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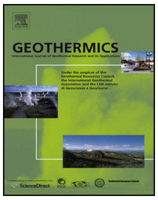

Thermo-economic analysis of combined different ORCs geothermal power plants and LNG cold energy

A.H. Mosaffa[a,*], N. Hasani Mokarram[a], L. Garousi Farshi[b]

[a] *Department of Mechanical Engineering, Azarbaijan Shahid Madani University, Tabriz, Iran*
[b] *Faculty of Mechanical Engineering, University of Tabriz, Iran*

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ABSTRACT

Thermo-economic analysis is applied to four combined liquefied natural gas (LNG) cold energy and (1) simple, (2) with internal heat exchanger, (3) regenerative and (4) dual-fluid ORCs. These power plants use geothermal fluid energy as low-grade heat source and cold energy of LNG as thermal sink. Also, after vaporization in the organic fluid condenser, natural gas expands in a turbine to generate power. The effects of operating parameters on energy and exergy efficiencies as well as total annual cost rate are studied for the proposed systems. The operating parameters considered include inlet pressure of the organic fluid and natural gas turbines, condensing temperature of organic fluid, minimum temperature difference in evaporator, inlet temperature and mass flow rate of geothermal fluid. Moreover, optimal values of operating parameters of the system are evaluated to maximize the energy and exergy efficiencies and minimize the total product unit cost. The results show that the highest energy and exergy efficiencies are obtained for regenerative system and for the system with internal heat exchanger, respectively, while the simple system has the lowest total product cost. Furthermore, the maximum net power output is obtained using dual-fluid system at the same operating condition. Also, the higher and lower total cost rate in optimum performance condition belong to dual-fluid and regenerative systems, respectively.

1. Introduction

Energy and electricity demands are increased in the industrial, commercial and utility sectors. This results the increasing of fossil fuel consumption, and therefore serious environmental pollution and energy shortage. In order to avoid these effects, many studies have recently been conducted on the use of low-grade heat source to generate power (Hung, 2001; Wei et al., 2008; Li et al., 2014; Astolfi et al., 2011; Chagnon-Lessard et al., 2016; Proctor et al., 2016). Zheng et al. (2006) thermodynamically assessed an absorption power/cooling combined cycle based on the Kalina cycle to determine the overall thermal efficiency and exergy efficiency. Wang et al. (2008) proposed a combined Rankine cycle and the absorption refrigeration cycle, which used a binary NH_3/H_2O mixture as the working fluid with only one heat source. They also presented the effect of the operational parameters on system performance and developed an optimization method to achieve the maximum second law efficiency based on genetic algorithm. Wang et al. (2009) carried out the previous work by introducing an ejector in absorption refrigeration loop to improve system performance.

Due to the high level of energy production and low global warming potential, natural gas as a fossil fuel is used widely. When natural gas is liquefied for transportation, it can be released considerable amounts of energy during the regasification process. This energy is wasted during the regasification if no recovering process is applied. For this reason, much work has been carried out on various methods to recover this energy into some form of application during regasification process. Hisazumi et al. (1998) proposed a high-efficiency power plants consisting of Rankine cycle, natural gas Rankine cycle and a combined cycle with steam and gas turbine. Miyazaki et al. (2000) thermodynamically assessed a combined NH_3/H_2O Rankine cycle using refuse incineration and a liquefied natural gas (LNG) cold energy. They also developed a parametric analysis to investigate the influence of operating parameters on the first and second law efficiencies. Wang et al. (2004) thermodynamically analyzed a combined power generation cycle with Rankine cycle and natural directly expanding cycle using LNG cold energy and the low-grade heat source. They also investigated the influence of key parameters on the energy and exergy efficiencies such as the temperature of low-grade heat source, the inlet pressure of the turbine and the condensing temperature. Zhang and Lior (2006)

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[*] Corresponding author.
E-mail address: mosaffa@azaruniv.ac.ir (A.H. Mosaffa).

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Nomenclature

A	Area (m^2)
c	Unit cost of exergy (\$ kJ^{-1})
$\dot{C}$	Cost rate (\$ s^{-1})
CRF	Capital recovery factor
$\dot{Ex}$	Exergy rate (kW)
F	Correction factor
HX	Heat exchanger
h	Specific enthalpy ($kJ\,kg^{-1}$)
i	Annual interest rate
IHX	Internal heat exchanger
LNG	Liquefied natural gas
$\dot{m}$	Mass flow rate ($kg\,s^{-1}$)
n	System life time (year)
N	Operational hours in a year (h)
ORC	Organic Rankine Cycle
P	Pressure (kPa)
$\dot{Q}$	Heat rate (kW)
s	Specific entropy ($kJ\,kg^{-1}\,K^{-1}$)
T	Temperature (°C or K)
ΔT_{lm}	Logarithmic mean temperature difference (K)
U	Overall heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
$\dot{W}$	Electrical power (kW)
$\dot{Z}$	Capital cost rate (\$ s^{-1})
Z	Capital cost (\$)

Greek symbols

ϕ	Maintenance factor
η	Efficiency

Subscripts

0	Ambient
CD	Condenser
CI	Capital investment
D	Destruction
en	Energy
ex	Exergy
EV	Evaporator
F	Organic fluid
G	Geothermal fluid
M	Natural gas
OM	Operation and maintenance
PH	Pre-heater

developed a thermodynamic model for a carbon dioxide quasi-combined two stage turbine using the LNG evaporation system as the thermal sink. The results show that thermal and exergy efficiencies can be over 65% and 50%, respectively. Shi and Che (2009) performed a thermodynamic analysis for a combined NH_3/H_2O mixture Rankine cycle and LNG cold energy to evaluate the influence of operational parameters on the system performance such as inlet pressure of ammonia turbine and the ammonia mass fraction. Liu and Guo (2011) proposed a combined cryogenic cycle using a binary mixture as working fluids and a vapor absorption process to recovery LNG cold energy. Wang et al. (2013) developed an optimization of a combined NH_3/H_2O mixture Rankine cycle and LNG cold energy to maximize the energy and exergy efficiencies. Gómez et al. (2014) proposed a combined power plant consisting of a closed Brayton cycle, a steam Rankine cycle and LNG cold energy. They also investigated the effect of key parameters on the thermal efficiency such as the compression ratio, the temperature at the compressor inlet, the inlet temperature of turbine in Brayton cycle and the LNG pressure during the regasification process.

Organic Rankine cycles (ORCs) can be one of the most effective solutions to utilize low-grade heat source and LNG cold energy as the heat sink (Lecompte et al., 2015). Choi et al. (2013) presented a thermodynamic analysis for the cascade Rankine cycle that recovers cold energy of LNG to generate power, and showed that the performance of their proposed cycles improved significantly in comparison to that of the conventional cycles. Lee et al. (2014) developed an optimization for a combined carbon dioxide ORC with steam cycle and LNG cold energy. They showed that the net power generation increased about 73% in comparison to that of the conventional power plants.

In the present work, combination of different ORCs geothermal power plants and LNG cold energy are proposed and analyses from the viewpoints of energy, exergy and economic. Typically, thermo-economic analysis of such power plants has not been reported, but is needed to provide a more comprehensive view. These systems use geothermal fluid as the heat source and LNG cold energy as thermal sink where natural gas expands in the turbine to generate power after LNG vaporization in the organic fluid condenser. Furthermore, the effects of operational parameters on performance and total annual cost for each system are investigated. The inlet pressure of the organic fluid and natural gas turbines, minimum temperature difference in the evaporators, organic fluid condensing temperature, inlet temperature and mass flow rate of geothermal fluid are considered as the operational parameters. Also an optimization is performed based on maximum energy and exergy efficiencies and the minimum total product unit cost. The present results are validated with the results reported in Yari (2010) for the stand alone ORC.

2. System description

Fig. 1 provides configurations of combined different ORCs and LNG cold energy. In the ORCs, heat of geothermal fluid and cold energy of LNG are employed as the heat source and thermal sink, respectively. After absorbing the heat of geothermal fluid in the evaporator, the organic fluid evaporates to a saturated vapor and sent to the organic fluid turbine to generate power. The organic fluid turbine exhaust is condensed to a saturated liquid in the condenser by utilizing the low temperature natural gas. The saturated liquid organic fluid is pumped to the inlet pressure of the organic fluid turbine and sent to the pre-heater before entering the evaporator to complete the cycle.

In the natural gas power generation system, the heat of the organic fluid turbine exhaust stream and the heat of geothermal fluid are used as the heat source. The saturated liquid LNG at a low temperature is extracted from the LNG storage tank and pumped into the organic fluid condenser. In the condenser, natural gas evaporates to a saturated vapor while organic fluid condenses to a saturated liquid. The saturated vapor natural gas is further heated in a heat exchanger (HX 1) by the geothermal fluid to a higher temperature and then enters the natural gas turbine. After expanding to generate power, the natural gas is heated in the heat exchanger (HX 2) and sent to the gas supplying system.

Below each proposed ORC which connected to the LNG cold energy is presented in detail.

2.1. Simple ORC

The schematic of combined simple ORC and LNG cold energy is shown in Fig. 1a. In the simple ORC, the pre-heated organic fluid enters to the evaporator and evaporates to the saturated vapor. Then the organic fluid vapor expands in the turbine to generate power. The turbine exhaust stream flows to the condenser and condenses to the saturated liquid. The pressure of saturated liq-