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Thermodynamic analysis of dual-loop organic Rankine cycle using zeotropic mixtures for internal combustion engine waste heat recovery

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ABSTRACT

The dual-loop organic Rankine cycle (DORC) is a promising technology for internal combustion engine waste heat recovery. Zeotropic mixtures can improve temperature matches with heat source and sink in the phase change process for its non-isothermal phase change characteristic. Thus, zeotropic mixtures are adopted for high-temperature loop (HTL) and low-temperature loop (LTL) of DORC. Cyclopentane/cyclohexane and benzene/toluene mixtures are used for HTL, whereas isobutane/isopentane (R600a/R601a) mixtures are selected as working fluids for LTL. The mole fraction effects of mixtures on net power output, exergy efficiency, exergy destruction rate (HTL evaporator, condenser/evaporator, LTL preheater, and condenser), and heat utilization ratio of waste heat are analyzed. The influences of engine exhaust gas temperature on net power output and exergy destruction rate are also discussed. Results show that the use of mixtures for the two loops can reduce the exergy destruction rate of HTL evaporator and LTL condenser compared to that of pure working fluids system and the exergy destruction rate of condenser/evaporator compared to that of mixtures using only one loop system. Furthermore, these mixtures increase the heat utilization ratio of waste heat, net power output, and exergy efficiency compared to those of a pure working fluid system. When cyclopentane/cyclohexane or benzene/toluene mixtures are used for HTL and R600a/R601a mixtures are used for LTL, the system net power output relative increment rates of mixture systems are 2.5–9.0% and 1.4–4.3%, respectively, compared to those of corresponding pure working fluids system with 573.15–623.15 K engine exhaust gas temperature.

1. Introduction

Global energy resources are increasingly approaching dangerous levels, and environmental pollution is becoming serious due to the increasing level of fossil fuel consumption [1,2]. Owing to the internal combustion engine which is the main consumer of fossil fuel and less than 45% of fuel energy which can be converted into useful power for internal combustion engines, utilizing these exhausted waste heat from internal combustion engine has immense potential to reduce fossil fuel consumption [3–6].

Organic Rankine cycle (ORC) is a promising technology for waste heat recovery due to its simple structure, good applicability, and user-friendliness [7,8]. Numerous studies on ORC application for internal combustion engine waste heat recovery have been conducted and indicated good potential [9–13].

Owing to the high internal combustion engine exhaust gas temperature, the single-stage ORC using conventional organic fluid with low critical temperature may cause a mismatch with the engine exhaust gas [5]. Working fluids suitable for high heat source temperatures typically have high critical temperature. If these are used in a single-stage ORC, there is the risk that condensation happens at pressures below ambient. As such, a risk for contamination with non-condensable gases exists [14]. Furthermore, the temperature difference between the engine exhaust gas and jacket cooling water in single-stage ORCs is large, thereby resulting in slight utilization of engine coolant waste heat [5]. To avoid these, a new cycle needs to be established. The dual-loop organic Rankine cycle (DORC) comprises high-temperature loop (HTL) and low-temperature loop (LTL). HTL is driven by engine exhaust gas, whereas the residual heat of HTL and jacket cooling water facilitates LTL evaporation. Working fluid suitable for high temperature heat source is used for HTL, whereas working fluid with good low-temperature performance is used for LTL, which can effectively solve the preceding problems mentioned. Many researchers adopted DORC for waste heat recovery of internal combustion engines and researched working fluids selection, parameters analysis and optimization, system configuration improvements, and so on. Shu et al. [6,15,16] conducted

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Nomenclature

c_p	specific heat capacity at constant pressure (kJ·kg^{-1}·K^{-1})
E	exergy (kW)
g	gravitational acceleration (9.8 m·s^{-2})
H	pressure head (m)
I	exergy destruction rate (%)
h	specific enthalpy (kJ·kg^{-1})
m	mass flow rate (kg·s^{-1})
P	power (kW)
Q	thermal power (kW)
s	specific entropy (kJ·K^{-1}·kg^{-1})
T	temperature (K)
ΔT	temperature difference (K)

Greek symbols

η	efficiency

Subscripts

0	ambient temperature
1–6, 1′–8′	state points shown in Fig. 2
c	condenser
ce	condenser/evaporator
d	destruction
dew	dew point
e	evaporator
ex	exergy
g	engine exhaust gas
H	high temperature loop
i	section point i
in	inlet
jw	jacket cooling water
L	low temperature loop
net	net
p	pump
pp	pinch point
w	water

working fluid selection and performance analysis for several different system configurations of DORC. Results showed that water was a good choice for HTL, R143a and R1234yf could be used for LTL for improving performance; low condensation temperature of HTL was beneficial for performance optimization. Tian et al. [5] proposed a regenerative transcritical DORC to recover the waste heat of exhaust and engine coolant. Their study discussed the turbine influence of inlet temperature on mass flow rates, net power output, energy conversion efficiency, volumetric expansion ratio, ratio of power consumed to power output, and component irreversibility; toluene used for HTL could provide good performance. Wang et al. [17] studied the waste heat recovery of gasoline engine using DORC, R245fa and R134a were used for HTL and LTL respectively. The results revealed that the DORC can increase net power for the combined system by 50%. Yao et al. [18] designed a DORC for waste heat recovery from a heavy-duty compressed natural gas engine using R245fa as working fluid. The results indicated that power output and brake specific fuel consumption could be improved by 33.73% and 25% compared with the original compressed natural gas engine. Yang et al. [19] investigated the DORC system for diesel engine under various operating conditions using effective thermal efficiency and brake specific fuel consumption as evaluation criteria. The conclusion showed that the DORC can increase thermal efficiency of the combined system by 13% compared with the diesel engine. Zhang et al. [20] studied a novel system that combines vehicular light-duty diesel engine with DORC and calculated heat waste from the exhaust, intake air, and coolant. The performance of DORC was then evaluated throughout the entire operating region of the engine. Choi and Kim [21] applied DORC for waste heat recovery from an internal combustion engine, in which the HTL drove the waste heat of engine exhaust gas and the LTL absorbed the heat of low-temperature exhaust and HTL. The analysis demonstrated that the DORC could improve 2.824% propulsion efficiency compared to a base engine. Song and Gu [22,23] presented a DORC for engine waste heat recovery and conducted parametric analysis. They discovered that the power generated by the DORC could increase the engine power. From the aforementioned studies, DORC system can effectively recover the waste heat from internal combustion engines and pure working fluids were used for DORC.

Temperature matches between cycle and heat source and sink can significantly affect ORC performance [24,25]. Unlike the latent heat source (such as condensing steam, thermal storage with phase change material), the temperature of the sensible heat source (such as engine exhaust gas, jacket cooling water) will decrease during the heat release process, when sensible heat source temperature decreases, the ORC that uses pure working fluid demonstrates poor temperature matches between working fluid and heat source and sink due to the isothermal phase characteristic of pure fluids, thus leading to significant irreversibility in heat transfer [26,27]. The use of zeotropic mixtures with non-isothermal phase change characteristic can improve temperature matches between the heat source (hot water, heat conduction oil, and flue gas) and sink, which then reduces irreversible losses and improve cycle performance [14,25,28–35].

Furthermore, a few researchers adopted zeotropic mixtures for DORC. Tian et al. [36] conducted thermo-economic analysis of DORC by using siloxane mixtures in HTL and pure R123 in LTL. Their results showed that D4/R123 (0.3/0.7) system has the best thermodynamic performance and MD2M/R123 (0.35/0.65) system represents the most economic system. Zhou et al. [37] presented a dual-loop system for engine waste heat recovery using mixtures of RC318/R1234yf, butane/R1234yf, and RC318/R245fa in LTL. The use of mixtures increased engine output by nearly 14.4% when RC318/R1234yf was used as working fluid in LTL.

Previous studies indicated that the use of mixtures for DORC can improve system performance. However, current studies introduced mixtures for only one loop (HTL or LTL) while other loops still use pure working fluid. Though the use of mixtures for only one loop can improve temperature match of mixtures loop with heat source or sink, the temperature match of pure working fluid loop with heat source or sink still needs to be improved. Moreover, owing to different phase change characteristics of mixtures and pure working fluid, the temperature match between HTL and LTL deteriorates compared to that of pure working fluid system. Therefore, adopting mixtures for HTL and LTL is important. When mixtures are used, the selection of working fluids for DORC expands, the performance comparison among systems with mixtures using one and two loops and pure working fluid systems remain unclear. Furthermore, the temperature matches and heat utilization ratio simultaneously affect ORC performance. Thus, effects of mole fractions on net power output, exergy efficiency, exergy destruction rate, and heat utilization ratio need to be analyzed, what are the best mole fractions for HTL and LTL mixtures? In addition, the performance research with various engine exhaust gas temperatures is insufficient.

DORC that comprises HTL and LTL and uses zeotropic mixtures is