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A regenerative supercritical-subcritical dual-loop organic Rankine cycle system for energy recovery from the waste heat of internal combustion engines

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HIGHLIGHTS

- A dual-loop ORC system using R1233zd and R1234yf is proposed.
- The performance of the system with different working fluids has been analysed.
- The integrated ICE-ORC system has been analysed.
- The off-design performance has been analysed.

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ABSTRACT

Organic Rankine cycle (ORC) system is considered as a promising technology for energy recovery from the waste heat rejected by internal combustion (IC) engines. However, such waste heat is normally contained in both coolant and exhaust gases at quite different temperatures. A single ORC system is usually unable to efficiently recover energy from both of these waste heat sources. A dual loop ORC system which essentially has two cascaded ORCs to recover energy from the engine's exhaust gases and coolant separately has been proposed to address this challenge. In this way, the overall efficiency of energy recovery can be substantially improved. This paper examines a regenerative dual loop ORC system using a pair of environmentally friendly refrigerants, R1233zd and R1234yf, as working fluids, to recover energy from the waste heat of a compressed natural gas (CNG) engine. Unlike most previous studies focusing on the ORC system only, the present research analyses the ORC system and CNG engine together as an integrated system. As such, the ORC system is analysed on the basis of real data of waste heat sources of the CNG engine under various operational conditions. A numerical model is employed to analyse the performances of the proposed dual loop cycle with four pairs of working fluids. The effects of a regenerative heat exchanger and several other key operating parameters are also analysed and discussed in detail. The performance of the integrated engine-ORC system is then analysed under actual engine operating conditions which were measured beforehand. The performance of the proposed system under off-design conditions has also been analysed. The obtained results show that the proposed dual loop ORC system could achieve better performance than other ORC systems for similar applications.

1. Introduction

Internal combustion (IC) engines are still the main power sources for transportation nowadays, and their dominance will not be changed in the foreseeable future. Over half of the energy contained in the fuel consumed by IC engines is ultimately discharged to the environment as waste heat via their cooling and exhaust systems. The energy efficiency of IC engines can be improved using waste heat recovery technologies such as organic Rankine cycle (ORC) systems [1], thermoelectric power generators [2], and combined heat and power (CHP) systems [3]. In the past decade or so, there has been a rapid increase of patent applications in the area of waste heat recovery technologies [4]. Such waste heat recovery systems could substantially improve the IC engine's overall thermal efficiency. For instance, Agudelo et al. evaluated the potential of exhaust heat recovery from a diesel engine of a

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Nomenclature

P	pressure (MPa)
$\dot{Q}$	heat quantity (kW)
SP	size parameter (cm)
T	temperature (K)
V	volume flow rate (m^3/s)
VFR	volume flow ratio
$\dot{W}$	power (kW)
h	enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
s	entropy (kJ/kg·K)
Greek letters	
η	efficiency
ψ	performance improvement
Subscript	
HTi	state points in the HT loop
LTi	state points in the LT loop
abs	absolute change
c	condenser
$comb$	engine-DORC combined system
$cool$	coolant
$e1$	Evaporator 1
$e2$	Evaporator 2
eng	engine
exh	exhaust gas
f	fuel
in	inlet
is	isentropic
lm	logarithmic mean temperature difference
n	net
out	outlet
$p1$	Pump 1
$p2$	Pump 2
pre	preheater
$r1$	Regenerator 1
$r2$	Regenerator 2
rel	relative change
s	superheater
$t1$	Turbine 1
$t2$	Turbine 2
th	thermal efficiency
Acronyms	
CNG	compressed natural gas
DORC	dual-loop organic Rankine cycle
HT	high temperature
GWP	global warming potential
LT	low temperature
ODP	ozone depletion potential
ORC	organic Rankine cycle
PPTD	pinch point temperature difference
bsfc	brake specific fuel consumption

passenger car under European driving cycle conditions, and revealed that it can reduce the engine's fuel consumption by 8–19% [5]. Mondejar et al. performed a quasi-steady state simulation of an ORC system for a passenger ship, and reported that it could meet around 22% of the total power demand on board [6].

The thermal efficiency of ORC systems strongly depends on the characteristics of its working fluid. It is therefore critical to select a suitable working fluid for a specific application of waste heat recovery [7,8]. Firstly, the critical temperature of the working fluid should be close to the heat source temperature. Braimakis et al. performed a simulation of ORC system with the heat source temperatures in the range from 150 to 300 °C, and reported that the system's exergetic efficiency was strongly affected by the critical temperature of the working fluids [9].

Secondly, the system structure of an ORC can also affect the working fluid selection. Larsen studied subcritical and supercritical ORCs with 109 working fluids, and reported that recuperated ORC systems with hydrocarbons achieved the best efficiencies while wet and isentropic fluids were more suitable for non-recuperated ORC systems [10]. For power generation from a heat source at 150 °C, Le et al. found that R32 and R152a were the best working fluids for the basic and regenerative cycles, respectively [11].

Thirdly, the effect of operating parameters such as evaporation pressure and temperature should also be considered for working fluid selection [12]. Toffolo et al. used a multi-criteria approach, including the pressure and temperature at the turbine inlet, to compare the performance of different working fluids [13]. The selection of working fluids also depends on the design target. For instance, Yang and Yeh investigated an ORC system for waste heat recovery from a diesel engine, and found that their system achieved the optimal economic performance and the highest thermal efficiency with R245fa and R1234ze as working fluid, respectively [14]. In addition, the working fluids for ORC systems on vehicles and ships should be non-toxic, non-flammable, and environmentally friendly.

There are two types of waste heat sources discharged by IC engines, exhaust gases with a temperature above 200 °C and coolants with a temperature in the range 80–120 °C. Shu et al. investigated the performance of an ORC system for recovering heat from an engine's exhaust gases, and found it could reduce the engine's fuel consumption by up to 10% when using cyclohexane as working fluid [15]. Di Battista et al. conducted an experimental study of a regenerative ORC system to recover energy from the exhaust gases of an IVECO F1C diesel engine, and reported that it could improve the overall energy efficiency by 4–5% [16].

It is challenging to use a single ORC system to recover heat energy from both the exhaust gases and coolant of IC engines due to their different temperatures. Song et al. developed an ORC system that uses the coolant of an IC engine to preheat, and subsequently uses its exhaust gas to evaporate the working fluid. The net power output was slightly lower than that of two separate ORC systems but the capital cost of the single-loop system was lower [17]. Kim et al. reported that a single-loop ORC system recovering energy for such application could generate approximately 20% extra power [18]. In an IC engine, apart from its exhaust gases, the coolant also contains a considerable amount of waste heat, however at a much lower temperature. The maximum temperature of the single-loop ORC is usually constrained due to the utilisation of a single working fluid, resulting in higher irreversibility within the evaporator.

To address this challenge, BMW proposed a dual-loop Rankine cycle system which uses water and ethanol as working fluids for the high-temperature (HT) and low-temperature (LT) cycles, respectively [19]. Since then, several studies have been conducted