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Analysis of regenerative dual-loop organic Rankine cycles (DORCs) used in engine waste heat recovery

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ABSTRACT

In this paper, three regenerative dual-loop organic Rankine cycle (DORC) systems are proposed to compare with the simple DORC system. Waste heat of the exhaust, engine coolant and residual heat of the HT loop are recovered in these four systems. In the HT loop, water and siloxane are chosen as working fluid candidates, transcritical cycle and subcritical cycle are evaluated. In the LT loop, R143a is used as the working fluid and transcritical cycle is adopted. Net output power and exergy efficiency are selected as objective functions. Based on the engine data and mathematic model, operating parameters are optimized and component irreversibility is analyzed. Results show that low condensation temperature of the HT loop is beneficial to performance optimization. The inlet temperature of turbine T_{HT} should be high for wet fluids in subcritical cycle and low for dry fluids in both subcritical and transcritical cycles. Maximum net output power and exergy efficiency are obtained when water is used as the working fluid of the HT loop and no regenerator is adopted in the system. Corresponding values are 39.67 kW and 42.98%. When siloxane is used as the working fluid of the HT loop, DORC with double regenerators performs better. For all systems evaluated, irreversibilities of condenser C_{LT} and turbine T_{LT} are large.

1. Introduction

As energy crisis and environment pollution are increasingly severe, many technologies have been proposed to save energy and reduce emission in the field of internal combustion engine (ICE) [1], which is main consumer of fossil fuel. Among these technologies, organic Rankine cycle (ORC) is an effective one because of its flexibility, economy and good thermal performance [2–4]. Vaja [5,6], Ringer et al. [7], Teng et al. [8–10], and Srinivasan et al. [11] designed various single-stage ORC systems, among which preheated cycle and regenerative cycle were preferable because in these cycles working fluid could match better with the heat source in the evaporator. Whereas, in existing single-stage systems, the coupling of high-temperature exhaust and low-decomposition-temperature organic working fluid was dominant issue to be settled. Waste of the exhaust residual heat and little utilization of engine coolant waste heat were another two issues. Because the exhaust temperature after one heat exchange was still rather high and direct rejection would result in great waste. In addition, in single-stage preheated ORCs, the engine coolant and exhaust were in large temperature difference, resulting in little utilization of low-grade engine coolant waste heat. Therefore, designing dual-loop ORCs (DORCs) is significant; whereas, there is little knowledge presently.

In order to utmostly optimize system performance, selections of cycle mode (subcritical cycle or transcritical cycle) and working fluid are important. In subcritical low-temperature ORCs, performance improvement is limited by the pinch point problem in constant-temperature heating process of the working fluid, which results in a mismatch between the working fluid with the heat source [4,12–14]. Therefore, transcritical cycle is better for low-temperature ORCs, in which R125, R143a and R218 are mainly used as working fluids presently [15–17]. For high-temperature ORCs, cycle mode is limited by working fluid's decomposition temperature. Water and siloxanes are mainly used in existing high-temperature ORCs [15,18,19]. As the critical pressure of water is very high, subcritical cycle is mostly adopted [20]. In addition, regenerators can decrease energy waste in the condenser and make the working fluid match better with the heat source in the evaporator, which can enhance system performance [21,22]. Therefore, working fluid and cycle mode selection and study of regenerators' influence is of great significance.

In this paper, three regenerative DORC systems are proposed to compare with simple DORC system which is without regenerators (system N). The system with a regenerator in the HT loop is named system HT. The system with a regenerator in the LT loop is named system LT. The system with double regenerators (one in the HT

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Nomenclature

c_p	constant-pressure specific heat (kJ/kg K)
E	exergy (kW)
h	specific enthalpy (kJ/kg)
I	exergy destruction or loss (kW)
m	mass flow rate (kg/s)
W	work consumed or output (kW)
Q	heat injected or rejected (kW)
s	specific entropy (kJ/kg)
P	pressure (MPa)
T	temperature (K)

Greek letters

η	efficiency
δT	temperature increment of regenerator (K)

Subscripts

c	supplied cooling water
e	exergy
f	working fluid
g	exhaust
j	component j
p	pump
r	regenerator
s	system
t	turbine
w	engine coolant
in	come in
ec	energy conversion
evp	evaporation
net	net output
out	leave out
$cond$	condensation
HT	high temperature loop
LT	low temperature loop
$m_{f,HT}$	means the working fluid mass flow rate of the HT loop
$I_{rege,HT}$	means the exergy destruction of regenerator in the HT loop

loop and the other one in the LT loop) is named system D. In DORC systems, a high-temperature (HT) loop and a low-temperature (LT) loop are contained. The HT loop uses high-decomposition-temperature working fluid to recover high-temperature part of exhaust waste heat to settle the coupling issue of exhaust and organic working fluid, guaranteeing system safety. The LT loop uses traditional organic working fluid to recover low-grade engine coolant waste heat and low-temperature part of exhaust waste heat. In addition, residual heat of the working fluid at the turbine outlet in the HT loop (i.e. residual heat of the HT loop) is also low-and-medium grade, which is also completely recovered in the LT loop. In the LT loop, these three heat sources are in smaller temperature difference, resulting in the enhancement of engine coolant waste heat's utilization. The exhaust also goes through two heat exchanges and final outlet temperature lowers, resulting in more complete utilization. In these four systems, three cycle modes are evaluated. The LT loop stays same in all modes, in which R143a is used as the working fluid and transcritical cycle is adopted. Whereas, the HT loops of these modes are different. Mode 1 adopts a subcritical cycle, in which water is used as the working fluid. Mode 2 also adopts a subcritical cycle, in which siloxane is used as the working fluid. Mode 3 adopts a transcritical cycle, in which siloxane is used as the working fluid. Net output power and exergy efficiency are chosen as objective functions to evaluate the performance of all systems and cycle modes. Influences of operating parameters and component irreversibility are also evaluated.

2. System description

2.1. Bottoming DORC

Take system D as an example to describe the configuration and thermodynamic processes of the system, which are shown in Figs. 1–3. The HT loop consists of an exhaust evaporator (E_{HT}), a turbine (T_{HT}), a regenerator (R_{HT}), a condenser (C_{HT}) and a pump (P_{HT}). The LT loop consists of three evaporators ($E_{1,LT}$, $E_{2,LT}$ and $E_{3,LT}$), a turbine (T_{LT}), a regenerator (R_{LT}), a condenser (C_{LT}) and a pump (P_{LT}). These three evaporators in the LT loop are driven by the engine coolant, residual heat of the HT loop and low-temperature exhaust, respectively. These two loops are coupled through the condenser of the HT loop (C_{HT}), which is also the second evaporator of the LT loop ($E_{2,LT}$). These two loops both include five typical thermodynamic processes: non-isentropic pumping process, isobaric heating process, non-isentropic expansion process, regeneration process and isobaric condensing process. Corresponding thermodynamic processes of these two loops are shown in detail in Table 1. The total heating process of the LT loop (process 6*s*–9) comprises of three evaporation processes: process 6*s*–7, process 7–8 and process 8–9.

Now take the HT loop as an example to describe the thermodynamic processes. Low-pressure saturated liquid is pumped into high pressure by the pump (non-isentropic pumping process) and then flows into the regenerator to be preheated by the low-pressure vapor out of the turbine (regeneration process). The working fluid then flows into the evaporator to be heated into a superheated or saturated vapor (isobaric heating process). The

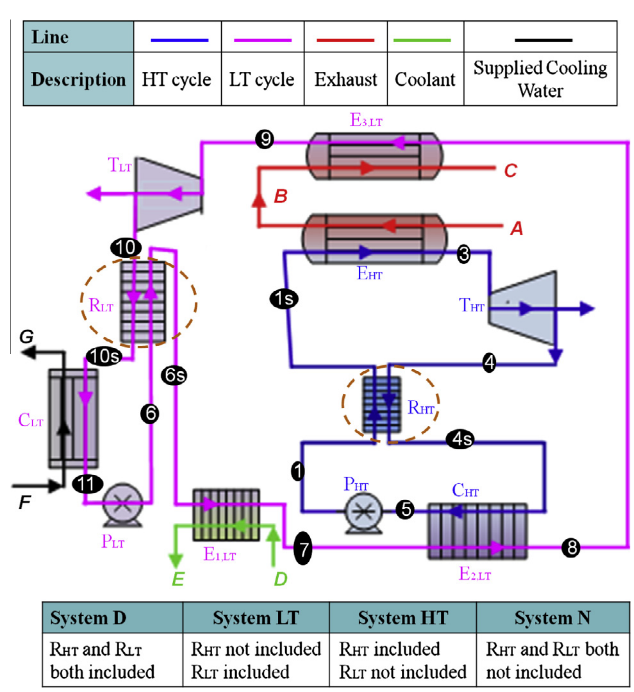

Fig. 1. Configuration diagram.