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A comparative thermodynamic analysis of two tri-generation systems utilizing low-grade geothermal energy

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ABSTRACT

A comparative thermodynamic analysis and optimization is presented for two different designs of geothermal energy-based tri-generation systems. The two considered systems are distinguished by their power generation units, as organic Rankine cycle is employed in one system while Kalina cycle is used in the other system. To provide cooling and heating loads, a LiBr/water absorption chiller and a water heater are coupled to the Organic Rankine and Kalina cycles. To assess the systems' performances, thermodynamic models are developed and a parametric study is carried out prior to the optimization with respect to the second law efficiency, as the objective function. Also, an exergy destruction modeling is conducted to identify the major sources of irreversibilities within the components of the considered systems. The Kalina cycle-based system is found to be more efficient as its maximum second law efficiency is 50.36% while the organic Rankine cycle-based system has a maximum second law efficiency of 46.51%. The results also indicate that, for a heat source temperature of 120 °C, the Kalina cycle-based system can produce more power than the other system by around 12.2%, under the optimized conditions.

1. Introduction

Increasing energy consumption and environmental impacts of fossil fuels, have urged the researchers to pay more attention on switching toward renewable energy resources. Among the renewable energies, geothermal one is a promising and reliable source which is mainly used for power generation, heating and cooling applications, industrial drying, distillation and desalination, depending on the source conditions. Simultaneous production of power, heating and cooling, which is referred to as tri-generation, is one of the most promising technologies with technical, economical and environmental benefits [1].

Different heat sources and technologies have been employed in the literature as the fuel and prime movers for tri-generation systems. Natural gas is the most commonly used fuel while the Internal Combustion Engines (ICE), gas turbines and fuel cells are of the most common prime movers considered for tri-generation systems [1]. Many research works have been presented in the literature employing the mentioned prime movers for Combined Cooling, Heating and Power (CCHP) systems. The performance of a tri-generation system using a 6.5 MW gas–diesel engine, combined with a HRSG and an absorption chiller, is analyzed by Balli et al. [2], who showed that, the energy and exergy efficiencies of the system are 58.97% and 36.13%, respectively. Rey et al. [3] examined the performance of micro-CCHP system based on a Honda IC gas engine and validated the model with experimental data. They showed that their system is an appropriate one for use as a stand-alone system in buildings to produce electricity, heating and cooling. For an office building in Hong Kong, the performance of three types of tri-generation systems, driven by ICEs, are investigated and compared with a conventional chiller powered by the grid electricity [4]. The results indicated that, the year-round total electricity demand from the building is reduced by 10.4% for the natural gas–fueled engine. For an ICE-based tri-generation system, two different operational strategies are investigated and compared by Santo [5]. His results revealed an energy utilization factor between 65% and 81% and an exergy efficiency between 35% and 38.4%. Parise et al. [6] analyzed the performance of a tri-generation system in which a biofuel-driven compression ignition engine is employed as the prime mover. They reported a reduction of around 50% and 95% in primary energy consumption and CO_2 emissions, respectively. In an experimental investigation, Angrisani et al. [7] proposed a micro tri-generation system based on a natural gas–fueled ICE coupled with an absorption cooling unit. They reported that, besides providing a considerable reduction of greenhouse gas emissions, the system produces 5.4 kWe power. Another experimental investigation of a micro-CCHP system with a diesel engine coupled to an absorption chiller is performed by

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Nomenclature

$\dot{E}$	exergy rate (kW)
h	specific enthalpy (kJ kg^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
P	pressure (bar)
$\dot{Q}$	heat transfer rate (kW)
s	specific entropy (kJ kg^{-1} K^{-1})
T	temperature (°C or K)
$\dot{W}$	power (kW)

Subscripts and abbreviations

0	ambient
a	actual process
AB	absorber
AC	absorption chiller
CCHP	combined cooling, heating and power
CD	condenser
D	destruction
DWH	domestic water heater
EVA	evaporator
EUF	energy utilization factor
EX. V.	expansion valve
GB	geothermal brine
Gen	generator
HTR	high temperature recuperator
KC	Kalina cycle
LTR	low temperature recuperator
ORC	organic Rankine cycle
P	pump
PP	pinch point
s	isentropic process
SHE	solution heat exchanger
SEP	separator
T	turbine

Greek symbols

η_{ex}	second law efficiency
η_P	pump isentropic efficiency
η_T	turbine isentropic efficiency
ε	heat exchanger effectiveness

Khatri et al. [8]. They showed that, the thermal efficiency of the system is 86.2% with 60.71% reduction on the CO_2 emissions.

For a tri-generation system, consisting of a 30 MW gas turbine coupled to a H_2O/Li–Br absorption refrigeration cycle, conventional and advanced exergetic and exergoeconomic analyses are performed by Anvari et al. [9] who indicated that around 29% of the total exergy destruction and overall cost rates associated with exergy destruction are endogenous-avoidable. Another gas turbine-based system with 100 MW power production, 70 MW heat and 9 MW cooling capacity is considered as a tri-generation unit by Salehzadeh et al. [10], for which the effects of various parameters on the endogenous and exogenous exergy destructions and fuel consumption are investigated. Arsalis et al. [11] analyzed the performance of a tri-generation system consisting of a gas turbine and a double-effect absorption chiller unit. They concluded that the considered CCHP system, with a 10 MWe gas turbine, would be able to cover the needs in electricity, heating and cooling of approximately 21,000 average households. A test rig of a tri-generation system, using a gas turbine as the prime mover, is set up by Ge et al. [12] to investigate the system feasibility and performance. They validated their theoretical model with the test results and analyzed the system performance at different operating and design conditions, such as: ambient temperature, fuel flow rate and pressure ratio.

Recently, some research works have been devoted to analyze tri-generation systems with fuel cell prime movers. Al-Sulaiman et al. [13] proposed a tri-generation system based on a solid oxide fuel cell and organic Rankine cycle coupled with an absorption chiller and conducted the energy analysis of the system. The results indicated a tri-generation efficiency of 74%, cooling cogeneration efficiency of 57% and heating cogeneration efficiency of 71%. Energy, exergy and exergoeconomic assessments for a novel tri-generation system based on a solid oxide fuel cell coupled to a GAX absorption refrigeration system are performed by Chitsaz et al. [14,15]. For their proposed system, they reported the maximum values of 79% and 47% for the energy and exergy efficiencies, respectively. Tippawan et al. [16] analyzed the performance of a tri-generation system based on an ethanol-fueled SOFC integrated with an absorption chiller through energy and exergy analyses. They concluded that there is at least a 32% gain in efficiency in the tri-generation plant compared to the conventional power cycle. Another integrated SOFC-CCHP system, based on a LiBr/H_2O absorption refrigeration cycle and fueled by coke oven gas, is proposed and investigated by Zhao et al. [17] who reported an overall tri-generation efficiency of about 90%.

In addition to the above mentioned tri-generation systems, other technologies are introduced in the literature to serve as prime movers for CCHP applications. These technologies consist of: steam turbine and ORC-based CCHP systems, solar energy-driven technologies, biomass-driven tri-generation systems, stirling engine-based tri-generation systems and systems with multiple prime movers. For a novel ORC-based multi-generation system producing power, pure water, cooling and heating, Mehr et al. [18] reported the maximum thermal and exergy efficiencies of 89.2% and 43.05%, respectively. Boyaghchi and Heidarnejad [19] analyzed a micro solar-energy based CCHP system integrated with an ORC for summer and winter seasons. They concluded that the thermal and exergy efficiencies and the product cost rate are 23.66%, 9.51% and 5114.5 $/year, respectively. For a solar energy-based CCHP system with flat-plate solar collectors, a multi-objective optimization is conducted by Wang et al. [20] using genetic algorithm for power mode, CHP mode, and CCP mode. A biomass-fueled CCHP system is investigated by Wang et al. [21], who reported a maximum energy efficiency of 37% for the proposed system in summer operation mode. Karellas et al. [22] conducted thermodynamic modeling and economic analysis for a tri-generation system utilizing biomass fuel and solar energy. The economic analysis showed that the savings in fuel oil and electricity consumption account for an IRR of 12%, with a payback period of 7 years. Design, simulation and optimization of a small tri-generation plant supplied by geothermal and solar energies, with a 6 kW micro ORC and a 30 kW single effect LiBr/H_2O chiller is presented by Buonomano et al. [23]. They concluded that for the most convenient considered scenario for working and funding conditions, the payback period is 2.5 years.

Based on the above explained literature review, the literature lacks about geothermal energy-based tri-generation systems. Also, for low and medium heat source temperatures no attention is paid to the Kalina Cycle (KC) as the power generating device in tri-generation systems and comparing its performance with the well-known Organic Rankine Cycle (ORC). The present study aims to address this shortcoming in which the performance of a KC is