Renewable Energy 89 (2016) 154–167

Contents lists available at ScienceDirect

Renewable Energy

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

Thermodynamic analysis and optimization of a geothermal Kalina cycle system using Artificial Bee Colony algorithm

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ARTICLE INFO

Article history:
Received 19 August 2015
Received in revised form
17 November 2015
Accepted 30 November 2015
Available online xxx

Keywords:
Geothermal Kalina cycle
Artificial Bee Colony algorithm
Thermodynamic optimization
Thermal efficiency
Exergy efficiency

ABSTRACT

In this paper, thermodynamic analysis is carried out for a geothermal Kalina cycle employed in Husavic power plant. Afterwards, the optimum operating conditions in which the cycle is at its best performance are calculated. In order to reach the optimum thermal and exergy efficiencies of the cycle, Artificial Bee Colony (ABC) algorithm, a new powerful multi-objective and multi-modal optimization algorithm, is conducted. Regarding the mechanism of ABC algorithm, convergence speed and precision of solutions have been remarkably improved when compared to those of GA, PSO and DE algorithms. Such a relative improvement is indicated by a limit parameter and declining probability of premature convergence. In this research, exergy efficiency including chemical and physical exergies and thermal efficiency are chosen as the objective functions of ABC algorithm where optimum values of the efficiencies for the Kalina cycle are found to be 48.18 and 20.36%, respectively, while the empirical thermal efficiency of the cycle is about 14%. At the optimum thermal and exergy efficiencies, total exergy destruction rates are respectively 4.17 and 3.48 MW. Finally, effects of the separator inlet pressure, temperature, basic ammonia mass fraction and mass flow rate on the first and second law efficiencies are investigated.

1. Introduction

Today, due to ongoing reduction in non-renewable resources' reserves, the importance of decreasing environmental contaminations generated by fossil fueled engines and in order to save energy, studies are oriented toward utilizing clean and renewable energies such as geothermal energy, solar energy and waste heat recovery as heat sources. Geothermal resources are categorized as low-temperature resources in which the temperature is usually less than 100 °C. In some countries, more than 10% of the whole power generation is supplied by the geothermal power plants [1]. In Iceland, about 85% of total heating needs is supplied by geothermal energy [2]. Organic Rankine Cycle (ORC) is one of the low-temperature thermodynamic cycles in which organic fluids are employed as the working fluid [3–6]. Alexander Kalina proposed and developed a new power generation cycle whose working fluid was ammonia–water mixture. This cycle was indeed an improved type of the ORC [4,7–12]. Kalina cycle was first proposed as a bottoming cycle producing power from waste heat. It was mainly employed as a combined cycle to decline heat losses [4,5,13]. Unlike pure water, saturation temperature of ammonia–water mixture is not constant in two-phase region during heat absorption and heat rejection processes at a constant pressure [14,15]. This causes the working fluid temperature profile to approach the heat source temperature profile more than pure water or pure ammonia does as a working fluid, so the exergy losses caused by temperature difference between working fluid and heat source or heat sink are remarkably lower in a Kalina cycle system when compared to single-pressure and subcritical-pressure ORCs [4,16–18].

An important subject in thermodynamic analysis of Kalina cycle systems is the precision of calculating ammonia–water thermodynamic properties. Ziegler and Trepp presented correlations to compute the mixture properties [19]. El-Sayed and Tribus also provided significant correlations to anticipate the properties of ammonia–water mixture [20]. Afterwards, they compared thermal efficiency of a Kalina cycle with that of Rankine cycle by utilizing analogous heat sources showing 10–20% better first law efficiency for the Kalina cycle rather than the Rankine cycle [11,21–25]. Important correlations for calculating ammonia–water properties were presented by Ibrahim and Klein, which are used in EES

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http://dx.doi.org/10.1016/j.renene.2015.11.087
0960-1481/

Nomenclature

e^0_{Ch}	standard molar specific chemical exergy, kJ/kmol
$\dot{E}$	exergy rate, kW
g	gas
h	specific enthalpy, kJ/kg
l	liquid
$\dot{m}$	mass flow rate, kg/s
M	molar mass, kg/kmol
P	pressure, bar
$\dot{Q}$	heat transfer rate, kW
s	specific entropy, kJ/kg-K
T	temperature, K
$\dot{W}$	power, kW
x	quality, %
X	ammonia mass fraction

Greek letters

η	efficiency, %
$\in$	effectiveness, %
υ	new food source position

Subscripts

ABC	Artificial Bee Colony
Cons	consumption
Ch	chemical
Cond	condenser
D	number of optimization parameters
De	destruction
DE	Differential Evolution
EES	Engineering Equation Solver
ES	Evolution Strategy
Evap	evaporator
Ex	exergy
Exp	expansion
Fit	fitness
GA	Genetic Algorithm
HTR	high-temperature recuperator
LNG	Liquefied Natural Gas
LTR	low-temperature recuperator
MC	mixing chamber
NP	number of colony size
ORC	Organic Rankine Cycle
Pro	production
Ph	physical
PSO	Partial Swarm Optimization
Sep	separator
SN	food source number
Th	thermal
Tot	total
Tur	turbine
0	reference state

software [17]. Correlations presented by Reiner Thillner showed more accurate results, which are utilized in NIST REFPROP software [18]. Bombarda indicated that bottoming Kalina cycle generates larger net power than ORC by recovering waste heat from exhaust gas of gas diesel engines [3]. Goswami suggested a solar Kalina cycle and presented the results of thermodynamic analysis. Subsequently, he presented correlations for calculation of thermodynamic properties of ammonia–water mixture for power cycle applications with Xu [4,26–28]. Liu Y et al. designed a Kalina cycle with seawater as its heat source and an LNG reservoir as its heat sink [4]. Thermodynamic analysis and optimization of Liu suggested Kalina cycle accomplished by Wang J et al. via genetic algorithm [10]. A combined Kalina cycle using low-temperature waste heat as the heat source and LNG cold energy as its heat sink was proposed and optimized via DE algorithm by Shi X. and Che D [7]. Lolos and Rogdakis offered a Kalina power system driven by solar energy for which operating pressures and optimum interval of ammonia mass fraction in vapor phase were computed [21]. The first geothermal Kalina cycle employed in a power plant was built in Husavic, Iceland. It generated about 2 MW net power [13,29].

Simultaneous analysis of energy and exergy is now playing a significant role in thermodynamic cycles. Besides, exergy analysis is a suitable tool to evaluate the contribution of heat transfer and pressure drop in thermodynamic mechanisms [30]. In this study, we have chosen a geothermal Kalina cycle system applied in Husavic power plant. Thermodynamic analysis of the cycle is carried out by using Matlab software and in order to compute the thermodynamic properties of ammonia–water working fluid, EES software is conducted. Assumptions such as pressure drops in the recuperators, evaporator and condenser, turbine and pump efficiencies are made so that for the same input conditions, the thermodynamic properties resulting from the thermodynamic analysis are close to those of the available empirical data at each point of the cycle. Afterwards, in order to determine the optimum values of thermal and exergy efficiencies, Artificial Bee Colony algorithm is employed. Finally, effects of separator inlet temperature, pressure, basic ammonia mass fraction and mass flow rate of the working fluid on the first and second law efficiencies are investigated.

2. System description and thermodynamic analysis

Variable saturation temperature of ammonia–water mixture at a constant pressure over the saturation region extracted from EES software is shown in Fig. 1 [4,13]. Knowing the ammonia–water mixture characteristics on two-phase region, exergy losses corresponding to the temperature difference between working fluid temperature profile and that of heat source or heat sink decrease considerably.

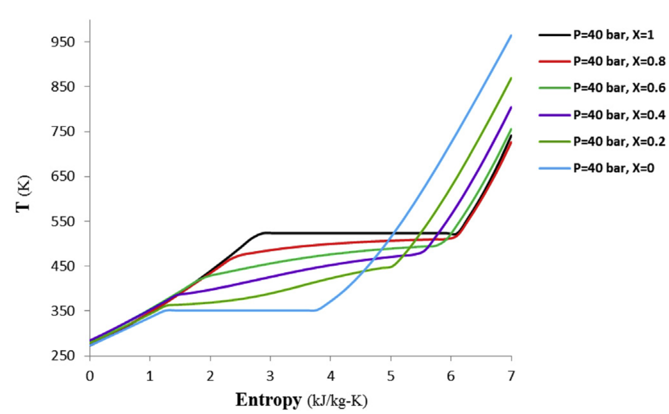

Fig. 1. Temperature–Entropy diagram of ammonia–water mixture for different ammonia mass fraction at pressure 40 bar.