Energy Conversion and Management 128 (2016) 303–316

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Thermo-economic analysis and optimization of a combined cooling and power (CCP) system for engine waste heat recovery

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ARTICLE INFO

Article history:
Received 29 June 2016
Received in revised form 28 August 2016
Accepted 27 September 2016

Keywords:
Internal combustion engine
Waste heat recovery
Brayton cycle
Organic Rankine cycle
Ejector refrigeration cycle
Optimization

ABSTRACT

A combined cooling and power (CCP) system is developed, which comprises a CO_2 Brayton cycle (BC), an organic Rankine cycle (ORC) and an ejector refrigeration cycle for the cascade utilization of waste heat from an internal combustion engine. By establishing mathematical model to simulate the overall system, thermodynamic analysis and exergoeconomic analysis are conducted to examine the effects of five key parameters including the compressor pressure ratio, the compressor inlet temperature, the BC turbine inlet temperature, the ORC turbine inlet pressure and the ejector primary flow pressure on system performance. What's more, a single-objective optimization by means of genetic algorithm (GA) is carried out to search the optimal system performance from viewpoint of exergoeconomic. Results show that the increases of the BC turbine inlet temperature, the ORC turbine inlet pressure and the ejector primary flow pressure are benefit to both thermodynamic and exergoeconimic performances of the CCP system. However, the rises in compressor pressure ratio and compressor inlet temperature will lead to worse system performances. By the single-objective optimization, the lowest average cost per unit of exergy product for the overall system is obtained.

1. Introduction

With the development of world economy and industry, the energy shortage and environmental problems caused by fossil fuel consumption have attracted more and more attention. Internal combustion engines (ICES) which act as the major source of motive power, consume a large proportion of petroleum resources in the world. It is reported that only about one-third of the fuel energy in the internal combustion engines is converted into mechanical work, the remaining energy is mainly wasted by rejecting heat to the environment through the exhaust and the coolant [1]. Therefore, it would be of great significance to recover the waste heat effectively from internal combustion engines.

The technique of organic Rankine cycle (ORC) has been proven to be a potential method to convert the engine waste heat into power, since it presents some advantages of operation flexibility and desirable efficiency [2,3]. Much work has been carried out on the ORC configurations for the engine waste heat recovery. Vaja and Gambarotta [4] examined three different ORC setups, namely a simple cycle only recovering engine exhaust gases, a simple cycle recovering both exhaust gases and engine cooling water with a preheater and a cycle with regeneration. Tahani et al. [5] introduced two different kinds of ORC including the preheat and two-stage configurations for the waste heat recovery of engine exhaust gases and coolant. He et al. [6] developed a combined thermodynamic system which contains two cycles: an ORC for the recovery of waste heat from high temperature exhaust gases and the lubricant, a Kalina cycle for the recovery of waste heat from cooling water. Wang et al. [7] studied the thermal performance of a dual-loop ORC coupled with a gasoline engine. Kim et al. [8] proposed a highly efficient single-loop ORC for the waste heat recovery of exhaust gases and coolant from a gasoline vehicle. Since the choice of working fluids had a great influence on thermodynamic performance of an ORC [9], other researchers had put their focuses on working fluid selection [10–13], considering both pure working fluids and zeotropic mixtures for ORCs used in waste heat recovery of ICEs.

Regarding all these studies mentioned above, the heat exchanges between exhaust gases and organic working fluids were conducted directly, that may cause decompositions of organic working fluids, due to the high temperature of exhaust gases (about 450–600 °C) and the low decomposition temperatures of organic working fluids (about 200–300 °C). In order to avoid this issue, an intermediate loop with thermal oil is placed between the exhaust gases and the ORC [14,15]. Although the stability

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http://dx.doi.org/10.1016/j.enconman.2016.09.086
0196-8904/

Nomenclature

A	area, m^2
Bo	boiling number
C	cost rate, $\$$ year^{-1}
CRF	capital recovery factor
$CEPCI$	chemical engineering plant cost index
c	average cost per unit of exergy, $\$$ (MW h)$^{-1}$
c_p	specific heat, kJ kg K^{-1}
D	diameter, m
E	exergy flow rate, kJ s^{-1}
f	friction factor
G	mass velocity, kg m^{-2} s^{-1}
h	enthalpy, kJ kg^{-1}
i_{eff}	interest rate
L	length, m
M	mass flow rate, kg s^{-1}
n	lifetime, year
Nu	Nusselt number
P	pressure, MPa
Pr	Prandtl number
P_t	center distance between tubes, m
p_r	reduced pressure
Q	heat transfer rate, kW
Q_{vs}	volumetric steam flow, m^3 s^{-1}
q_m	average imposed wall heat flux, W m^{-2}
r	enthalpy of vaporization, kJ kg^{-1}
s	entropy, kJ kg^{-1} K^{-1}
T	temperature, K
U	overall heat transfer coefficient, W m^{-2} K^{-1}
V	volume, m^3
v	velocity, m s^{-1}
W	power, kW
X	size or capacity parameter
x	vapor quality
Z	annually levelized cost value, $\$$ year^{-1}
Greek symbol	
α	convection heat transfer coefficient, W m^{-2} K^{-1}
η	efficiency, %
λ	thickness, m
ρ	density, kg m^{-3}
μ	dynamic viscosity, m^2 s^{-1}
π	compressor pressure ratio
Subscript	
1–29	state points
a–e	state points
0	ambient state
BC	Brayton cycle
BM	bare module
bt	BC turbine
cf	cold fluid
cnd	condensation
comp	compressor
cool	refrigeration capacity output
cond1	condenser 1
cond2	condenser 2
D	destruction
eq	equipment
es	equivalent diameter
evp	evaporation
exg	exergy
evap	evaporator
F	fuel
gh	gas heater
he	heat exchanger
hf	hot fluid
in	inside
ip	inlet pipe
L	loss
l	liquid
M	material
m	mean
ORC	organic Rankine cycle
ot	ORC turbine
out	outside
P	product; pressure
pc	precooler
pump	pump
pump1	pump 1
pump2	pump 2
sp	single-phase
sep	separator
turb	turbine
v	vapor
w	tube wall
wbt	power produced by BC turbine
wot	power produced by ORC turbine

and safety of the system could be improved through this method, the great amount of high-temperature exhaust gases heat is not exploited at all. Several studies has been performed on exploring novel dual-loop systems combined ORCs with other thermodynamic cycles for engine waste heat recovery. Mliller et al. [16] developed a system that combined ORC with thermoelectric conversion. Through a thermoelectric generator (TEG), the high temperature exhaust heat was converted into power, and the working fluid of ORC was preheated. But the application of this combined system is constrained due to the low energy conversion capacity of TEG [17]. Zhang et al. [18] analyzed the characteristics of a dual loop ORC system which was combined with a vehicular light-duty diesel engine. Yang et al. [19] explored system performance of the dual loop ORC system used for diesel engine waste heat recovery under various operating conditions. Choi and Kim [20] presented a dual-loop power generation system including an upper trilateral cycle with water and a bottoming ORC. The former utilized the waste heat from the high-temperature exhaust gases discharged by a marine engine, and the latter reused the turbine exhaust heat of the upper cycle and the low-temperature exhaust gases waste heat. Shu et al. [21] designed a novel dual-loop ORC system which consists of a high-temperature (HT) loop and a low-temperature (LT). The HT loop was a steam Rankine cycle used for the waste heat recovery of the high-temperature part of exhaust gases, while the LT loop was an organic Ranking cycle recovering the coolant heat, the turbine exhaust heat from HT loop and the waste heat from low-temperature part of exhaust gases. With regard to the same dual-loop ORC system, Song and Gu [22] considered the exploiting of wet steam expansion by applying a screw expander to the HT loop, and investigated the effect of the