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Thermodynamic optimization and thermoeconomic analysis of four double pressure Kalina cycles driven from Kalina cycle system 11

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ABSTRACT

In this paper four configurations of double pressure Kalina cycle system are presented and optimized all of which are modifications of Kalina cycle system 11. In order to set the exact pinch temperature difference an iterative method is applied. Prior to the optimization, the base cycle is validated by comparing the result with a reference. The heat transfer fluid of the inlet stream is supposed to be the product of combustion at 3 different temperatures, 383.15 K, 413.15 K and 443.15 and the results are compared at the base case and the optimum conditions. In order to present a thorough evaluation, thermoeconomic analysis is also presented in which levelized cost of electricity is selected as the criterion. Different decision variables can be defined for the cycles based on the cycle's degrees of freedom. Pressure levels, mass flow rate and ammonia concentration of the base stream and split ratio are the decision variables. Exergy efficiency is considered as the objective function and the innovated double pressure Kalina cycles as well as the base Kalina cycle are compared. Results show that the Kalina cycle system named 112b is the most efficient cycle at the base condition. It is also shown that by increasing the heat source temperature the exergy efficiency and the purchased equipment cost at the optimum condition rises while the levelized cost of electricity lowers. Thermoeconomic evaluation indicates that at both base and the optimum conditions, the levelized cost of electricity of the base cycle is less.

1. Introduction

Emission of hot flue exhaust gas to atmosphere not only results in waste of energy but also unfavorably affects global warming. In order to extract electricity from these waste sources and control the environmentally hazardous emission, two types of power cycles, ORCs [1] and Kalina cycles are proposed. Unlike ORCs that operate with a pure fluid, Kalina cycles employ water-ammonia mixture which is a zeotropic mixture.

Zeotropic mixtures have been extensively studied for refrigeration cycles and heat pumps [2]. In recent years the application of fluid mixtures in a power cycle has attracted researchers' attention since the use of such mixtures has proposed a potential to reduce irreversibility. Braimakis et al. [3] examined the effect of utilization of different zeotropic mixtures and compared with those of pure fluid for heat source temperatures of 150–300 °C. Results indicated that when the heat source temperature is above 170 °C, the cases of mixtures and supercritical operation perform more efficiently. Angelino and Colonna di Paliano [4] studied the effect of using mixture of organic fluids as the working fluid. They concluded that fine selection of the working fluids results in a considerable improvement in the cycle efficiency. Similar study is also performed by Chys et al. [5]. In their study, they also found the optimum concentration for heat source temperatures in the range of 150–250 °C. In fact a non-isothermal evaporation and condensation brings about a potential for point by point temperature difference reduction and heat transfer between closer hot and cold temperature profiles imposes less irreversibility. Reducing the irreversibility, the thermal efficiency and exergy efficiency of the cycle can be improved. Therefore, different cycles are innovated and improved that show the advantages of Kalina cycles.

Kalina cycle was first introduced by Dr. Alexander Kalina in 1984 [6]. Afterward, different configurations of Kalina cycles are introduced and their performance versus effective parameters are examined and optimized. Elsayad and Tribus presented a simplified version of the cycle that A. Kalina had proposed and compared the results [7]. Marson et al. simulated their presented simplified Kalina's cycle as the bottoming cycle of a diesel gas engine and conducted a thorough parametric analysis [8]. Marson and Hyre compared single-stage and triple-stage Kalina cycle with a triple pressure steam cycle [9]. Modi and Haglind presented four configurations of Kalina cycles adopted for high temperature heat sources [10]. They also implemented a robust methodology to conduct the optimization of the four cycles which resulted in

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Nomenclature

A	area surface
C	cost
CRF	capital recovery factor
$\dot{Ex}$ (W)	exergy rate
h (J/kg)	enthalpy
H (m)	height
$\dot{Q}$ (W)	heat transfer rate
LCOE	levelized cost of electricity
$\dot{m}$ (kg/s)	mass flow rate
n	number of sections
opt	optimum
P (kPa)	pressure
PEC	purchased equipment cost
T (K)	temperature
v	stream velocity
$\dot{W}$ (W)	power
x	ammonia mass fraction
z (m)	altitude

Greek letters

η	efficiency

Subscript

0	dead state
bs	basic stream
cs	cold stream
con	condenser
e	exit
ex	exergetic
eva	evaporator
flue	flue gas
gen	generator
Hp, hp	high pressure
Lp, lP	low pressure
hs	hot stream, heat source
ht	high temperature
htf	heat transfer fluid
i	inlet, interest, index
is	isentropic
inv	investment
lt	low temperature
misc	miscellaneous
O&M	operating and maintenance
pp	pinch point
pu	pump
reg	regenerator
sep	separator
th	thermal
tur	turbine
y	yearly

selection of the best cycle. Guo et al. proposed a double pressure vaporization configuration of a Kalina cycle and compared it with the base cycle [11]. The result declared that the new configuration is 17 percent more efficient than the base cycle. Nguyen et al. simulated a configuration of split Kalina cycle and compared the results with some simpler configurations from thermodynamic and exergetic points of view [12]. Their results showed that, the Kalina cycles are more efficient than the steam cycle. [11]. Their results revealed that the innovated cycle requires less amount of energy when the separator pressure increases. Coskun et al. studied four configurations of the Kalina cycle system for thermodynamic and thermoeconomic optimization for a medium temperature geothermal heat source [13]. All the configurations discussed in the above papers only match high temperature heat sources in which the heat gain from the heat source happens at in a single-stage unit.

Although, Kalina cycles considered for small power plants and also for utilization of high temperature heat sources are able to generate more power, are found to have a small opportunity to be economically justified as compared to its much more simple rival, ORC cycles [14]. Therefore, a successive application of Kalina cycles is achievable when low temperature heat sources are under consideration. Bombarda et al. [15] considered both Kalina cycle and ORC as the bottoming cycle of a diesel engine and compared the results. Although it is found that Kalina cycle is able to generate power slightly more than the other cycles, it seems to be unjustified for high-medium temperature heat sources. Madhawa Hettiarachchi et al. [16] studied KCS 11 for low temperature heat sources. They analyzed the cycle for varying ammonia mass fraction and turbine inlet pressure. It is concluded that the Kalina cycle performs more efficiently at moderate pressures than its rival, organic Rankin cycle. Jonsson and Yan [17] studied water-ammonia Kalina cycle as the bottoming cycle of a gas engine and a gas diesel engine. Moreover they considered a single pressure organic Rankin cycle as the basis for their comparison. The found that when the gas engine is the prime mover, the Kalina cycle performs more efficiently than the base cycle.

Different applications of low and moderate temperature Kalina cycles are studied by researchers. One of the simplest configurations for this category is KCS 11. Lu et al. [18] considered KCS 11 as an efficient cycle for utilization of geothermal energy. They studied and modeled KCS 11 and compared the results with an existing binery plant. Sun et al. [19] studied KCS 11 coupled with a solar system that is also enhanced with a superheater. They identified the important operating parameters and optimized the cyle from exergy point of view. Li et al. [20] introduced E-Kalina cycle and compared the results with the convensional Kalina cycle. He et al. [21] examined the utilization of a two-phase turbine on the weak stream of KCS 11. Result revealed that the enhanced cycles are more efficient than the base cycle. The study indicated that the innovative cycle is more efficient than the base cycle, KCS 11. Madhawa et al. [16] studied the KCS 11 for low temperature geothermal heat source and compared the cycle's performance with that of Organic Rankine Cycle (ORC). Sadeghi et al. [22]considered a double turbine Kalina cycle which is able to match a heat source at a temperature in the range of 80–200 °C properly. Other configurations of low and medium temperature Kalina cycles are reviewed by Zhang et al. [14]. In order to simulate a Kalina cycle properly, it is essential to consider the complicating aspects in simulation of its including heat exchangers.

The determination of pinch point in a heat exchanger in which water-ammonia mixture flows is much more complicated than the same task for a pure stream. In order to find the pinch temperature difference in a heat exchanger involving the mixture of water and ammonia, a number of studies have been published. Kim et al. studied the variation of ammonia mass fraction in a simple Kalina cycle [23]. Their study included the simulation of the Kalina cycle in which the pinch temperature difference is set in the corresponding heat exchanger via an iterative procedure. Another research develops a method namely" imaginary outlet temperature" which is claimed to be more efficient in assessment of the pinch temperature difference [24]. Few studies have been conducted which include economic analysis. Modi et al. [25] investigated Kalina cycle coupled with a central receiver concentrating