Applied Thermal Engineering 133 (2018) 645–658

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Process development and thermodynamic analysis of a novel power generation plant driven by geothermal energy with liquefied natural gas as its heat sink

Mirhadi S. Sadaghiani[a,*], M.H. Ahmadi[b,*], Mehdi Mehrpooya[a,c], F. Pourfayaz[a], Michel Feidt[d]

[a] Renewable Energies and Environment Department, Faculty of New Sciences and Technologies, University of Tehran, Tehran, Iran
[b] Faculty of Mechanical Engineering, Shahrood University of Technology, Shahrood, Iran
[c] Hydrogen and Fuel Cell Laboratory, Faculty of New Sciences and Technologies, University of Tehran, Tehran, Iran
[d] Laboratoire d'Energétique et de Mécanique Théorique et Appliquée, ENSEM, 2, avenue de laForêtde Haye, 60604 54518 Vandoeuvre, France

HIGHLIGHTS

- A novel combined power generation plant has been introduced.
- The power plant consists of two ORCs and one Kalina power cycle.
- Suitable working fluids for ORCs have been selected.
- The effect of the various decisive factors on the performance of the plant has been investigated.
- The optimum operating point of the system has been found by the results of the analyses.

ARTICLE INFO

Keywords:
Organic Rankine cycle
Geothermal energy
Liquid natural gas
Exergy analysis
Cold energy recovery

ABSTRACT

ORC and Kalina cycles can produce power from low-temperature heat sources. There is, also, a great potential in Liquid Natural Gas gasification units to generate power derived from cold energy within these streams. This work proposes a new power generation plant to convert the trapped energies of geothermal hot water and Liquid Natural Gas streams to useful power. The combined power plant consists of 7 units, which each unit includes three discrete cycles of Kalina and two Organic Rankine power generation cycles to produce power from its heat sources. Geothermal hot water is supplied at 163 °C and pressure of 7 bar with a mass-flow of 39 kg/s from a geothermal well, and moreover, natural gas is supplied at −162 °C and pressure of 10 bar with a mass-flow of 8 kg/s to each unit of the power plant as a cold source. Energy and exergy analyses have been employed to evaluate the performance of the proposed plant. The energy analysis shows that each unit of the proposed plant could produce 1924 kW net power and the energy efficiency of each unit is 13.25%. On the other hand, the exergy analysis reveals that the exergy efficiency of each unit of the proposed plant is 26.13%, while each unit could recover 57% exergy of the LNG stream. Considering the results of the energy and exergy analyses along with sensitivity analysis, the system is amended to maximize the exergy efficiency, which after implementing modifications, the exergy efficiency of the system increases to 32.15%. Also, the net power output of each unit increases to 2485 kW after modifications.

1. Introduction

The upward trend of the energy demand in contemporary societies is one of the most challenging problems that authorities are confronting with due to such various factors as depletion of fossil fuels, the detrimental effects of using such polluting energy carriers and the vulnerable circumstances of the environment. Today, it is upon fossil fuels that most of energy supply chains rely, reflecting the dire needs for reasonable and effective solutions to be suggested. In recent years, the growing consensus is that renewable energies are the possible solution which a glaring future is deemed for these energy carriers. Amongst sundry renewable energies, geothermal energy has introduced itself as one the most reliable energy resources that could dwindle the amount of GES emissions in the context of the power generation. According to

* Corresponding authors.
E-mail addresses: Hadisadagiani@ut.ac.ir (M. S. Sadaghiani), mhosein.ahmadi@shahroodut.ac.ir (M.H. Ahmadi).

https://doi.org/10.1016/j.applthermaleng.2018.01.077
Received 15 October 2017; Received in revised form 30 December 2017; Accepted 21 January 2018
1359-4311/

Nomenclature

G	Gibbs free energy (kJ/kg mol)
I	irreversibility (kW)
e	exergy (kJ/kg mol)
E	exergy (kJ/s)
T	temperature (°C)
P	pressure (bar)
s	entropy (kJ/kg mol °C)
h	enthalpy (kJ/kg mol)
x	component mole fraction
$\dot{m}$	flow rate (kg mol/h)
Q	heat duty (kW)
$\dot{W}$	work transfer rate (kW)

Greek letters

η	energy efficiency
ε	exergy efficiency
ϵ	cold recovery efficiency
Δ	gradient

Subscripts

in	inlet
i	component
o	outlet
REV	reversible
sh	shaft
a	air
D	destruction
h	hot
c	cold
F	fuel
P	product

Superscripts

ΔP	pressure component
ΔT	thermal component
°	standard condition
ph	physical
ch	chemical
mix	mixture

Abbreviations

ORC	organic Rankine cycle
HE	heat exchanger
tot	total

International Energy Agency, the share of the geothermal energy in energy supply by 2050 can account for 3.5% of the total energy demand if the resources will be well exploited. The Organic Rankine Cycle (ORC) and Kalina power generation cycle, moreover, are the most appropriate cycles for energy generation using low-temperature reservoirs.

A certain number of studies have been conducted in literature endeavoring to propose a well-optimized Organic Rankine and Kalina cycles due to the relatively low thermodynamic efficiency of these power generation cycles, derived from their low temperature heat sinks, to enjoy the economically acceptable performance. Kalina cycle has been proposed as an alternative cycle for Rankine cycle [1], which having variable boiling temperature due to multicomponent working fluid and consequently less energy dissipation in heat exchangers, recovering the energy of low temperature hear sinks by distillation not evaporation as a more efficient process are the most important advantages of this power cycle. However, the freezing temperature of water have put strict constrictions on using these cycles at lower temperature, so Rankine cycles with natural working fluid, notwithstanding the traditional fashion of energy recovery, the have been proposed to be used [2]. Overall, by integrating these cycles more effective power plants could be achievable, where Srinivas and Reddy [3] have shown that integrated power plant would have better performance than the basic heat and power combined systems.

An ORC power generation plant with HFC-245fa working fluid was analyzed and optimized by Wei et al. [4], emphasizing the point that maximum use of the hot source heat will improve the plant's efficiency and output net power. Multi-objective optimization of an Organic Rankine cycle [5], designed to recover power from a low-grade waste heat, revealed that there is flow-on effect between exergy efficiency and overall capital cost of the plant, which by increasing the former, the latter item will be increased too. The performance of an ORC system was optimized [6] with variegated working fluids, honing on the thermodynamic parameters of the ORC, which the temperature of the hot source, a waste heat, deemed to be constant. The investigation revealed that for working fluids with a non-positive slope of the saturation vapor curve, the performance of the cycle will be improved if the inlet of the turbine is in saturated vapor situation. An Organic Rankine Cycle integrated with absorption refrigeration cycle has been investigated [7], which can generate power and cooling for miscellaneous usage alike. Again, an ORC power generation plant integrated with two discrete adsorption refrigerator has been studied to evaluate its performance [8]. The study reveals that there is a high potential for employing combined ORC and adsorption cooling cycles to produce power and refrigeration simultaneously. A low-temperature ORC plant integrated with adsorption cooling system has been assessed [9], casting light on the fact that by increasing cooling temperature of the condenser, the generated power and cooling will decline. The effect of the various working fluids of ORCs has been investigated in terms of the economy [10], exposing the fact that iso-pentane is the most cost-effective working fluid among the rest at the specified operating conditions. The performance of an ORC system recovering the waste heat of an internal combustion engine has been evaluated [11], showing that working fluid with the greatest enthalpy of phase change is not always the most appropriate option. A transcritical CO_2 power generation cycle for recovery of the cold energy of LNG stream has been investigated and optimized [12]. The impact of an ORC system installed on the heavy-duty truck has been simulated and discussed [13], revealing that the performance of the truck engine coupled with ORC system is affected by the speed of the truck and engine remarkably. The thermal stability of five hydrofluorocarbons as supercritical Organic Rankine cycle's working fluid have been investigated [14]. An innovative ORC integrated with refrigeration system has been studied [15], showing that these systems could be an alternative option where mere producing electricity would be unreliable. A diesel engine combined with an ORC system recovering the wasted heat of the exhausts is studied [16], exposing that the effects of the ORC system on the acceleration performance of the engine is quite low. Various ORC system configurations for recovering energy low-temperature geothermal hot water has been investigated and optimized [17], showing that the costs associated with ORC system affect the overall performance of the plant substantially. The various characteristics of the working fluid, especially wet-to-dry transition, of the ORC system has been investigated [18], which indicates that this transition is affected by the isochoric heat capacity. Various types of ORC systems for recovering the energy from medium-low temperature waste heats has been studied [19], revealing that S-