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Advanced exergy analysis of the Kalina cycle applied for low temperature enhanced geothermal system

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ABSTRACT

In recent years, the possibility of using low temperature heat sources has been followed as a hot topic in different research and academic centers. In this regard, the Kalina cycle has been paid a lot of attention because of its promising features. Using the engineering equation solver (EES) software, conventional exergy analysis is carried out in this study for the Kalina cycle driven by a low temperature enhanced geothermal source. After validating the developed model for conventional exergy analysis, the advanced exergy analysis, i.e., splitting exergy destruction rate into endogenous, exogenous, avoidable and unavoidable parts, is performed to provide detailed information about improvement potential of the system components. The results of advanced exergy analysis show that the cycle has high potential for efficiency improvement. It is also revealed that the advanced exergy analysis gives the improvement priority first for the condenser, then for the turbine and the evaporator. From the conventional exergy analysis however, the exergy destruction calculated for the evaporator is higher than that for the turbine.

1. Introduction

Generating electricity from geothermal sources has a history of more than 100 years [1]. The worldwide installed capacity of electrical power generation from these sources in 2015 is around 12,635 MW and it is expected that this capacity will reach 21,443 MW in 2020 [2]. Nearly 11–12% of this power is generated from geothermal plants with binary working fluids [1]. As defined in literature, the binary cycle is the main technology for generating power from low to medium temperature (<180 °C) geothermal energy sources [3]. The organic Rankine cycle (ORC) and Kalina cycle (KC) are two major groups of these binary geothermal cycles [4]. Using the KC with a mixture of ammonia–water as working fluid brings about a performance enhancement of nearly 20% compared to some other power cycles [5].

The Kalina cycle was designed and developed by Alexander Kalina to be used as a bottoming cycle instead of the Rankine cycle in combined cycle power plants. Kalina showed that the efficiency of this new cycle is about 30–60% higher than that of the Rankine cycle [6]. A lot of research works have been carried out on the Kalina cycle all over the world. In this section, some of these works are reviewed. Hettiarachchi et al. [7] examined and compared the performances of an ORC and a KC (known as KCS 11) used for low temperature geothermal heat sources. They concluded that, under specified conditions and at moderate turbine inlet pressures, the KCS 11 performs better than the ORC. Using binary working fluids, the performances of a KC (KCS 34) and an ORC for producing electricity from geothermal sources in the Republic of Croatia was investigated by Guzović et al. [8]. In the proposed binary plants with ORC and Kalina cycles for this study, geothermal fluid has transferred heat to the working fluid by cooling. Their results showed that the ORC efficiency increases when the geothermal fluid is cooled from 175 °C to 69 °C. At the same time, the results emphasized that the cycle produces higher output power when the temperature of geothermal fluid increases. Guzović et al. concluded that for geothermal sources with lower temperatures, the KCS 34 demonstrates better performance. Using a variety of working fluids and working fluid compositions, Rodríguez et al. [9] carried out comparative exergoeconomic analyses for the KC and ORC employed for an advanced geothermal system in Brazil. They suggested R-290 and a mixture of 84% ammonia–16% water (in mass fraction) as working fluids for the ORC and KC, respectively and reported the superiority of the KC to the ORC from the viewpoints of thermodynamics and economics. Singh et al. [10] performed a parametric study on the combined KCS 11 – Rankine cycle and reported that the best cycle performance is achieved with an ammonia concentration of between 78% and 82% for the working fluid of KCS 11 and a moderate pressure of 4000 kPa for the ammo-

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nia turbine inlet. Li et al. [11] compared the performances of KC and CO_2 transcritical power cycle (CTPC) utilizing low temperature geothermal sources in China. Results of this study showed that the KC has higher thermal efficiency and net output power and better economic performance than the CTPC. A detailed review about the results of the references [7–11] are shown in Table 1. Yari et al. [12] compared thermodynamic and economic performances of the KCS 11, ORC and trilateral power cycle (TLC) and showed that for both the KCS 11 and the ORC, the optimum operating conditions for maximum net output power is different from those for minimum product cost.

In most of the above mentioned research works, conventional exergy analysis plays an important role, especially in determining the exergy destruction in different components. The analysis however, doesn't specify the internal or external sources of irreversibilities for system components (concepts which can be very useful for thermodynamic system designers). The concept of the advanced exergy analysis, which has been proposed in recent years, however, provides this information for the designers. In the advanced exergy analysis, the exergy destruction in each system component is split into avoidable and unavoidable parts and also into endogenous and exogenous components. The advanced exergy analysis offers a great opportunity for improving a system performance and identifies system components which play a major role in this improvement. The idea of advanced exergy analysis was proposed by Tsatsaronis et al. [13]. In recent years, Tsatsaronis and his research group (in technical university of Berlin) have presented several research works using advanced exergy, exergoeconomic and exergoenvironmental analyses for various thermodynamic systems. They applied advanced exergy method to analyze vapor-compression and absorption refrigeration machines and also to the gas turbine power systems [14,15]. Petrakopoulou et al. [16] used advanced exergoeconomic method to analyze the performance of a gas turbine-low pressure steam turbine combined cycle

Table 1
Detailed review of Refs. [7–11].

Refs.	Cycle, input parameters and their ranges	Main results	Values of the parameters for Kalina cycle[a]
Hettiarachchi et al. [7]	**Kalina Cycle** Turbine inlet temperature = 90 °C Turbine inlet pressure = 15 to 40 bar Ammonia fraction (X) = 0.7 to 0.95 **Organic Rankine Cycle** Turbine inlet temperature = 90 °C **Working fluid**: Ammonia Turbine inlet pressure = 15 to 40 bar **Working fluid**: Isobutane Turbine inlet pressure = 5 to 15 bar	• For given conditions, an optimum range of operating pressure and ammonia fraction that result in the best overall cycle performance can be identified. • Generally, for moderate turbine inlet pressures, the KCS 11 performs better than the ORC.	Input parameters TIT = 90 °C P = 25 bar X = 0.8 Output parameters η_{th} = 8.7%
Guzović et. al. [8]	**Kalina Cycle** Geofluid temperature = 176 °C Turbine inlet temperature = 108.8 °C Turbine inlet pressure = 28 bar Ammonia fractions (X) = 0.885 **Organic Rankine Cycle** Turbine inlet temperature = 110 °C Turbine inlet pressure = 9 bar **Working fluid**: Isopentane	• The ORC is more convenient to be utilized at medium geothermal heat sources while the Kalina cycle performs better at lower geothermal source temperature. The difference in performances however, is not significant. • Considering the problems associated with new technologies experience in the starting phase, for geothermal sources with lower temperatures in Croatia, the application of ORC with binary working fluid is proposed.	Input parameters TIT = 108.8 °C P = 28 bar X = 0.885 Output parameters η_{th} = 10.6% η_{ex} = 44%
Rodríguez et. al.[9]	**Kalina Cycle** Geo-fluid Temperature = 90 to 140 °C Turbine inlet temperature = 80 to 130 °C Turbine inlet pressure = 15 to 50 bar Ammonia fractions (X) = 0.65, 0.75 and 0.84 **Organic Rankine Cycle** Geo-fluid Temperature = 90 to 140 °C Turbine inlet temperature = 80 to 130 °C Working fluid: *i*-butane, *n*-butane, *i*-Pentane, *n*-Pentane, R13aa, R141b, R142b, R290, R40, R152a, R-11, R-12, R-113, R-114, R-21, NH_3	• For the Kalina cycle, the best performance was obtained with 84% ammonia + 16% water in ammonia–water solution as working fluid. With this working fluid, compared to the ORC, the Kalina cycle offers 18% more output power, requires 37% less mass flow rate and achieves 17.8% lower levelized electricity cost. • For Organic Rankine cycle, the best performance was obtained with R-290 as working fluid.	Input parameters Geothermal source Temperature = 100 °C TIT = 90 °C P = 25 bar X = 0.84 Output parameters η_{th} = 6% η_{ex} = 36.5%
Singh et. al. [10]	**Kalina Cycle** Source: exhaust gas Turbine inlet temperature = 132.6 °C Turbine inlet pressure = 15 to 40 bar Ammonia fraction (X) = 0.5 to 0.9	• For a given turbine inlet pressure, there is an optimum value of ammonia fraction that yields in the maximum cycle efficiency. • Specification of different ammonia mass fraction for higher performance in literature may be due to the difference in the correlations used for ammonia–water mixture properties and/or due to the difference in the algorithms used in the simulation procedure. • An Increase in the turbine inlet pressure is more effective that an increases in the ammonia mass fraction for having efficient cycle.	Input parameters T = 132.6 °C P = 25 bar X = 0.8 Output parameters η_{th} = 9%
Li et. al. [11]	**Kalina Cycle** Geofluid temperature = 120 °C Turbine inlet temperature = 91, 98 and 108 °C Turbine inlet pressure = 10 to 40 bar Ammonia fraction = 0.6, 0.7 and 0.8 **CO_2 transcritical power cycle (CTPC)** Geofluid temperature = 120 °C Turbine inlet temperature = 91, 98 and 108 °C Turbine inlet pressure = 10 to 40 bar	• The output power and thermal efficiency of the Kalina cycle are higher than those of the CTPC, while a reverse result is achieved for exergy efficiency. • The adoption of the Kalina cycle may be reasonable in the low-temperature geothermal sources due to the better thermo-economic performance in contrast to the CTPC.	Input parameters TIT = 91 °C P = 25 bar X = 0.8 Output parameters η_{th} = 7 % η_{ex} = 39%

[a] The input data are approximately the same as the ones in the present work.