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Comparative study of alternative ORC-based combined power systems to exploit high temperature waste heat

Chengyu Zhang, Gequn Shu *, Hua Tian, Haiqiao Wei, Xingyu Liang

State Key Laboratory of Engines, Tianjin University, China

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ABSTRACT

In this paper, various combined power systems which regard organic Rankine cycle (ORC) as bottoming cycle to recover engine's high temperature exhaust heat are proposed. The topping recovery cycle includes steam Rankine cycle (RC), Brayton cycle (BC) and thermoelectric generator (TEG). Comprehensive evaluations are conducted under five typical engine conditions, ranging from high load to low load, and system performance is assessed in terms of many thermodynamic indexes, such as net output power, thermal efficiency, recovery efficiency and exergy efficiency. Besides that, the irreversibility of each component is also discussed in detail. R123, R245fa and R600a for ORC system are considered to analyze the influence of working fluids. Considering the system techno-economy, the turbine size parameter (SP) and heat transfer capacity (UA) are chosen as key indicators. The results show that compared with the other two investigated approaches, dual-loop ORC (DORC) possesses the highest energy exploitation capacity under the whole operating region, with a 5.57% increase of fuel economy under the rated condition, but its values of SP and UA are large as well. TEG–ORC becomes appealing while under the relatively low load.

1. Introduction

Energy conservation and emission reduction have always been topics of great concern. As the main source of motive power, internal combustion engines (ICEs) constitute a large proportion of global fuel consumption. Meanwhile, a large amount of fuel energy is released to the ambience in the form of exhaust without effective utilization. In general, it represents approximately one third of energy generated from fuel combustion [1]. If this part of waste heat could be exploited effectively, fuel utilization efficiency for ICEs would improve dramatically, thus alleviating the problem of energy shortage and producing fewer emissions at the same time. Therefore, a number of researchers have showed their interests in this field and many techniques are proposed [2–5]. Among them, organic Rankine cycle (ORC) shows great potential for its desirable thermal efficiency, low maintenance requirements, and high reliability [6,7]. Focuses have been mainly given on the working fluid selection [8–10] and ORC configurations [11–13], including regenerative ORC, preheat ORC, etc. Most of them belong to one-stage system. However as a matter of fact, ICEs can provide high temperature exhaust gases ranging from 300 °C to 600 °C, depending on the engine operating condition, which is beyond most organic working fluids' decomposition temperature. Hence, it may pose a threat to the system safety. To avoid this, in some situations, a thermal-oil circuit is added between exhaust gases and ORC system so that waste heat is transferred to the working fluid via thermal-oil [14–16]. Even though it allows ORC to work at a suitable temperature under the premise of ensuring safety, the great majority of high-grade exhaust heat is not exploited at all.

In the case of ORC for high-temperature waste heat recovery, such as engine exhaust heat, recovering this part of energy completely, and in the meanwhile, preventing the working fluid from decomposition is a problem. For this reason, another technique is proposed to establish combined system with ORC to extend the temperature range of heat source and produce additional power.

The steam Rankine cycle (RC) is environmentally friendly as water has no negative effects on the environment, moreover, water can bear high temperature and it is cheap and abundant. BMW [17] designed a turbosteamer system (i.e. dual-loop Rankine system) which used water and ethanol as high- and low-temperature Rankine cycle working fluids respectively to recover waste heat from exhaust gases and jacket water. Further researches [18,19] indicate that DORC has great potential for waste heat recovery.

* Corresponding author at: State Key Laboratory of Engines, Tianjin University, No. 92, Weijin Road, Nankai Region, Tianjin 300072, China. Tel.: +86 022 27409558; fax: +86 022 27402609.

E-mail address: sgq@tju.edu.cn (G. Shu).

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Nomenclature

c_p	specific heat (kJ/kg K)
h	specific enthalpy (kJ/kg)
m	mass flow rate (kg/s)
q	heat flux (W)
r	thermal resistance (K/W)
s	specific entropy (kJ/kg K)
x	vapor quality at turbine outlet
E	exergy (kW)
I	exergy destruction (kW)
K	thermal conduction (W/K)
M	row number for TEG scale
N	column number for TEG scale
P	Pressure (MPa)
Q	heat (kW)
SP	turbine size parameter (cm)
T	temperature (K)
UA	heat transfer capacity (W/K)
V	volumetric flow rate (m^3/s)
W	power (kW)

Greek letters

α	Seebeck coefficient
η_{th}	thermal efficiency
η_e	exergy efficiency
ε_R	effectiveness of regenerator

Subscripts

all	combined system
c	cold side of thermoelectric couple
cond	condensation
e	exergy
evp	evaporation
exh	exhaust
f	working fluid
h	hot side of thermoelectric couple
in	input the system
net	net output
w	water
out	output by the system
C	cooler
CP	compressor
H	heater
P	pump
R	regenerator
T	turbine
ise	isentropic
max	maximum

Acronyms

BC	Brayton cycle
RC	steam Rankine cycle
TEG	thermoelectric generator
HT	high temperature cycle, i.e. RC, BC or TEG
LT	low temperature cycle, i.e. ORC bottoming cycle
C_{HT}	cooler C_{HT} of the HT cycle
$C_{1,HT}$	first cooler of the HT cycle
$C_{2,HT}$	second cooler in the HT cycle
C_{LT}	cooler C_{LT} of the LT cycle
CP_{HT}	compressor CP_{HT} of the HT cycle
H_{HT}	heater H_{HT} in the HT cycle
$H_{1,LT}$	first heater of the LT cycle
$H_{2,LT}$	second heater of the LT cycle
P_{HT}	pump P_{HT} of the HT cycle
P_{LT}	pump P_{LT} of the LT cycle
T_{HT}	turbine T_{HT} in the HT cycle
T_{LT}	turbine T_{LT} in the LT cycle
ICE	internal combustion engine

Unlike ORC, Brayton cycle (BC) regards gas as working medium which suits high temperature operation well and it has some interesting advantages over Rankine cycle, such as simplicity and reliability, because it does not involve phase change during the whole process and can work at low pressure ratios [20]. Previous studies [21,22] have explored its application in waste heat recovery, and air is considered as working fluid. However, primarily limited by the compression consumed power, its performance is not always desirable. While on the other hand, CO_2 Brayton cycle becomes appealing for its high ratio of turbine work to compressor work [23], and many scholars are engaged in this field, mainly for nuclear and solar power applications [24–26]. In such situations, the temperature of heat sources can come up to 600 °C or even more. Chen et al. [27] investigated CO_2 power cycle to utilize the energy in the exhaust gases. As a feasible recovery technology, CO_2 Brayton cycle is also included in our study for comparison.

Thermoelectric generator (TEG) is another promising technology in the area of waste heat recovery [4,28,29], and it has drawn great attention with the development of thermoelectric materials which leads to significant promotion in conversion efficiency. It can convert thermal energy into electricity directly without any moving component. Apart from that, it is also attractive for its simple structure and great flexibility. Miller et al. [30,31] first proposed the idea of combining TEG with ORC, and TEG did not only convert high temperature exhaust heat into power, it preheated ORC working fluid as well. The detail mathematical model of such combined system is established and discussed in other researches [32,33].

In this work, our main objective is to provide an adapted solution to exploit exhaust waste heat from ICEs, and three different combined systems which regard ORC as bottoming cycle are evaluated, i.e. dual-loop organic Rankine cycle (DORC), CO_2 Brayton–ORC (BC–ORC) and TEG–ORC. Comparative investigations are performed on some key indexes, namely net output power, thermal efficiency, recovery efficiency, exergy efficiency, the turbine size parameter (SP) and heat transfer capacity (UA), thus providing comprehensive information. Besides that, five typical engine conditions are picked out to evaluate the performance of these combined systems on the whole.

2. System description

2.1. ICE system

The engine we analyzed here is an inline 6-cylinder 4-stroke supercharged diesel engine. In our present study, as a commercial diesel generator set, the engine's speed remains constant at 1500 rpm while its load changes under different working conditions. Five typical engine conditions are chosen and their main parameters are collected in Table 1. Normally, the engine works under the condition 2, i.e. rated condition. Throughout these five conditions, exhaust temperature is between 693 and 808 K. We assume that the air fuel ratio is 19.7 under the assumption of perfect combustion. Accordingly, the exhaust gases compositions on mass basis are calculated as follows: CO_2 = 15.1%, H_2O = 5.5%,