Energy Conversion and Management 167 (2018) 9–20

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Thermodynamic analysis of a new cascade ORC and transcritical CO_2 cycle to recover energy from medium temperature heat source and liquefied natural gas

Amirhassan Sadreddini[a], Muhammad Ali Ashjari[b,*], Maryam Fani[c], Amin Mohammadi[a]

[a] Faculty of Mechanical & Energy Engineering, Shahid Beheshti University, A.C., Tehran, Iran
[b] Faculty Member of Mechanical Engineering, Islamic Azad University Jolfa International Branch, Jolfa, East Azerbaijan, Iran
[c] Department of Energy Engineering and Physics, Amirkabir University of Technology, Tehran, Iran

ARTICLE INFO

Keywords:
Organic Rankine cycle
Transcritical carbon dioxide cycle
Exergy
LNG
Optimization

ABSTRACT

In this paper, a novel cascade cycle is proposed to recover energy from a medium temperature waste stream and a liquefied natural gas vaporization unit simultaneously. To analyze the system, its performance is compared with a single organic Rankine cycle and a single transcritical carbon dioxide cycle at the same operation conditions. Both energy and exergy analyses are applied to the system. In addition, different working fluids are examined in this study. In order to find the best configuration and working fluid, optimization algorithm is utilized. Results showed that the best performance is for a cascade cycle with Pentane as working fluid for ORC section. Its exergy efficiency is evaluated 13.08%, while the highest exergy efficiency for an ORC and a transcritical CO_2 cycle is 12.3% and 11.24%, respectively. This increase in efficiency is because of better thermal match between hot and cold streams in vapor generator and condenser sections. Based on the exergy analysis, the highest rate of exergy destruction in all cycles belongs to the preheater and condenser respectively. Finally, sensitivity analysis showed that in the proposed cascade cycle, ORC's condenser pressure and pinch temperature of the heat exchanger are the most important parameters which can significantly affect the system performance and their value should be selected carefully.

1. Introduction

Electricity demand has increased rapidly during the recent years. Based on data published by IEA [1] almost 65 percent of produced electricity throughout the world is generated by burning fossil fuels in thermal power plants. Since utilization of fossil fuels leads to environmental problems and also they are considered as an exhaustible source of energy, it is necessary to find new methods to produce clean electricity. Renewable energy has gained much attention in this respect [2], but since their technology is still very expensive, they are not being used in a widespread manner. Therefore instead of using renewable energy sources, it is suggested to increase performance of the current energy systems by recovering energy from waste heat streams.

Organic Rankine cycle (ORC) is the most well-known low temperature cycle and it is widely used in different industries. Due to its flexibility and good operation, it could be coupled with other energy systems, such as power plants [3], absorption refrigeration cycles [4], compressed air energy storage systems [5], biogas plants [6], etc. Since its first introduction, it has been studied from different aspects. Rahbar et al. [7] reviewed ORC utilization for power production considering the effect of working fluid and cycle configuration. Working fluid has an important effect on the ORC performance. Its effect has been studied by many researchers such as Vivian et al. [8], Chen et al. [9], Wang et al. [10]. Also the effect of cycle configuration on its performance has been studied by Lecompte et al. [11] and Braimakis et al. [12].

As it has been known, decreasing condenser pressure in ORC results in more power production. But the problem is that the saturation temperature of many organic fluids at low operation pressures is lower than the ambient temperature, therefore water cannot be used as the cooling agent in the condenser. To tackle the problem, some researchers suggested to use liquefied natural gas (LNG) as the cooling agent.

LNG is the liquid form of natural gas which is stored at ambient pressure, but at low temperature such as $-162\,^{\circ}C$. LNG should be converted into gas form again before being used through a process known as "regasification". This process could be done in a condenser of a power cycle in which LNG plays the role of the cooling agent [13]. Therefore the condenser can operate in lower pressures. Also, another turbine could be used in LNG cycle to generate more power [14]. Rao

* Corresponding author.
E-mail address: maliashjari@iauj.ac.ir (M.A. Ashjari).

https://doi.org/10.1016/j.enconman.2018.04.093
Received 6 January 2018; Received in revised form 23 April 2018; Accepted 24 April 2018

Nomenclature

C_p	specific heat at constant pressure [kJ/kg K]
E	exergy [kW]
e	specific exergy [kJ/kg]
$\bar{e}^{ch}$	standard chemical exergy [kJ/kmol K]
$\dot{E}^D$	exergy destruction [kW]
h	specific enthalpy [kJ/kg]
m	mass flow rate [kg/s]
Q	heat transferred [kW]
R	universal gas constant (kJ/kg K)
s	specific entropy [kJ/kg K]
T	temperature [K]
W	power [kW]
y	molar fraction

Greek letters

η	isentropic efficiency
ψ	exergy efficiency

Subscripts

ch	chemical exergy
cond	condenser
eco	economizer
eva	evaporator
hs	heat source
HX	heat exchanger
in	inlet stream
ki	kinetic exergy
out	outlet stream
ph	physical exergy
po	potential exergy
s	isentropic8
sup	superheater
tur	turbine
VG	vapor generator
w	water
wf	working fluid

et al. [15] coupled ORC to LNG system with solar energy as their heat source. They compared performance of the proposed system with separated solar ORC and LNG vapor systems and concluded that in their system, area of the solar collector and heat exchanger is reduced by 82% and 31%, respectively compared to the separated systems. Mosaffa et al. [16] performed techno-economic analysis on four different ORC configurations to recover energy from low temperature geothermal water and LNG.

It is well known that high temperature difference between hot and cold streams in a heat exchanger results in higher exergy destruction and consequently lower exergy efficiency. Power cycles which use LNG as their heat sink suffer from this fact, because temperature of the LNG is far lower than condensation temperature of the working fluid. To overcome this problem, some researchers tried to use other low temperature cycles such as transcritical carbon dioxide cycle. Walnum et al. [17] compared off-design performance of transcritical CO_2 cycle with ORC and showed that changes in available heat has a bigger effect on ORC than the transcritical CO_2 cycle which indicates that CO_2 cycle is more robust than the ORC. Therefore CO_2 cycle could be an alternative for ORC to be coupled with LNG. As an example, Wang et al. [18] coupled transcritical CO_2-LNG cycle with geothermal water and Song et al. [19] and Sun et al. [20] coupled CO_2-LNG system with solar

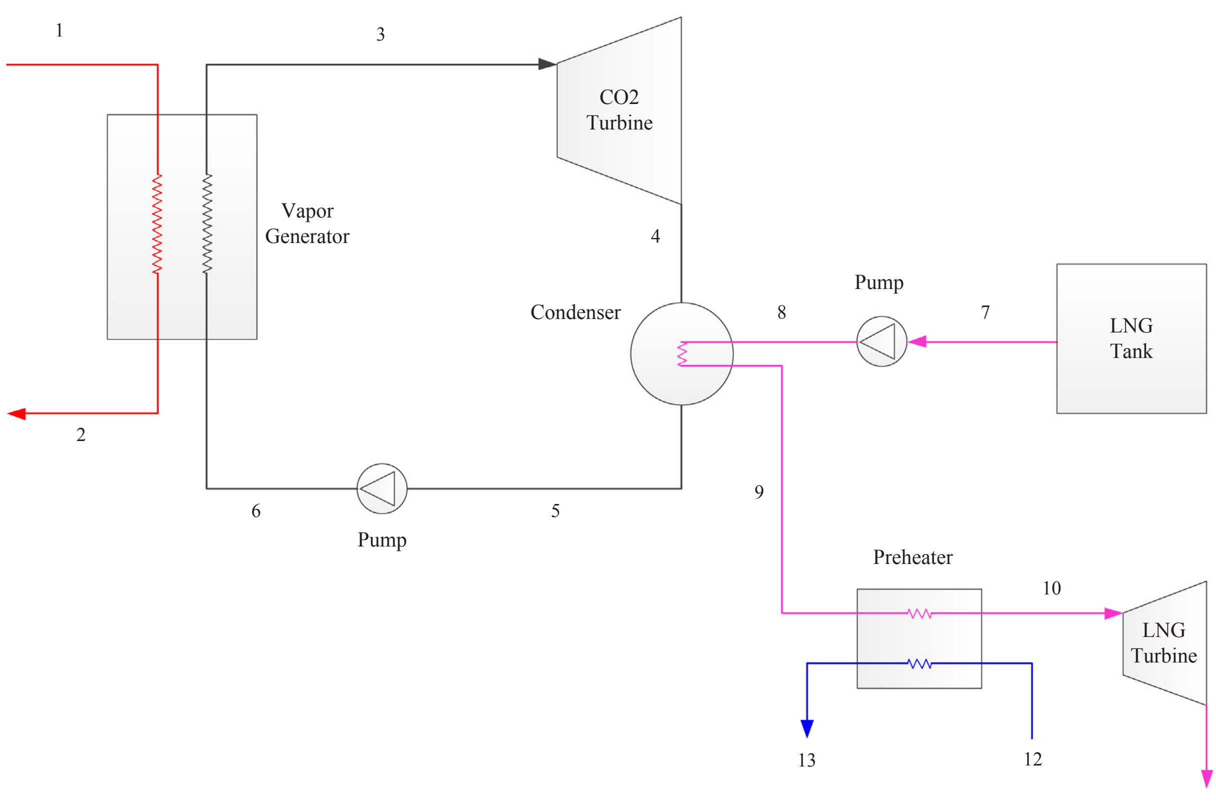

Fig. 1. Schematic diagram of the proposed transcritical carbon dioxide cycle.