Applied Energy 205 (2017) 1100–1118

Contents lists available at ScienceDirect

Applied Energy

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

Thermoeconomic multi-objective optimization of a dual loop organic Rankine cycle (ORC) for CNG engine waste heat recovery

Fubin Yang[a,b,c], Heejin Cho[b,*], Hongguang Zhang[a,c,*], Jian Zhang[b]

[a] *College of Environmental and Energy Engineering, Beijing University of Technology, Pingleyuan No. 100, Beijing 100124, China*
[b] *Department of Mechanical Engineering, Mississippi State University, 210 Carpenter Engineering Building, P.O. Box 9552, Mississippi State, MS 39762, USA*
[c] *Collaborative Innovation Center of Electric Vehicles in Beijing, Pingleyuan No. 100, Beijing 100124, China*

HIGHLIGHTS

- A dual loop ORC system is used to recover the waste heat of a CNG engine.
- Sensitivity analysis of the decision variables is performed.
- Thermoeconomic multi-objective optimization of dual loop ORC system is conducted.
- Genetic algorithm is employed to solve the multi-objective optimization problem.
- The optimal operating regions of the decision variables are obtained.

ARTICLE INFO

Keywords:
CNG engine
Waste heat recovery
Dual loop organic Rankine cycle
Thermoeconomic analysis
Multi-objective optimization

ASBTRACT

In this paper, a thermoeconomic model of a dual loop organic Rankine cycle (ORC) system has been developed to analyze both the thermodynamic and economic performance of several working fluid groups for the purpose of compressed natural gas (CNG) engine waste heat recovery. The effects of six key parameters on the thermoeconomic indicators of the dual loop ORC system are investigated. Furthermore, a multi-objective genetic algorithm (GA) is employed to solve the Pareto optimal solutions from the viewpoints of maximizing net power output and minimizing total investment cost over the whole operating range of the CNG engine. The most suitable working fluid group is screened out, then the optimal parameter regions are determined. The results show that a higher evaporation pressure and a lower condensation temperature exhibit a positive effect on the thermoeconomic performances of the dual loop ORC system while the effects of variation in superheat degree and exhaust outlet temperature on the thermoeconomic performances are not obvious. The optimal evaporation pressure of the high temperature loop ORC (HT cycle) is always above 2.5 MPa. The optimal condensation temperature of the HT cycle, optimal evaporation temperature and condensation temperature of the low temperature loop ORC (LT cycle) are all kept almost constants. In addition, the optimal exhaust outlet temperature is mainly influenced by the engine speed. At the rated condition, the dual loop ORC system has the maximum net power output of 23.62 kW and the minimum electricity production cost (EPC) of 0.41 $/kW h. The thermal efficiency of the dual loop ORC system is in the range of 8.97–10.19% over the whole operating range.

1. Introduction

Due to the substantially increase of fossil fuel consumption, the energy saving and emission reduction of internal combustion (IC) engines have received more and more attention. As one of the main prime movers used in transportation industry, engineering machinery and farm machinery, the maximum thermal efficiency of the IC engines is usually less than 40% [1]. Considering increasingly stringent emission regulations, clean alternative fuels are considered to be a good choice for the spark ignition engines. Among various alternative fuels, compressed natural gas (CNG) has been regarded as one of the best substitutions because of its abundant reserves and environmental benefits [2,3]. Overall energy efficiency and fuel consumption can be greatly improved by recovering waste heat from the CNG engines [4,5]. In the current literatures, organic Rankine cycle (ORC) is considered to be one of the most advantageous technologies for the engine waste heat

---

[*] Corresponding authors at: Department of Mechanical Engineering, Mississippi State University, Mississippi State, MS 39762, USA (H. Cho), College of Environmental and Energy Engineering, Beijing University of Technology, Pingleyuan No. 100, Beijing 100124, China (H. Zhang).

E-mail addresses: cho@me.msstate.edu (H. Cho), zhanghongguang@bjut.edu.cn (H. Zhang).

http://dx.doi.org/10.1016/j.apenergy.2017.08.127
Received 17 April 2017; Received in revised form 30 June 2017; Accepted 12 August 2017

Nomenclature

$\dot{W}$	power (kW)
$\dot{Q}$	heat transfer rate (kW)
$\dot{m}$	mass flow rate (kg/s)
h	specific enthalpy (kJ/kg) or convective heat transfer coefficient (W/m^2 K)
s	specific entropy (kJ/kg K)
T	temperature (K)
P	pressure (MPa)
K	overall heat transfer coefficient (W/m^2 K)
A	heat transfer area (m^2)
Nu	Nusselt number
d	diameter (m)
r	fouling resistance (m^2 K/W)
Re	Reynolds number
Pr	Prandtl number
l	length (m)
c_t	temperature difference correction factor
f	resistance coefficient
F	forced convective heat transfer enhancement factor
S	suppression factor
x	quality
p_r	reduced pressure
q	heat flux (W/m^2)
M	molecular weight (kg/kmol)
i_{fg}	enthalpy of vaporization (J/kg)
q''_{wall}	imposed wall heat flux (W/m^2)
G	mass velocity (kg/m^2 s)
w	channel width (m)
D	port diameter (m)
N	number
b	channel spacing (m)
Bo	boiling number

Greek symbols

β	rib effect coefficient or chevron angle
α	heat transfer coefficient (W/m^2 K)
λ	thermal conductivity (W/m K)
η	efficiency
δ	fin height (m)
ε	correction factor or effectiveness of the heat exchanger
ρ	density (kg/m^3)

Subscripts

exp1	expander 1
H	high temperature
H1−H7	state points in HT cycle
ise	isentropic
pre	preheater
p1	pump 1
eva1	evaporator 1
exh	exhaust
a−d	state points in exhaust gas
exp2	expander 2
L	low temperature or all the mass flow rate taken as liquid
L1−L8	state points in LT cycle
in	inner
out	outer
con	condenser
p2	pump 2
int	intercooler
eva2	evaporator 2
cool	coolant
tot	total
th	thermal
max	maximum
min	minimum
ft	fin-and-tube
wf	working fluid
l	liquid
v	vapor
tp	two-phase
fb	film boiling
nb	nucleate boiling
pla	plate
h	hydraulic
eq	equivalent
out	outlet

Acronyms

ORC	organic Rankine cycle
CNG	compressed natural gas
GA	genetic algorithm
HT	high temperature
LT	low temperature
HT	internal combustion
ODP	ozone depletion potential
GWP	global warming potential
CFCs	chlorofluorocarbon
HCFCs	hydrochlorofluorocarbons
LMTD	logarithmic mean temperature difference
MCT	module costing technique
BSFC	brake specific fuel consumption
TOPSIS	Technique for Order Preference by Similarity to an Ideal Solution
CEPCI	Chemical Engineering Plant Cost Index
EPC	electricity production cost
TIC	total investment cost
CRF	capital recovery factor

recovery applications [6–10]. Currently, studies of the ORC system mainly focus on working fluid selection, configuration improvement, parametric optimization, and thermoeconomic analysis.

Many investigations have been conducted to select the favorable working fluids for ORC applications. Wang et al. adopted an ORC system to recover exhaust waste heat from an IC engines and evaluated nine different organic working fluids based on the thermodynamic properties [11]. Shu et al. discussed the feasibility of alkanes as working fluid for diesel engine waste heat recovery based on ORC system [12]. They studied thermodynamic and economic aspects and made a comparison with the traditional steam cycle. Yang et al. examined the effects of eight different zeotropic mixtures on the ORC system under engine various operating conditions [13]. Amicabile et al. introduced a systematic method to screen out the candidate working fluids considering thermodynamic, environmental and safety criteria [14]. Ethanol, pentane and R245fa were used in their research.

Various ORC system configurations have been proposed by many researchers to improve the system performance and efficiency. A dual loop ORC system including a high temperature loop and a low temperature loop was proposed by Zhang et al. to recover the waste heat from a light-duty diesel engine [15]. Song and Gu designed a dual loop ORC system to utilize the waste heat of a diesel engine and analyzed the