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Research Paper

Thermodynamic and exergy analysis and optimization of a transcritical CO_2 power cycle driven by geothermal energy with liquefied natural gas as its heat sink

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HIGHLIGHTS

- A small scale transcritical Carbon dioxide cycle is investigated.
- Exergy analysis of a transcritical CO_2 power cycle driven by geothermal energy with liquefied natural gas as its heat sink.
- Multi-objective optimization approach is carried out for performance optimization.
- Three decision-making methods are employed to select final answers.

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ABSTRACT

The main objective of this research is to study a transcritical CO_2 cycle via geothermal resources to produce electrical energy. Heat sink of this cycle is Liquefied natural gas (LNG) to drop back pressure of the CO_2 turbine greatly. It is presumed that the system works under steady state situations to establish the mathematical model of the transcritical CO_2 geothermal power generation system. To evaluate the impacts of different main thermodynamic parameters in the performance of the system a parametric investigation is employed. Furthermore, to determine an optimum system performance from an economical and thermodynamic point of view, a multi-objective optimization jointed to NSGA-II algorithm is employed. To calculate the final solution three decision makers comprising TOPSIS, LINAMP and FUZZY were use. Moreover, sensitivity analysis and error examination were performed on the solutions gained from the decision makers. In conclusion, outputs achieved from this investigation were compared to the other related studies and this comparison reveals that the solutions gained in this study are satisfactory compared to the previous works.

1. Introduction

Sustainable development is among the major issues in the World. Economical and environmental topics may be considered as two of the most important one. Especially clean and sustainable energy production should be really focused on because of the increasing energy need and the environmental problems. Besides economical problems, environmental issues, such as global warming, have begun to affect our life concretely. Obtaining energy from the fossil fuels is the most important reason of the environmental pollution. For preventing the environmental problems as well as economic aspects, more efficient energy conversion tools are required.

Huge efforts exist for designing more efficient thermal cycles. First studies about investigating actual thermal cycles were conducted by Curzon-Ahlborn and Novikov [1,2]. They presented famous Curzon-Ahlborn-Novikov (CAN) engine that is the endoreversible (internally reversible, however external irreversible). Thus, finite-time thermodynamic (FTT) was developed. First FTT research was about a cycle called as Curzon-Ahlborn-Novikov (CAN) engine which is endoreversible (it is external irreversible, but internal reversible) [1,2]. Finite time thermodynamics (FTT), as a branch of modern thermodynamics, is a valuable theory in performance analyses of various thermodynamic cycles [3–10].

Recently, there is growing attention in using moderate and low temperature heat sources that are obtainable through geothermal, solar, waste heat from industries and biogenic energy systems. To generate power, we can consider various cycles including ORCs (organic Rankine cycles) [11–22], Kalina cycles [23–31] and TLCs

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(trilateral cycles) [32–37]. Although the ORC systems, have great advantages and suitability for utilizing low-temperature heat source to produce useful power [38–40], there is a pinch point happened between heat source and working fluid in a constant temperature boiling process of a pure fluid. This minimum temperature difference follows by a largest resistance in heat transfer and results in a major destruction in energy conversion [41]. Chen [41] carried out a comprehensive study for low-grade heat conversion between a CO_2-based and a R32-basedtranscritical Rankine cycle via energy and exergy analysis.

Zhang et al. [20] examined the economic and thermodynamic performance for low-temperature geothermal power plant of both subcritical and transcritical ORC power cycle systems. DiPippo [12] compared the Kalina and the ORC geothermal plant with the aim of the second law of thermodynamics and proposed a method to compare the plant efficiencies with similar environmental circumstances and inputs. Walraven et al. [42] investigated the low-temperature geothermal sources via analyzing and optimizing the performance of different categories of Kalina and ORC cycle. Arslan and colleagues [43,44] carried out a thermodynamic optimization for a Kalina and an ORC geothermal power plant via the ANN model, correspondingly.

Velez et al. [45] studied and evaluated a CO_2 transcritical power cycle with and without an internal heat exchanger. Wang et al. [46] implemented an exergy analysis and a parametric analysis for supercritical CO_2 power cycle. Furthermore, they tried to optimize the exergy efficiency through hybrid of genetic algorithm (GA) and ANN. Baik et al. [47] optimized and compared the power output between a CO_2 transcritical cycle and a R125 transcritical cycle for the utilization of low-grade heat source of about 100 °C. Lakew et al. [16] improved the performance of a supercritical CO_2 Rankine cycle through replacement the mechanical pump by a thermal driven pump and using low temperature heat source. Kim et al. [48] suggested a partial condensation transcritical CO_2 cycle by employing both the high temperature and low-temperature heat source, and compared it with the basic Brayton and transcritical CO_2 Rankine cycle via exergy and energy analysis. Zhang and colleagues [49,50] studied a supercritical CO_2 Rankine cycle driven via solar energy correspondingly for joint heat generation and power and hydrogen production.

Lin et al. [51] investigated a transcritical CO_2 Rankine cycle where the heat sink was the liquefied Natural Gas (LNG). Gao et al. [52] proposed two different light hydrocarbon separation processes through using the cryogenic energy of LNG. Salimpour and colleagues [53] employed LNG as a heat sink of middle-pressure nitrogen gas cycle besides to cool the inlet air of a Brayton gas turbine cycle they used the cold energy of LNG. Wang et al. [54] carried out a thermodynamic analysis and a MOEA for an ammonia-water power system operates where heat sink is LNG. To cool the exhausted gas from the turbine in a solar-driven transcritical CO_2 power cycle, Song et al. [55] employed the LNG.

One of the main tools for optimization in engineering area is multi-objective optimization. For answering a multi-objective issue, different algorithms (i.e., evolutionary algorithms (EA)) were proposed to overcome multi objective issues [59,60]. Multi-objective optimization approach has frequently been used in area of energy systems optimization [60–85]. Özyer et al. [56] developed a machine learning approach for prospect computation via evolutionary algorithms. However, MOEA was used in other area of engineering issue, for instance, vehicle routing problems with Time Windows [57]. Moreover, Blecic et al. [58] developed a decision support system named Bay MODE based on the MOEA and Bayesian analysis.

This paper investigates a transcritical CO_2 geothermal power generation system via the cold energy exploitation of LNG. The influences of different main thermodynamic variables on the performance of the system are evaluated via developing the mathematical approach for simulating the system under steady-state circumstances. Moreover, a MOEA is employed to achieve a modified performance of the system via NSGA-II algorithm. In first scenario, three objective functions comprising the total heat exchange area is minimized and the ECOP and exergy-based ecological function are maximized simultaneously via employing multi objective optimization algorithms. In second scenario, three objective functions comprising the total heat exchange area is minimized and the exergy efficiency and Exergetic performance criteria are maximized concurrently through MOEA. To calculate the final solution three decision makers comprising TOPSIS, LINAMP and FUZZY were use. Furthermore, sensitivity analysis and error examination were performed on the solutions gained from the decision makers

2. System description

Fig. 1 depicts the graphical illustration of the transcritical CO_2 geothermal power production system through the cold energy utilization of LNG. The deep underground geothermal water was used and conveyed to the evaporator. The geothermal water is formerly re-injected to the underground later discharging a vast heat value. To pressurize the liquid CO_2 from condenser to the supercritical condition the supporter pump I was used. To acquire the heat and produce high temperature and high pressure supercritical CO_2 vapor, this liquid CO_2 then flow in the evaporator. Expansion process of the supercritical CO_2 vapor was occurred through CO_2 turbine to push the electrical generator to produce electrical energy. The LNG in the storage tank pressurized initially via the booster pump II to rise LNG pressure to a supercritical pressure. LNG plays role of a heat sink in the condenser to reduce the temperature of the exhausted gas from the CO_2 turbine. It nonstop comes into the heater and absorbs heat from environmental water to increase the heated natural gas temperature. Through a natural gas turbine the high pressure heated natural gas expands to produce electrical energy. Lastly, the exhausted natural gas from the natural gas turbine is transmitted to the natural gas entertaining station to put forward natural gas to the customers.

Fig. 2 demonstrates the plot of enthalpy versus temperature for the geothermal power generation system. Employing the cold energy of LNG for reducing the CO_2 turbine back pressure is the main advantage of this process because it results in increasing in the output power of the CO_2 turbine. Moreover, the natural gas heated through the environmental water expansion by the NG turbine also enhanced the output power of the whole system.

3. Mathematical models and performance criteria

3.1. Mathematical models

With the purpose of simplifying the mathematical model of the entire system, the below presumptions were taken into account:

1. The system operates under steady state situations.
2. The heat transfer between the equipment of the system and the environment is neglected.
3. The pressure changes in the pipe constructions are neglected.
4. The CO_2 at the condenser outlet is saturated liquid.

The abovementioned system is normally contained four groups of amenity comprising turbine, heat exchanger, condenser and pump. Based on the conservation theory we have following equations: