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Performance analysis of waste heat recovery with a dual loop organic Rankine cycle (ORC) system for diesel engine under various operating conditions

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ABSTRACT

To take full advantage of the waste heat from a diesel engine, a set of dual loop organic Rankine cycle (ORC) system is designed to recover exhaust energy, waste heat from the coolant system, and released heat from turbocharged air in the intercooler of a six-cylinder diesel engine. The dual loop ORC system consists of a high temperature loop ORC system and a low temperature loop ORC system. R245fa is selected as the working fluid for both loops. Through the engine test, based on the first and second laws of thermodynamics, the performance of the dual loop ORC system for waste heat recovery is discussed based on the analysis of its waste heat characteristics under engine various operating conditions. Subsequently, the diesel engine-dual loop ORC combined system is presented, and the effective thermal efficiency and the brake specific fuel consumption (BSFC) are chosen to evaluate the operating performances of the diesel engine-dual loop ORC combined system. The results show that, the maximum waste heat recovery efficiency (WHRE) of the dual loop ORC system can reach 5.4% under engine various operating conditions. At the engine rated condition, the dual loop ORC system achieves the largest net power output at 27.85 kW. Compared with the diesel engine, the thermal efficiency of the combined system can be increased by 13%. When the diesel engine is operating at the high load region, the BSFC can be reduced by a maximum 4%.

1. Introduction

With the rapid development of the auto industry, the automobile population has skyrocketed, and the energy sources consumed by automobiles have been growing rapidly. Meanwhile, given the low utilization rate, the effective power output of the total fuel combustion energy is less than 40% in internal combustion (IC) engines, and the remaining heat is released into the atmosphere. This mechanism not only harms the environment; it also results in energy dissipation. Currently, numerous research institutes and scholars are devoted to developing new energy vehicles and alternative fuel technologies. Therein, biodiesel is a kind of clean biofuel that holds much promise. However, the application of biodiesel remains limited by technology and cost, such that this technology cannot displace traditional IC engines in the near future [1–3]. Therefore, recovering the waste heat from IC engines is an effective method for the improvement of thermal efficiency, reducing pollutant emission, and saving fuel.

Reasonable measures should be employed to recover and utilize the low-grade waste heat of IC engines. Numerous scholars have recently investigated the use of organic Rankine cycle (ORC) system to recover low-grade waste heat. Research has focused on the selection of working fluids, optimization parameters, system configuration improvements, and so on. Mago et al. employed a basic ORC system and a regenerative ORC system to convert waste energy into power from low-grade heat sources. The results showed that the regenerative ORC system achieved a higher efficiency compared with the basic ORC system [4]. Wang et al. presented a method for selecting the working fluid and parametric optimization using a multi-objective optimization model by simulated annealing algorithm. They concluded that different working fluids should be selected to match the different heat source temperatures [5]. Roy et al. designed a set of ORC system, using R-12, R-123 and R134a as working fluids to recover the waste heat from flue gas. The analysis showed that R-123 had the maximum

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Nomenclature

$\dot{W}$	power (kW)
$\dot{Q}$	heat transfer rate (kW)
$\dot{m}$	mass flow rate (kg/s)
h	specific enthalpy (kJ/kg)
s	specific entropy (kJ/kg K)
$\dot{I}$	exergy destruction rate (kW)
T	temperature (K)
P	pressure (MPa)
$\dot{F}$	fuel consumption (kg/h)
x, y, z	mole amount
bsfc	brake specific fuel consumption (g/kW h)

Greek letters

η	efficiency
ε	effectiveness of the recuperator
φ	heat transfer efficiency
χ	mass fraction

Subscript

0	reference state
H	high temperature loop ORC system
L	low temperature loop ORC system
H1, H2, H2s, H3, H4, H5, H5s, H6	state points in HT loop ORC system
L1, L2, L2s, L3, L4, L4s, L5, L6	state points in LT loop ORC system
p1	pump 1
p2	pump 2
r	recuperator
e1	evaporator 1
e2	evaporator 2
exp1	expander 1
exp2	expander 2
pre	preheater
int	intercooler
a	intake air
in	at the inlet
out	at the outlet
con	condenser
n	net
oa	overall
w	waste
exh	exhaust gas
cool	coolant
HTH	high temperature heat source in HT loop ORC system
HTL	high temperature heat source in LT loop ORC system
LTL	low temperature heat source in LT loop ORC system
HS	heat source
comb	combustion
f	fuel
misc	miscellaneous
th	thermal
eff	effective
cs	combined system
eng	engine

Acronyms

ORC	organic Rankine cycle
HT	high temperature
LT	low temperature
WHRE	waste heat recovery efficiency
BSFC	brake specific fuel consumption
ODP	ozone depletion potential (relative to R11)
GWP	global warming potential (relative to CO_2)
IC	internal combustion

work output and efficiencies among all the selected fluids [6]. Wei et al. studied the performance and optimization of an ORC system using HFC-245fa (1,1,1,3,3-penta-fluoropropane) as a working fluid driven by exhaust heat. The results revealed that utilizing the exhaust heat as much as possible was a good method for improving the system output net power and efficiency [7]. Liu et al. presented a two stage Rankine cycle for power generation, which was composed of a water steam Rankine cycle and an Organic Rankine bottoming cycle. Optimal points were found at different cold source temperatures and steam turbine outlet pressures for each cycle [8]. Wang et al. conducted a multi-objective optimization of the ORC system to achieve the system optimization design from both thermodynamic and economic aspects using an evolutionary algorithm [9]. Gao et al. assessed 18 organic working fluids according to their physical and chemical properties for a supercritical ORC driven by exhaust heat. The effects of these working fluids on the performance of the supercritical ORC system were discussed. The results showed that R152a and R143a are recommended as the working fluids for the supercritical ORC system [10]. Hung proposed an ORC system to recover waste heat from low enthalpy heat sources using dry fluids. The study indicated that R113 and R123 performed better in recovering low temperature waste heat [11]. Quoilin et al. proposed a dynamic ORC model and three different control strategies. Their simulation results showed that a model predictive control strategy based on the steady-state optimization of the cycle under various conditions was the one showed the best results [12]. Dai et al. described an ORC for recovering low-grade waste heat using different working fluids. The effects of thermodynamic parameters on ORC performance were examined, and the thermodynamic parameters of the ORC for each working fluid were optimized with exergy efficiency as an objective function. The results indicated that the cycle with R236EA had the highest exergy efficiency [13]. Guo et al. proposed an innovative cogeneration system powered by low temperature geothermal sources, and the system consisted of a low temperature geothermal-powered ORC subsystem, an intermediate heat exchanger, and a commercial R134a-based heat pump subsystem. The suitable working fluids were screened and the performances of the novel cogeneration system under disturbance conditions were studied [14]. Hung et al. investigated the effects of dry, wet, and isentropic organic fluids as working fluids on the performance of ORC system. The results revealed that wet organic fluids with very steep saturated vapor curves in *T*–*s* diagram had a better overall performance in terms of energy conversion efficiencies than that of dry organic fluids. Furthermore, an appropriate combination of solar energy and an ORC system with a higher turbine inlet temperature and a lower condenser temperature would provide an economically feasible energy conversion system [15]. Wang et al. conducted an experimental study to investigate the performance of a low temperature solar Rankine cycle system. The results showed that the highest heat collecting efficiency of the collector is about 50% [16].

The ORC system has been widely applied to the recovery of waste heat from IC engines. Gao et al. proposed a waste heat recovery system where a high-speed turbocharged diesel engine acts as the topper of a combined cycle system and exhaust gases were used for a bottoming Rankine cycle. The conclusion was that introducing a heat recovery system could increase the engine power output by 12% [17]. Srinivasan et al. designed an ORC system to