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Theoretical research on working fluid selection for a high-temperature regenerative transcritical dual-loop engine organic Rankine cycle

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ABSTRACT

In this paper, a regenerative transcritical dual-loop organic Rankine cycle is proposed to recover the waste heat of the exhaust, engine coolant and all the residual heat of the HT loop. Double regenerators are adopted in this system. Transcritical cycles are used in both loops. Hexamethyldisiloxane (MM), octamethyl cyclotetrasiloxane (D_4), octamethyltrisiloxane (MDM), cyclohexane, toluene and n-decane are chosen as the candidate working fluids of the HT loop and R143a is chosen as the working fluid of the LT loop. Influences of inlet temperature of turbine T_{HT} (T_3) on mass flow rates ($m_{f,HT}$ and $m_{f,LT}$), net output power (W_{net}), energy conversion efficiency (η_{ec}), volumetric expansion ratio (VER), ratio of power consumed to power output (COR) and component irreversibility are analyzed and performance comparison of these working fluids is also evaluated. Results show that toluene possesses the maximum W_{net} (42.46 kW), highest η_e (51.92%) and η_{ec} (12.77%). The increase of T_3 worsens system performance, decreasing W_{net}, η_e and η_{ec}. Condenser C_{LT} and turbine T_{LT} possess the least system irreversibility. In addition, turbines and exhaust evaporators are optimized components.

1. Introduction

As energy crisis and environmental pollution become more severe worldwide, researches on waste heat recovery (WHR) technologies have been increasingly significant, especially WHR of internal combustion engine (ICE), which is the main consumer of fossil fuel. However, lots of waste heat is discarded by the exhaust gas and engine coolant, recovery of which is of great importance [1,2]. Many methods on ICE WHR have been proposed [3], among which the organic Rankine cycle (ORC) is considered as a promising one for its high thermal efficiency, safety, flexibility and low maintenance requirements [4–6].

Various ORC systems have been designed, among which regenerative ORCs are seen as high-performance ones [7–9]. Because the addition of regenerators decreases the heat wasted by the condenser and makes the working fluid match better with the heat source in the evaporator, resulting in more output power and less irreversibility. Vaja and Gambarotta [10] carried out a detailed comparison between simple ORC, preheated ORC and regenerative ORC and found that the thermal efficiency of regenerative ORC with benzene showed a 12.3% and 1.6% relative increase compared with simple ORC and preheated ORC, respectively. In addition, cycle types are also studied and it is found that transcritical cycles are preferable due to the circumvention of the pinch-point problem [11,12]. In transcritical cycles, working fluid is evaporated from the saturated liquid directly into a superheated state, bypassing the two-phase region, resulting in a better match with the heat source in the evaporator. Therefore, more output power with less irreversibility is obtained in transcritical cycles. As for the working fluid selection of transcritical ORCs, many researchers have carried out relative studies. R143a is found to be a preferable working fluid in low-temperature waste heat recovery [13,14].

Whereas, present ORCs mainly focus on single-stage systems, of which there are some issues. First, the decomposition temperature of conventional organic fluid is mostly low, which makes mismatch with the high-temperature exhaust. When directly exchanging between them, the system will easily be unsafe due to the organic fluid's decomposition. This is also the dominant problem existing in single-stage ORCs. Furthermore, the temperature difference between the high-temperature exhaust and low-temperature engine coolant in single-stage ORCs is large, resulting in little utilization of the engine coolant waste heat. In addition, incomplete utilization of the exhaust waste heat is also an issue due to the still high temperature of the exhaust before being discarded into the environment. Therefore, design for regenerative dual-loop ORCs (DORCs), in which a high-temperature (HT) loop adopts a working

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Nomenclature

c_{pg}	constant-pressure specific heat of the exhaust (kJ/kg K)
c_{pw}	constant-pressure specific heat of the engine coolant or supplied cooling water (kJ/kg K)
e_f	exergy of working fluid (kW)
h	specific enthalpy (kJ/kg)
I	irreversibility (kW)
m_c	mass flow rate of the supplied cooling water (kg/s)
m_f	mass flow rate of the working fluid (kg/s)
m_g	mass flow rate of the exhaust (kg/s)
m_w	mass flow rate of the engine coolant (kg/s)
P_{cr}	critical pressure (MPa)
P_{evp}	evaporation pressure (MPa)
Q_c	heat rejected by the supplied cooling water (kW)
Q_f	heat absorbed from the HT loop (kW)
Q_g	heat absorbed from the exhaust (kW)
Q_w	heat absorbed from the engine coolant (kW)
Q_R	heat transferred in the regenerator (kW)
s	specific entropy (kJ/kg K)
T	temperature (K)
T_b	boiling temperature (°C)
T_{cr}	critical temperature (°C)
T_d	decomposition temperature (°C)
T_{cond}	condensation temperature (K)
Wp	power consumed by pumps (kW)
W_t	power output by turbines (kW)
W_{net}	net output power (kW)
$\Delta T_{pp,gl}$	pinch point temperature difference of gas–liquid heat exchangers (K)
$\Delta T_{pp,ll}$	pinch point temperature difference of liquid–liquid heat exchangers (K)
ΔT_{HT}	temperature increment of regenerator R_{HT} (K)
ΔT_{LT}	temperature increment of regenerator R_{LT} (K)
η_e	exergy efficiency
η_{ec}	energy conversion efficiency
VER	volumetric expansion ratio
COR	power consumed to power output
$m_{f,HT}$	means the mass flow rate of the working fluid in the HT cycle

fluid with high decomposition temperature to recover the high-temperature part of the exhaust waste heat and a low-temperature (LT) loop adopts a conventional organic fluid to recover the waste heat of the engine coolant, residual heat of the HT loop and LT part of the exhaust waste heat, is of great significance. In this system, the issues above can be effectively solved.

In this paper, a regenerative DORC is proposed to recover the waste heat of the exhaust, engine coolant and all the residual heat of the HT loop. Double regenerators are adopted in this system: one in the HT loop, the other one in the LT loop. Transcritical cycles are used in both loops. Six organic fluids with low-temperature critical temperature and high decomposition temperature are chosen as the candidate working fluids of the HT loop and R143a is chosen as the working fluid of the LT loop. Influences of inlet temperature of turbine T_{HT} (T_3) on mass flow rates ($m_{f,HT}$ and $m_{f,LT}$), net output power (W_{net}), energy conversion efficiency (η_{ec}), volumetric expansion ratio (VER), ratio of power consumed to power output (COR) and component irreversibility are analyzed and performance comparison of these working fluids is also evaluated.

2. System description

2.1. Topping engine

In this paper, a six-cylinder four-stroke turbocharged diesel engine is chosen as the topping system to couple with the regenerative DORC. In order to better evaluate the performance of the DORC system, the engine is assumed to operate at rated condition, whose main parameters are shown in Table 1. The composition of the exhaust is calculated with the assumption of complete combustion: $CO_2 = 15.2\%$, $H_2O = 6.0\%$, $N_2 = 73.0\%$, $O_2 = 5.8\%$.

2.2. Bottoming DORC

Figs. 1 and 2 show the configuration diagram and corresponding *T–s* diagram of the regenerative DORC, which contains a HT loop and a LT loop. The HT loop consists of an evaporator driven by the high-temperature exhaust (E_{HT}), a turbine (T_{HT}), a regenerator (R_{HT}), a condenser (C_{HT}) and a pump (P_{HT}). The LT loop consists of an evaporator driven by the engine coolant ($E_{1,LT}$), an evaporator driven by the residual heat of the HT loop ($E_{2,LT}$), an evaporator driven by the low-temperature exhaust ($E_{3,LT}$), a turbine (T_{LT}), a regenerator (R_{LT}), a condenser (C_{LT}) and a pump (P_{LT}). The condenser in the HT loop (C_{HT}) is also the evaporator in the LT loop ($E_{2,LT}$), through which these two loops are combined and in which the residual heat of the working fluid at the turbine T_{HT} outlet in the HT loop is used as the heat source and the working fluid R143a of the LT loop is used as the working fluid.

The thermodynamic process of the HT loop is defined as 5-1-1s-3-4-4s-5 and described as follows. The generated high-pressure working fluid (point 1) firstly flows into the regenerator to be preheated by its residual heat at the turbine outlet (regeneration process). The working fluid after regeneration (point 1s) flows into the evaporator to be heated by the high-temperature part of the exhaust waste heat and changes into a superheated vapor directly (point 3), bypassing the two-phase region (isobaric heating process). The high-pressure superheated vapor flows into the turbine to export mechanical work by expansion and changes into a low-pressure vapor (point 4) (non-isentropic expansion process). The vapor flows into the regenerator to preheat itself at the pump outlet and lowers its temperature (point 4s) (regeneration process). It then flows into the condenser to be completely liquefied by the working fluid of the LT loop (point 5) (isobaric condensation process). The saturated liquid flows into the pump and changes into a high-pressure liquid (point 1) (non-isentropic pumping process). A complete HT loop is finished. The thermodynamic process of the LT loop is defined as 11-6-6s-7-8-9-10-10s-11, which is similar to that of the LT loop. The isobaric heating process 6–9 consists of three heating process 6–7, 7–8 and 8–9. In addition, in the isobaric condensation process, the supplied cooling water is used as the refrigerant to completely liquefy the low-temperature vapor out of the turbine.

In this system, the waste heat of the engine coolant and the residual heat of the HT loop are totally utilized. The waste heat

Table 1
Engine parameters.

Parameter	Value	Unit
Engine power output	235.8	kW
Engine Efficiency	41.81%	/
Exhaust temperature	792.2	K
Engine coolant temperature	356.5	K
Exhaust mass flow rate	0.275	kg/s