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Effect factors of part-load performance for various Organic Rankine cycles using in engine waste heat recovery

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ABSTRACT

The Organic Rankine Cycle (ORC) is regarded as one of the most promising waste heat recovery technologies for electricity generation engines. Since the engine usually operates under different working conditions, it is important to research the part-load performance of the ORC. In order to reveal the effect factors of part-load performance, four different forms of ORCs are compared in the study with dynamic math models established in SIMULINK. They are the ORC applying low temperature working fluid R245fa with a medium heat transfer cycle, the ORCs with high temperature working fluid toluene heated directly by exhaust condensing at low pressure and high pressure, and the double-stage ORC. It is regarded that the more slowly the system output power decreases, the better part-load performance it has. Based on a comparison among the four systems, the effects of evaporating pressure, condensing condition, working fluid, and system structure on part-load performance are revealed in the work. Further, it is found that the system which best matches with the heat source not only performs well under the design conditions, but also has excellent part-load performance.

1. Introduction

The ORC (Organic Rankine Cycle) is one of the most promising energy conversion technologies for electricity generation engine waste heat recovery [1]. The former study shows that the engine power can be increased by about 10–17% with the ORC [2–5]. Additionally, the ORC shows great flexibility, high safety, low cost, and low maintenance requirements [6]. In recent years, a number of engine-ORC combined systems have been installed, for example in Italy at Pavia (0.6 MW), Portogruaro (0.6 MW), Catania (0.6 MW), Pescara (0.7 MW), Chivasso (1 MW), Pisticci (1.8 MW) and Pisticci Scalo (4 MW); in Germany at Kempen (0.6 MW) and Senden (1 MW); and in Finland at Ammassuo, Espoo (1.3 MW) [2,7].

There are a number of different kinds of ORCs for engine waste heat recovery. In our previous research [8], the most common basic ORCs are classified as: the ORC with low temperature working fluid such as refrigerants, named LT-ORC; the ORC with high temperature working fluid such as benzenes, named HT-ORC; and the double-stage ORC, named DORC or binary ORC [9]. Comprehensive evaluation of different ORCs has been studied based on the first and second laws of thermodynamics, and the economy, revealing their own advantages and disadvantages, respectively. For example, Vaja and Gambarotta [10] compared the performance of LT-ORCs (R245fa and R11 working fluids) and the HT-ORC (benzene working fluid) as the WHRS (waste heat recovery system) for an internal combustion engine. It was found that the largest efficiency increase of the engine could be obtained by the ORC with benzene, while the smaller and cheaper turbine could be applied in the LT-ORC. Shu et al. [11] compared the performance of a single-loop ORC and a DORC as the WHRS of a heavy-duty diesel engine, based on a multi-approach evaluation system. It was demonstrated that the DORC system was a suitable configuration for engine waste heat recovery, as it performed excellently during thermodynamic and economic evaluating processes. The research of Invernizzi and Nadeem [9] showed performance limitations in simple cycles under realistic assumptions, such as the application of a single-stage turbine, and revealed the high efficiency of binary ORC (15–16%).

All of the above research focuses solely on steady performance under design working conditions. In fact, working conditions for electricity generation engines often vary, leading to large and frequent changes in waste heat [12,13], so it is crucial to study the part-load performance of ORCs [12]. Part-load performance can be predicted by the static off-design model and the dynamic model [10]. The static off-design model can calculate part-load performance under different stable working conditions, but it cannot reflect dynamic behavior in an unsteady state. On the other hand, it does not require much calculation resource. The whole dynamic varying process of the ORC can be figured

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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)
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	heat source
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
rec	receive
amb	ambient

Abbreviation

ORC	Organic Rankine Cycle
DORC	Dual-loop Organic Rankine Cycle
B-ORC	back pressure ORC
C-ORC	condensing ORC
MB	moving Boundary
WHRS	Waste Heat Recovery System
HT	high temperature
LT	low temperature

out by the dynamic model, which can be used to develop the control system, but doing so requires more calculation resource than the static model.

Fu et al. [14] investigated the effects of heat source temperature on ORC system part-load performance by the static part-load model. It was found that the heat source temperature variation of −10.3 °C to +19.8 °C from the design value resulted in variations of −13.6% to +22.6% and −11.5% to +17.4% in net output power and thermal efficiency, respectively. Badescu et al. [15] conducted a study on recovering exhaust waste heat from a power generation engine under different engine working conditions using the static part-load model. When the engine was coupled with an ORC, the overall thermal efficiency of the combined system could be higher than that of the engine alone by 6.00%, 5.85%, and 5.91% under engine loads of 100%, 75%, and 50%, respectively. Bamgbopa and Uzgoren [16] established both static and dynamic models of the ORC. The static model was used to develop a static state map to construct a control strategy. The dynamic model was used to study system part-load performance when the heat source gradually or abruptly varied with and without the control strategy. It was demonstrated that adjusting flow rates could not only improve thermal efficiency but also help to maintain steady state operation. Danov and Gupta [17] proposed a combined cycle which used the diesel engine as the top cycle and the ORC as the bottom cycle for exhaust waste heat recovery. A numerical dynamical model was established to assess part-load performance under different engine working conditions, and this showed tight interactions between the two cycles when the engine was not running under full load. Horst et al. [18] established a dynamic ORC model with a controller as the WHRS of an automotive engine to evaluate fuel saving potential during an exemplary dynamic motorway driving scenario. The results showed that the WHRS could improve fuel economy by 3.4%. Mazzi et al. [19] presented a dynamic model of an LT-ORC for exhaust waste heat recovery. Results showed that system efficiency at the design point only slightly decreased (from 24.45% to 24.21%) in the range of 80–110% of the nominal oil mass flow rate at constant temperature. By contrast, changes in oil temperature affected efficiency significantly.

All of the above researches about ORC part-load performance focus solely on the performance variation of a certain system when the parameters of the heat source or the ORC itself change. There are few studies that focus on comparing the part-load performance of different ORCs and finding the effect factors. Therefore, the part-load performance of different ORCs as the WHRS of an electricity generation engine is compared under different working conditions by the dynamic model with a control system in this study. As mentioned above, the most common basic ORCs are classified as LT-ORC, HT-ORC, and DORC, with HT-ORCs being divided into systems with high condensing pressure and low condensing pressure. Consequently, four different ORC configurations in total are compared. Based on this, the reasons why they perform differently under part-load conditions are analyzed in detail.

2. System description

2.1. The engine

The electricity generation engine in this study is a natural gas internal combustion engine of 1000 kW rated power. The heat balance experiments on the engine have been conducted by our research group, which aimed to understand the distribution of output energy under full engine working conditions, such as the proportion of effective power, exhaust heat, jacket water heat, and so on. However, in this work only the exhaust, which is the most important waste heat source and accounts for about 30–40% of input energy, is the heat source for different ORCs. Therefore, only the parameters related to exhaust under seven