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Dynamic analysis of the dual-loop Organic Rankine Cycle for waste heat recovery of a natural gas engine

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A B S T R A C T

Natural gas internal combustion engines for electric generating are important primary movers in distributed energy systems. However, more than half of the energy is wasted by exhaust, jacket water and so on. Therefore, it is very meaningful to recover the waste heat, especially the exhaust heat. The DORC (Double loop ORC) is regarded as a suitable way to recover exhaust heat and it can produce electric required by users all the year around. As the waste heat recovery system of the engine, it often works under different working conditions owing to the varying energy demand of users. However, there is few study on the part-load performance of the DORC under different working conditions. Consequently, the dynamic math model of the DORC for waste heat recovery of a natural gas engine with 1000 kW rated power is established by Simulink in this work. With the PID control of the system, the static performance and dynamic behavior of the DORC under five typical engine working conditions are simulated and analyzed. Besides, the effects of the mass flow rate of the HT (high temperature) cooling water which is the connection between the two loops on the DORC performance are researched as well. The results illustrate that the DORC can improve the efficiency of the combined system quite well from 100% to 60% engine working condition, showing good working condition adaptability. Besides, enlarging the mass flow rate of the HT cooling water can enhance the output power of the DORC system, but not very obviously.

1. Introduction

The DES (Distributed energy system) means small scale energy generation unit located near the end user and has high energy efficiency, so it has been valued increasingly [1,2]. The DES can employ a wide range of technologies [3]. Therein, natural gas ICEs (internal combustion engines) have attracted more and more concern as prime movers, because of the features of low carbon content, clean burn (low soot and smoke) and great resource [4]. However, the average thermal efficiency of the natural gas engine is just about 30–40% [5]. Most of the waste heat is discharged by exhaust, jacket water and machine oil. Therein exhaust contains the most heat which is nearly equal to the output power of the engine and jacket water comes second. As a result, the WHRS (waste heat recovery system) is a quite important part of the DES, which can improve the whole efficiency obviously. The ORC (organic Rankine cycle) is regarded as a promising method for engine waste heat recovery [5]. It can utilize the waste heat to generate electricity for DES users. Unlike cooling and heating, of which the requirement is greatly affected by seasons, electricity is necessary all the year around. Therefore, the ORC is quite suitable for applying in DES.

Many researchers have studied ORCs with different working fluids [6–10]. Refrigerants are traditional ORC working fluids, which usually have low critical temperature and decomposition temperature. They are called LT (low temperature) working fluids in the paper [6]. The ORC with the LT working fluid has large exergy loss and relatively small output power [7]. Furthermore, owing to the high temperature exhaust and low decomposition temperature of LT working fluids, a medium cycle like thermal oil cycle is required to avoid resolving, but it increases the complexity of the system [8]. Applying working fluids such as alkanes which have high critical temperature and decomposition temperature can get rid of the medium cycle. These working fluids are called as HT (high temperature) working fluids in the paper [6]. Fig. 1 describes a general comparison of ORC systems with LT and HT working fluids. It can be found that when condensing at the same temperature, HT working fluids have much less exergy loss and larger output power than LT working fluids [6]. However, the condensing pressure is much lower and the pressure ratio in turbine (the ratio of turbine inlet and outlet pressure) is much greater than LT working fluids,

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Nomenclature

T	temperature (K)
ρ	density (kg/m^3)
α	heat transfer coefficient (W/m^2·K)
C_p	specific heat (J/kg·K)
m	mass flow rate (kg/s)
A	area (m^2)
t	time (s)
D	diameter (m)
h	specific enthalpy (J/kg)
Re	Reynolds number
Nu	Nusselt number
Pr	Prandtl number
γ	void fraction (m^2/s)
S	slip ratio
μ	density ratio
u	velocity (m/s)
L	length (m)
p	pressure (Pa)
x	vapor quality
ω	revolution speed (rpm)
η_v	volumetric efficiency
V_{cyl}	cylinder volume (m^3)
$\dot{V}$	volume flow rate (m^3/s)
C_v	turbine coefficient
W	work (kW)
Q	absorbed heat (kW)
η_{st}	isentropic efficiency of expander
η	dynamic viscosity (Pa·s) or liquid fraction or efficiency
η_{sp}	isentropic efficiency of pump
c_s	isentropic gas speed(m/s)

Subscript

l	liquid
g	gas
e	exhaust
c	cold
f	fluid
i	inside
o	outside
w	wall
in	inlet
out	outlet
r	working fluid
avg	average
p	pump
s	isentropic
t	turbine

Abbreviation

DORC	Dual-loop Organic Rankine Cycle
ORC	Organic Rankine Cycle
MB	Moving Boundary
WHRS	Waste Heat Recovery System
HT	high temperature
LT	low temperature
ICE	internal combustion engine
DES	distributed energy system

resulting in a great difficulty for the manufacture of such a small turbine [7,9]. For the sake of reducing the pressure ratio to a reasonable level, the condensing pressure should be raised. At the same time, the condensing temperature gets high so that the condensing heat can be sequentially used to drive another LT ORC and this is the DORC (double-loop ORC). Obviously the DORC has relatively small exergy loss and its output power is the addition of the power of the LT and HT ORCs as shown in Fig. 1. Besides, the DORC can recover the waste heat both from exhaust and cooling water,

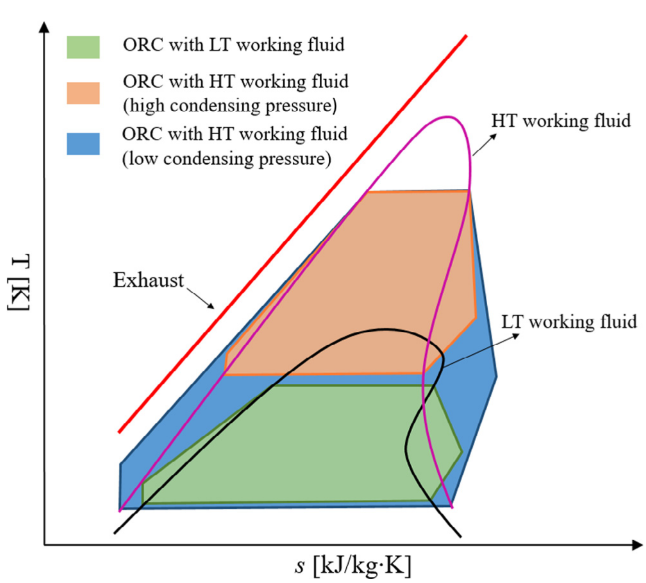

Fig. 1. The comparison of different ORCs.

improving the recovery efficiency further [10]. Therefore, the DORC is an excellent waste heat recovery system for engines and there have been a lot of researches on it [11–17].

BMW [11,12] proposed a DORC system coupling with a 1.8 L four-cylinder engine. The DORC could reduce fuel consumption by up to 15 percent and generate 10 kilowatts more power and 20 Nm more torque. At the same time, both of the turbines in the two loops did not have too large pressure ratio. Choi [13] made a theoretical analysis of a DORC for recovering the exhaust heat from a ship engine. Water was the working fluid in the HT loop and R1234yf was the working fluid of the LT loop. The results indicated that the DORC had less exergy loss than the single stage ORC and could improve the engine efficiency by 2.824%. Song [14] used a DORC to recover the exhaust heat of an ICE with 996 kW rated power. Three different DORC systems with the same HT ORC and three different LT ORCs (with R123, R236fa, R245fa as working fluid, respectively) were calculated and analyzed. It was found that the DORC with R236fa as the LT ORC working fluid could output the largest power 115.1 kW. Shu et al. [15–17] have made detailed researches about DORC for engine waste heat recovery, including the key operation parameters effects, selection of HT ORC and LT ORC working fluids, the structure of the DORC and so on. The results showed that the DORC could increase the engine efficiency much more than the single-stage ORC with traditional working fluids such as R245fa and R123.

The researches above are all under stable working conditions, aiming at improving the system efficiency. However, the working condition of ICE often varies. Exhaust is the most important waste heat source. Under different working conditions of the ICE, exhaust temperature of light-duty engines varies from 500 to 900 °C and that of heavy-duty engines is in the range of 400–650 °C [18,19]. Besides, the exhaust mass flow rate also changes a lot under different ICE working conditions. In a word, the WHRS often works at