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Exergoeconomic analysis and multi objective optimization of performance of a Carbon dioxide power cycle driven by geothermal energy with liquefied natural gas as its heat sink

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ABSTRACT

In this study a transcritical Carbon dioxide power cycle has been coupled to a liquefied natural gas to work either as the cold source and to further enhance to generate electricity. The detailed thermodynamic analysis is performed in order to investigate the effect of key parameters on the cycle performance. Also, heat exchangers are measured to find the heat transfer surface area for economic evaluation. To investigate the aforementioned cycle and for optimization purposes, an exergoeconomic analysis is done to know the important components with respect to exergoeconomic criterion. The exergoeconomic analysis reveals that Carbon dioxide turbine and condenser have the highest rate of sum cost rate associated with capital investment and the cost of exergy destruction and special attention should be paid to these components. The parametric analysis shows that there is an optimum turbine inlet pressure which brings about the highest exergy efficiency and lowest product cost rate. Moreover, the condensate pressure has the highest effect on system exergy efficiency compared to others. With the help of multi-objective optimization, the cumulative effects of these variables are investigated on the system to maximize the exergetic efficiency and to minimize the product cost rate of the system. Results show that the system is capable of producing power with exergy efficiency and product cost rate equal to 20.5% and 263592.15 \$/year, respectively, according to technique for order of preference by similarity to ideal solution decision making technique. Also, the system exergy efficiency of 22.1% and 295001.26 \$/year product cost rate is achieved through linear programming techniques for multidimensional analysis of preference technique and 23.97% exergy efficiency and 370378.758 \$/year product cost rate is given with FUZZY decision making technique.

1. Introduction

An enduring area of interest for engineers, in which lots of work has been performed, is the conversion of heat to electricity. Recently, there is growing interest in utilizing low and moderate temperature heat sources, which are available via solar, geothermal and biogenic energy systems, and as waste heat from industries. For producing power, one can consider such cycles as ORCs (organic Rankine cycles) [1–10], Kalina cycles [13–17] and trilateral cycles (TLCs) [18,19].

DiPippo [2] compared the ORC and the Kalina geothermal plant through the second law of thermodynamics and suggested an approach to evaluate the plant efficiencies with analogous environmental settings and inputs. Tchanche and colleagues [3] demonstrated several uses of organic Rankine cycles as a tool for power generation by employing low grade heat. Saleh and colleagues [4] investigated the thermodynamic performances of 31 pure working fluids for organic Rankine cycles on the basis of the BACKONE equation of state. Properties of a good fluid are: high efficiency, low specific volumes, low cost, moderate pressures in the heat exchangers, low ODP, low toxicity and low GWP among others. Maizza and Maizza [5], Badr and colleagues [6] are some of the scholars who investigated the features of various working fluids in view of their selection in an ORC use. Hettiarachchi et al. presented a cost-effective optimum design criterion for ORCs utilizing low temperature geothermal heat sources. The optimum cycle performance was compared for various working fluids including ammonia, HCFC123, n-Pentane, and PF5050 [7]. Drescher

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Nomenclature

T	temperature (K)
W	power (kW)
m	mass flow (kg/s)
Cp	specific heat (kJ/kg K)
TIP	turbine inlet pressure
TIT	turbine inlet temperature
p	pressure (bar)
h	specific enthalpy (kJ/kg)
E	exergy (kW)
e	specific exergy (kJ/kg)
Q	heat (kW)
s	specific entropy (kJ/kg K)
Z	capital cost rate ($/year)
c	cost per unit exergy ($/GJ)
C	flow cost rate ($/year)
i	inlet

o	outlet
0	ambient condition
ph	physical
ch	chemical
H	plant life time (year)
A	area (m^2)
U	total heat transfer coefficient
r	relative cost difference (%)
f	exergoeconomic factor (%)

Greek symbol

η	exergy efficiency

Subscript

HX	heat exchanger

and Bruggemann [8] developed software to find thermodynamically suitable fluids for ORC in biomass power and heat plants. Yamamoto et al. designed an ORC by using an electric evaporator instead of an external heat source. R123 and water were used as the working fluids and experiments were conducted to compare each fluid. Its maximum cycle efficiency and electric power were shown to be 1.25% and 150 W, respectively [9]. Zhang and colleagues [10] evaluated the economic and thermodynamic performance for low-temperature geothermal power plant of both transcritical and subcritical ORC power cycle systems. Various researches have been carried out to study the Kalina cycle, which was originally considered by Kalina [11]. El-Sayed and Tribus [12] conduct a theoretic evaluation of the Kalina cycle with Rankine cycle. The arrangements proposed by them were very much complex owing to a number of heat exchangers had more than two steams. Ashouri et al. [13] performed an exergy analysis on a Kalina cycle driven by Trough collector. Marston [14] carried out the parametric analysis of the Kalina cycle. He suggested an approach of settling the Kalina cycle and recognized the main variables for optimizing the Kalina cycle. Rogdakis [15] suggested formulas explaining the optimal operation of the Kalina cycle. Marston [16] evaluated the Kalina cycle with triple pressure. He found that Kalina cycle was more effective than the triple pressure steam cycle. Zamfirescu and Dincer [18] analyzed trilateral ammonia–water Rankine cycle that uses no boiler, but rather the saturated liquid is flashed by an expander. Fischer [19] found that exergy efficiency for power production is higher by 14–29% for the TLC with the two-phase expander utilization in comparison to the ORC. Exploitation of renewable energy has become an important topic due to the energy shortage and growing carbon dioxide emissions. Although the organic Rankine cycle systems, which contain lower boiling temperature working fluids, have great advantages and suitability for utilizing low-temperature heat source to produce useful power [20–22], there is a pinch point occurred between working fluid and heat source in a constant temperature boiling process of a pure fluid. In additional, with the development of the Kalina cycle for geothermal energy and waste heat applications, turbines with NH_3–H_2O as working fluid are existing technologies. There have been some commercial power plants using NH_3–H_2O for geothermal energy or industrial waste heat, such as Husavik plant in Iceland, Unterhaching plant in Germany, and several plants in Japan [20]. The technical feasibility of ORC application in general low-grade heat utilization has already been investigated and validated [21]. This minimal temperature difference results in a largest resistance in heat transfer and causes a significant destruction in energy conversion [23]. Chen et al. [23] implemented a thorough reasonable investigation for low-grade heat conversion between a R32-based and a CO_2-based transcritical Rankine cycle by exergy and energy analysis. Walraven and colleagues [24] studied the low-temperature geothermal sources by optimizing and investigating the performance of various groups of Kalina and ORC cycle.

Various studies were carried on the supercritical and transcritical CO_2 power generation cycles. Velez and colleagues [25] compared and investigated a CO_2 transcritical power cycle without and with an internal heat exchanger. Wang and colleagues [26] carried out an exergy analysis and a parametric analysis for supercritical CO_2 power cycle besides they made attempt to optimize the exergy efficiency via ANN and genetic algorithm (GA). Baik and colleagues [27] compared and optimized the power output between a R125 transcritical cycle and a CO_2 transcritical cycle for the exploitation of low-grade heat source of about 100 °C. Lakew and colleagues [6] by employing low temperature heat source and substitution the mechanical pump by a thermal driven pump, the performance of a supercritical CO_2 Rankine cycle enhanced.

Lin and colleagues [28] studied a transcritical CO_2 Rankine cycle which employed the liquefied Natural Gas (LNG) firstly as heat sink. Gao and colleagues [29] suggested two new light hydrocarbon separation processes via employing the cryogenic energy of LNG. Mehrpooya et al. [30] has investigated a novel integrated air separation processes, cold energy recovery of liquefied natural gas and carbon dioxide power cycle. Wang and colleagues [31] conducted a MOEA and a thermodynamic analysis for an ammonia-water power system works with LNG as heat sink. Song and colleagues [32] used the LNG to cool the exhausted gas from the turbine in a solar-driven transcritical CO_2 power cycle. Few of these aforementioned researches has conducted a MOEA for the supercritical or transcritical CO_2 power generation system with LNG as heat sink and carried out the performance analysis from the economical point of view.

In recent years, exergoeconomic concept has been applied in power plants and CCHP system analyses [33–44]. A techno-economic analysis of a ground heat pump system was carried out by Esen and colleagues [33]. Also they compared it with traditional heating system. From economic and efficiency viewpoints, the suggested heat pump system is valuable, except for natural gas. Esen and colleagues [34] implemented the same evaluations on horizontal ground heat pump systems. The outcomes of their analyses reveal that for a heat pump system at the depth of two meters the