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Research paper

Analysis of ORC (Organic Rankine Cycle) systems with pure hydrocarbons and mixtures of hydrocarbon and retardant for engine waste heat recovery

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HIGHLIGHTS

- ORC with zeotropic mixtures for engine waste heat recovery is discussed.
- Energetic and exergetic analysis of ORC system are conducted.
- Optimal mixture working fluid composition is identified.
- Greater utilization of jacket water and lower irreversible loss are important.

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ABSTRACT

The Organic Rankine Cycle (ORC) has been demonstrated to be a promising technology for the recovery of engine waste heat. Systems with hydrocarbons as the working fluids exhibit good thermal performance. However, the flammability of hydrocarbons limits their practical applications because of safety concerns. This paper examines the potential of using mixtures of a hydrocarbon and a retardant in an ORC system for engine waste heat recovery. Refrigerants R141b and R11 are selected as the retardants and blended with the hydrocarbons to form zeotropic mixtures. The flammability is suppressed, and in addition, zeotropic mixtures provide better temperature matches with the heat source and sink, which reduces the exergy loss within the heat exchange processes, thereby increasing the cycle efficiency. Energetic and exergetic analysis of ORC systems with pure hydrocarbons and with mixtures of a hydrocarbon and a retardant are conducted and compared. The net power output and the second law efficiency are chosen as the evaluation criteria to select the suitable working fluid compositions and to define the optimal set of thermodynamic parameters. The simulation results reveal that the ORC system with cyclohexane/R141b (0.5/0.5) is optimal for this engine waste heat recovery case, thereby increasing the net power output of the system by 13.3% compared to pure cyclohexane.

1. Introduction

Escalating fuel prices and strict emission limits have renewed interest in methods to increase the thermal efficiency of the diesel engines. In a typical diesel engine, less than 45% of the fuel energy is converted into useful power output, while the remaining energy is mainly lost through the engine exhaust gas, the jacket cooling water and other means, such as the air cooling system and the lubrication system [1]. The potential for recovering the waste heat of the diesel engine is appreciable.

Among all of the technologies, the Organic Rankine Cycle (ORC) has proven to be promising for engine waste heat recovery. Teng et al. [2,3] simulated an ORC system to recover waste heat from the engine exhaust gas, the charge air cooler and the EGR cooler. The case study showed a 20% increase in the engine power output. Zhang et al. [4] analyzed the characteristics of a novel system combining a vehicle diesel engine with a dual loop ORC that recovered waste heat from the exhaust gas, the intake air and the coolant. Hountalas et al. [5] researched waste heat recovery for a heavy-duty truck diesel engine using bottoming ORCs. When the

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Nomenclature

W	power, kW
$\dot{m}$	mass flow rate, kg/s
h	specific enthalpy, kJ/kg
I	exergy loss, kW
T	temperature, K
P	pressure, kPa
s	entropy, kJ/kg K
Q	heat load, kW
c_p	specific heat capacity, kJ/kg K

Greek symbols

η	efficiency

Subscripts

f	working fluid
HS	heat source
in	inlet
out	outlet
gas	engine exhaust gas
jw	jacket cooling water
$preh$	preheater
$evap$	evaporator
exp	expander
$cond$	condenser
w	cooling water
th	thermal
ex	exergy

Acronyms

ORC	Organic Rankine Cycle
WHR	waste heat recovery
EGR	exhaust gas recirculation

exhaust heat and the EGR heat were recovered, the brake specific fuel consumption improved by 6%–7.5%. Yu et al. [6] presented ORC systems with R245fa as the working fluid to recover waste heat from both the engine exhaust gas and the jacket cooling water. The influences of the evaporating pressure and the engine operating conditions on the system performance were observed. Vaja et al. [7] proposed three different ORCs to efficiently recover engine waste heat: a simple cycle with the use of engine exhaust gas only, a cycle with the use of engine exhaust gas and engine cooling water, and a regenerated cycle.

The temperature of the engine exhaust gas is relatively high; therefore, high-temperature ORC systems should be exploited to gain high thermal efficiency. To avoid decomposition of the organic fluids, those with high critical temperatures are generally selected as the working fluid candidates. In previous studies, hydrocarbons showed good thermal performance in high-temperature ORCs for engine waste heat recovery. Vaja et al. [7] compared benzene, R11 and R134a used in a bottoming ORC for an internal combustion engine. The results showed that the efficiency of the system was the highest with benzene. Shu et al. [8] suggested that alkane-based working fluids were preferable for engine waste heat recovery. Siddiqi et al. [9] investigated hydrocarbons from n-pentane to n-dodecane used in ORCs of different temperature levels. Carcasci et al. [10] selected toluene, benzene and cyclohexane as ORC working fluids. Their case study showed that cyclohexane was the best fluid under low temperature conditions, benzene was the best choice for medium temperature conditions, and toluene should be used under high temperature conditions. However, one obvious disadvantage of using hydrocarbons as the working fluid in an ORC system is their flammability and explosivity, which might limit their practical applications due to safety concerns. Blending non-flammable components (for example, some refrigerants), regarded as retardants, with the hydrocarbons to suppress the flammability is a viable solution [11]. In addition, the hydrocarbon and the added retardant can be mixed to form zeotropic mixtures, which have non-isothermal evaporation and condensation. During the evaporation and condensation processes, the temperature glides due to the changing component concentrations in each phase of the mixture. Therefore, using zeotropic mixtures instead of pure fluids as the ORC working fluids provides better temperature matches with the heat source and sink, reducing the exergy loss within the heat exchange processes and increasing the cycle efficiency. Garg et al. [12] evaluated the potential of using isopentane, R245fa and their mixtures as working fluids for an ORC in the temperature range of 380–425 K. The results showed that cycle efficiencies of 10–13% could be obtained. Lecompte et al. [13] conducted exergy analysis of ORC systems with different zeotropic mixtures and a 7.1%–14.2% increase in the second law efficiency was obtained compared to pure working fluids. Heberle et al. [14] compared ORC performance with pure and zeotropic mixture fluids for energy conversion of low-enthalpy geothermal resources. For heat sources below 120 °C, the efficiency increased up to 15% using mixtures. Angelina and Di Paliano [15] evaluated the merits of organic-fluid mixtures as working media for Rankine power cycles. Non-isothermal phase change, at both high and low temperatures, represented the main advantage compared to pure fluids. Wang and Zhao [16] presented analysis of low-temperature solar Rankine cycles for power generation using zeotropic mixtures. The results indicated that using zeotropic mixtures could improve the system performance and also extend the choices for working fluids. Wang et al. [17] presented an on-site experimental study of a low-temperature solar Rankine cycle system with pure and zeotropic mixture fluids. Chys et al. [18] considered several pure fluids as components, discussed a mixture selection method and suggested the optimal concentrations. The electricity production could be increased by 20%.

Research on mixtures of a hydrocarbon and a retardant as zeotropic mixture working fluids used in ORC systems is limited and is mainly focused on low-temperature cases. However, the flammability and explosivity of the working fluids need to be considered and avoided in high-temperature cycles, especially for ORC systems with hydrocarbons used in engine waste heat recovery. This paper examines the potential of using mixtures of a hydrocarbon and a retardant as ORC working fluids for engine waste heat recovery. Cyclohexane, benzene and toluene are selected as the pure working fluids, and the refrigerants R141b and R11 are chosen as the retardants, which are blended with the hydrocarbons to suppress the flammability. A limited range of the retardant mole fraction is considered, based on system safety and environmental concerns. The performances of the ORC systems with pure hydrocarbons and with mixtures of a hydrocarbon and a retardant are simulated and compared based on the first and the second laws of thermodynamics. The net power output and the second law efficiency are chosen as the evaluation criteria to select the suitable working fluid compositions and to define the optimal set of the thermodynamic parameters. The simulation results reveal that the ORC system with cyclohexane/R141b (0.5/0.5) is optimal in this engine waste heat recovery case.