing faster. Conventional sources, such as coal, oil and natural gas, have limited reserves that are expected not to last for an extended period. Renewable energy resources are expected to play an increasing role in energy consumption due to these potentials in reducing fossil fuel consumption and alleviating environmental problems. So, Kalina cycle is also used to utilize renewable energy resources, such as geothermal heat sources. Madhawa Hettiarachchi et al. [12] evaluated the performance of the Kalina cycle system for low temperature geothermal heat sources, compared it with an organic Rankine cycle, and examined the effect of the ammonia fraction and turbine inlet pressure on the cycle performance in detail. Nasruddin et al. [13] conducted the energy and exergy analysis of kalina cycle utilizing lower temperature geothermal resources, and optimized the Kalina cycle on the mass fraction of working fluid and the turbine output pressure. Arslan [14] investigated Kalina cycle to generate electricity generation from Simav geothermal field. He determined the optimum operating conditions for the KCS-34 plant on the basis of the exergetic and life-cycle-cost concepts. Due to limitation of region for geothermal resources, some researchers paid attention to use solar energy, which is available everywhere, to drive Kalina cycle enabling the distributed power generation. Lolos [15] investigated a Kalina cycle using solar energy to produce power. He used flat-plate solar collectors to heat the evaporator to make ammonia–water be partially vaporized and used an external heat source to superheat the ammonia–water vapor before entering a turbine.

In this study, a Kalina cycle driven by solar energy mainly as one heat source is investigated based on the thermodynamic analysis. A thermal storage system is added to store the collected solar energy and to provide continuous power output when solar radiation is insufficient. A mathematical model is developed to simulate the solar-driven Kalina cycle under steady-state conditions, and a modified system efficiency is defined to evaluate the cycle performance over a period of time. A parametric analysis is conducted to examine the effects of some key thermodynamic parameters on the system performance. The solar-driven Kalina cycle is also optimized with the modified system efficiency as an objective function by means of genetic algorithm (GA) under the given conditions.

2. System description

Fig. 1 illustrates a schematic diagram of the Kalina cycle driven by solar energy. The overall system is divided into two subsystems: the solar energy collecting and storing subsystem and the Kalina cycle. The solar energy collecting and storing subsystem consists of solar collectors, a thermal storage tank and an auxiliary heater. Compound parabolic collector (CPC) is used to collect the solar radiation to supply heat to the overall system because it can achieve higher concentration for large acceptance angle and requires only intermittent sun-tracking. In addition, the CPC can achieve a higher temperature than flat-plate solar collector. The thermal storage tank with thermal oil as working fluid is used as the heat source when solar radiation is not sufficient. The auxiliary heater is installed as the backup energy source to boost the temperature of thermal storage tank to the allowable temperature when the temperature of thermal storage tank drops below the allowable temperature. The Kalina cycle consists of two separators, a vapor evaporator, two recuperators, an air condenser, a feed pump, a turbine-generator and a throttle valve. The ammonia–water mixture is heated in the vapor evaporator where it is partially vaporized by absorbing heat from thermal storage system. The two-phase ammonia–water mixture is sent to separator 1 where the ammonia–water solution is separated into weak liquid solution and ammonia-rich vapor. The ammonia-rich vapor is expended to a low pressure through a turbine to drive a generator to generate