Performance evaluation of a diesel engine integrated with ORC system

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Abstract

Waste heat recovery from exhaust gas with organic Rankine cycle (ORC) systems is a promising method to improve the overall thermal efficiency of engines. The performance of a diesel engine integrated with an ORC system is evaluated in this paper. Simulation models of the diesel engine and the ORC system are developed in GT-suite separately, and a combined system model is developed in Simulink environment. The engine simulation results are validated experimentally. The steady performance evaluation of the engine with ORC system at different engine conditions is presented, and the acceleration performance of the diesel engine with and without ORC is evaluated. The performance of the engine during the ORC expander start-stop process is also discussed. The steady performance simulation results indicate that, the net power output increment, the brake specific fuel consumption (BSFC) reduction and the thermal efficiency improvement of the engine with ORC system can be up to 4.13 kW, 3.61 g/(kW·h) and 0.66 %, respectively. The transient performance simulation results show that the ORC system has minimal effects on the acceleration performance of the engine.

Key words

Diesel engine; ORC; Steady performance; Acceleration performance; Start-stop process of expander

1. Introduction

ORC systems have been considered as an effective approach for converting waste heat into power. ORC systems have high thermal efficiency and good applicability [1]. The applications of ORC on engine exhaust waste heat recovery (WHR) systems have been extensively investigated. F. Yang et al. [2] discussed the effects of superheat degree, evaporation pressure

1 and condensation temperature on the performance of a diesel engine WHR system and
2 optimized the system. M.-H. Yang et al. [3] analyzed the influences of the pressure at the turbine
3 inlet and outlet on the performance of an ORC WHR system for a marine engine. M.E.
4 Mondejar et al. [4] evaluated the performance of a regenerative ORC system in a passenger
5 vessel under quasi-steady states. Their results showed that the ORC system can provide 22%
6 of the vessel total power demand. V. Grelet et al. [5] presented the transient and steady
7 performance evaluation of an ORC WHR system for a heavy duty diesel engine. S. Bari et al.
8 [6] studied the effects of the shell and tube evaporator on ORC system performance with
9 different working conditions of a vehicle engine. G. Shu et al. [7] presents the experimental
10 comparison of R123 and R245fa as the working fluid of an ORC system for recovering engine
11 waste heat. G. Wenzhi et al. [8] developed an ORC system with a shell and tube evaporator and
12 a preheater for waste heat recovery from a diesel engine, and investigated experimentally the
13 system performance. C.O. Katsanos et al. [9] presented thermodynamic analysis of an ORC
14 system applied on a diesel engine.

15 Different ORC system layouts were also investigated. S. Amicabile et al. [10] presented a
16 comprehensive design methodology of ORC systems. A selection of the best waste heat source,
17 screening working fluids and system optimization were introduced. It was found that a
18 regenerative subcritical cycle using ethanol achieved the best performance and a subcritical
19 cycle with ethanol without a recuperator had the minimum capital cost. C. Yue et al. [11]
20 comparatively studied the performance of a Kalina cycle and an ORC system at various working
21 conditions. Moreover, E.H. Wang et al. [12] and J. Song et al. [13] evaluated the potential of
22 dual loop ORC systems. The effects of condensation temperature on performance of ORC

1 systems were discussed.

2 Recently, studies have been undertaken to analyze the performance of "on-board" ORC
3 systems. D. Di Battista et al. [14] analyzed the effects of increased backpressure and weight on
4 performance of the diesel engine and the truck respectively, and discussed an ORC system
5 performance at off-design operating conditions. M. Usman et al. [15] discussed the effects of
6 an ORC system on the performance of light duty vehicles. The results indicated that the
7 maximum power enhancement was 10.88%, however, the negative effects reduced the
8 improvement to 5.82%. A.F. Agudelo et al. [16] evaluated the performance of an ORC WHR
9 system on a passenger car under European driving cycle. The tests were performed under
10 environment temperature from -7 °C to 20 °C. The results showed that the fuel saving potential
11 were between 8% and 15% changed with the exhaust temperature from 115 to 320 °C. T.A.
12 Horst et al. [17] predicted the transient performance and potentiality of fuel saving of an ORC
13 WHR system on a passenger car. The results indicated that the ORC can improve fuel economy
14 by 3.4%, while the negative aspects such as increased weight, exhaust backpressure and cooling
15 demand led the potential reduction to 1.3%. S. Song et al. [18] evaluated the performance of an
16 ORC WHR system from a natural gas engine. The results indicated that the maximum net power
17 output is 62.7 kW of the ORC system and the maximum improvement of the combined electric
18 efficiency is 6%. T. Sung et al. [19] proposed an ORC system with two recuperators for
19 recovering exhaust waste heat and engine coolant energy from a gasoline vehicle.

20 Through investigations, many studies have been devoted to analyze the performance of ORC
21 systems and discuss the effects of engine working conditions on performance of ORC systems.
22 The literature about the performance evaluation of the engine with ORC combined system is

1 scarce to date and many questions remains to be addressed for the analysis of the effects of the
2 ORC system on performance of the engine. In this paper, the performance of a diesel engine
3 with ORC combined system is evaluated to discuss the potential of the ORC system for
4 improving thermal efficiency of the engine and analyze the effects of the ORC system on the
5 engine performance. Furthermore, the acceleration performance of the engine with and without
6 ORC is discussed, and the transient performance of the engine with the ORC system in the start-
7 stop process of the expander is also analyzed.

8 **2. Description of a diesel engine-ORC combined system**

9 The investigated ORC WHR system is shown in Fig. 1. The engine integrated with the ORC
10 system by an evaporator. The engine exhaust gas flows through the turbine into the evaporator,
11 where the liquid working fluid is vaporized after being pumped to a high pressure state. The
12 working fluid vapor flows through the expander where the thermal energy is converted into
13 useful power. The vapor is subsequently condensed into liquid in the condenser and flows into
14 the reservoir, then is pressurized again to form a cycle.

Fig. 1 Schematic diagram of the combined system

17 **2.1 ORC system layout**

18 The ORC system includes a shell and tube evaporator, a plate condenser, a scroll expander,

1 a generator, a diaphragm metering pump and a reservoir. R245fa is the working fluid due to the
2 high critical temperature and good environmental protection. The condenser adopts water
3 cooling method. The exhaust gas mass flow rate and temperature at the evaporator inlet are
4 0.199 kg/s and 626 K at the system design point. The mass flow rate of ORC working fluid and
5 the evaporation pressure are set to be 0.265 kg/s and 0.9 MPa. The temperature and mass flow
6 rate of the cooling water at the condenser inlet are 333.15 K and 3.2 kg/s. The heat transfer area
7 of two heat exchangers were calculated with the log-mean temperature difference method and
8 the parameters are as shown in Table 1.

Table 1 Parameters of the heat exchangers

Heat exchangers	Items	Parameters
Evaporator	Tube Length(mm)	1000
	Number of Tubes	120
	Number of Channels(in One Tube)	1
	Circular Channel Inner Diameter(mm)	9.52
	Shell Diameter(mm)	160
Condenser	Plate Length(mm)	350
	Plate Width(mm)	150
	Number of Channels	100
	Channel Height(mm)	3

2.2 Performance analysis of the diesel engine

The engine is a six-cylinder four- stroke turbocharged diesel engine for a heavy duty truck.

The specifications of the diesel engine are presented in Table 2.

Table 2 Specifications of the diesel engine

Items	Parameters
Rated power (kW)	258
Maximum torque (N·m)	1500
Rated speed (r/min)	2100
Speed under the Maximum torque condition (r/min)	1300~1600
Displacement (L)	8.6
Stroke and cylinder bore (mm)	112×145
Compression ratio	17.5

Fig. 2 Experiment results of exhaust gas mass flow rate

Fig. 3 Experiment results of exhaust gas temperature

Fig. 4 Experiment results of the engine BSFC

Engine performance was evaluated experimentally. The exhaust gas mass flow rate, exhaust gas temperature, and the engine BSFC are described in Fig. 2, Fig. 3 and Fig. 4, respectively.

As shown in Fig. 2, the mass flow rate of exhaust gas increases with the increment of the engine speed and the engine torque, and the exhaust mass flow rate reaches up to 0.417 kg/s when the engine speed is 2100 r/min and the torque is 1170 N·m. According to Fig. 3, the highest exhaust gas temperature is 754 K when the engine operates with the speed of 1600 r/min and the torque of 1422 N·m. The lowest BSFC of the engine is 195 g/(kW·h) for the engine speed of 1400

r/min and the torque of 1150 N·m according to Fig. 4. The energy and the exergy contained in exhaust gas were investigated by Eq. (1) and (2). Both energy and exergy of exhaust gas increase with the speed and torque of the diesel engine. The maximum exhaust energy is 372 kW, and the exhaust exergy is 72.5 kW under the ambient condition ($T=308.15$ K, $p=99.5$ kPa).

The energy and exergy contained in exhaust gas justify the potential of the ORC system.

Energy of exhaust gas:

$$\dot{Q}_{\text{exh}} = \dot{m}_{\text{exh}} \cdot h_{\text{exh}} \quad (1)$$

Exergy of exhaust gas:

$$\dot{E} = \dot{m}_{\text{exh}} \cdot [(h_{\text{exh}} - h_{\text{amb}}) - T_{\text{amb}} (s_{\text{exh}} - s_{\text{amb}})] \quad (2)$$

2.3 Numerical model of the combined system

2.3.1 Development of simulation models

The models of the diesel engine and the ORC system were developed in GT-suite environment respectively. The main parameters of the evaporator model and the condenser model are presented in Table 1. Simple models of positive displacement pump and expander in GT-suite model libraries were selected to simulate the diaphragm metering pump and the scroll expander respectively. And the working fluid volumetric flow rate and the change in specific enthalpy across the expander and the pump were calculated separately according to the constant displacement, volumetric efficiency and isentropic efficiency.

The engine model includes all the engine components such as engine cylinders, fuel injectors, pipelines and the turbocharger. The parameters of the cylinders are presented in Table 2. The properties of the inlet and the exhaust valves and the turbocharger were measured through tests.

The engine model and the ORC system model were developed separately and they were coupled by a bridging model developed in the Simulink environment which allows dynamic data transferring between the two models according to Fig. 5. The exhaust temperature and mass flow rate were calculated with the engine model and transmitted to the ORC system model via the bridging model. The exhaust gas pressure at the evaporator inlet was calculated in the ORC system model and transferred back to the engine model. The dynamic data was transferred between the two separate GT-suite models every 0.001 s. This allowed the coupled model to more accurately evaluate the steady and transient performance of the engine with and without

- 1 the ORC system. The backpressure increment, the power output increment, the thermal
- 2 efficiency improvement and the BSFC reduction of the engine with the ORC system are
- 3 analyzed by the following formulas Eq.(3), (5), (6) and (7).

4

5 Fig. 5 Schematic diagram of the combined system model

- 6 Backpressure increment of the engine integrated with ORC system is calculated by:

$$\Delta P_{\text{back}} = P_{\text{bw}} - P_{\text{bwo}} \quad (3)$$

The power output of the engine with ORC system is defined as:

$$\dot{W}_{\text{ew}} = \dot{W}_{\text{we}} + \dot{W}_{\text{exp}} - \dot{W}_{\text{pu}} \quad (4)$$

The net power output increment of the engine with the ORC system is defined as:

$$\dot{W}_{\text{n}} = \dot{W}_{\text{we}} + \dot{W}_{\text{exp}} - \dot{W}_{\text{pu}} - \dot{W}_{\text{e}} \quad (5)$$

The thermal efficiency improvement of the combined system is:

$$\Delta \eta = \frac{\dot{W}_{\text{n}}}{\dot{Q}_{\text{fu}}} \quad (6)$$

The BSFC reduction of the diesel engine with the ORC system is calculated by:

$$\Delta BSFC = \frac{\dot{m}_{\text{fu}}}{\dot{W}_{\text{e}}} - \frac{\dot{m}_{\text{fu}}}{\dot{W}_{\text{ew}}} \quad (7)$$

2.3.2 Validation of the engine model

The GT-suite engine model was validated against experimental results to justify its accuracy.

Errors of the engine BSFC and the exhaust gas mass flow rate between experiment and

simulation are shown in Fig. 6 and Fig. 7. The maximum error of the engine BSFC is lower

than 2%, and the maximum error of exhaust gas mass flow rate is lower than 2.5%. This

suggests that the engine model has high accuracy and can be used for the following

investigations.

Fig. 6 BSFC error between experiment and simulation

Fig. 7 Exhaust gas mass flow rate error between experiment and simulation

3. Steady performance of the diesel engine with ORC system

The ORC system is a subcritical system which has a moderate evaporation pressure. The temperature of exhaust gas at the evaporator outlet must be higher than the dew point to avoid the corrosion of the evaporator, and the working fluid should be at a saturation state or superheat state at the evaporator outlet to reduce the damage on the expander. Therefore, it is necessary to determine a suitable range of the engine operating condition for the ORC system in normal operation. If the liquid working fluid can't reach to a saturation state at the evaporator outlet or

1 the net output power increment of the engine with ORC combined system is negative, the
 2 corresponding engine operating conditions are named as “Unavailable conditions for ORC”.

3 The net power output increment of the engine with ORC at different engine operating
 4 conditions is presented in Fig. 8. The net power output increment of the combined system
 5 increases with the increasing of engine power output, and the maximum increment is 4.13 kW
 6 when the engine operates with the speed of 2100 r/min at full load condition. When the engine
 7 works at the conditions of “Unavailable conditions for the ORC system”, the exhaust gas of the
 8 diesel engine contains insufficient energy to completely evaporate the working fluid from liquid
 9 to vapor, which results in potential damage to the expander, or the power output of the engine
 10 with ORC is lower than that of the engine without ORC, because of the pump power
 11 consumption is higher than the expander output power. Therefore, the ORC system should be
 12 closed and the exhaust gas should be passed through a by-pass exhaust pipe when the engine
 13 operates at the unavailable conditions for the ORC system.

Fig. 8 Simulation results of the net power output increment

Fig. 9 shows the increment of exhaust backpressure at different engine operational conditions.

1 When the engine operates at “Unavailable conditions for ORC”, exhaust gas passes through a
2 by-pass exhaust pipe and doesn’t flow into the evaporator, and the ORC system is shut down,
3 therefore the backpressure of the engine is equal to the environment pressure. The engine
4 backpressure changes with the exhaust mass flow rate at different engine working conditions,
5 and the maximum increment of exhaust backpressure reaches to 4.805 kPa when the engine
6 operates at the rated condition.

Fig. 9 Simulation results of exhaust backpressure increment

9 The maximum thermal efficiency of the engine without ORC is 43.22% for the engine
10 operated with the speed of 1200 r/min at full engine load operational condition. Fig. 10
11 describes the thermal efficiency improvement of the engine with ORC system. The maximum
12 efficiency improvement is 0.66% when the diesel engine operates with the speed of 1600 r/min
13 at full engine load condition, and the minimum improvement is 0.42% for the engine speed of
14 1500 r/min and the torque of 700 N·m. When the engine operates at “Unavailable conditions
15 for ORC”, the improvement of thermal efficiency is zero, because the exhaust gas passes
16 through the by-pass exhaust pipe, and the ORC system is not working.

Fig. 10 Simulation results of thermal efficiency improvement of the diesel engine

The lowest BSFC of the engine without ORC is 195 g/(kW·h) according to Fig. 4. While the lowest BSFC of the diesel engine integrated with the ORC system is 192.5 g/(kW·h). The BSFC reduction of the engine with ORC system at different engine operational conditions is presented in Fig. 11. The reduction of BSFC increases with both the engine speed and the engine torque. The maximum BSFC reduction is 3.61 g/(kW·h) for the largest engine power output. And the lowest BSFC reduction of the engine with ORC is 1.89 g/(kW·h) when the engine operates at the speed of 1500 r/min and the torque of 700 N·m.

Fig. 11 Simulation results of the engine BSFC reduction at different operating conditions

4. Transient performance evaluation of the diesel engine

In this part, the transient performance of the engine integrated with and without ORC system is evaluated. The difference of acceleration performance of the engine with and without ORC system is analyzed, and the performance of the combined system during the start-stop process of the expander is also discussed.

4.1 Acceleration performance evaluation of the engine

The diesel engine was set operating with the cycle fuel injection quantity of $140 \text{ mm}^3/\text{c}$ and the speed of 1600 r/min . The cycle fuel injection quantity was increased to $198.8 \text{ mm}^3/\text{c}$ within 1 s from the 100th second, but the engine torque was remained at $985 \text{ N}\cdot\text{m}$. The power output of the ORC system was not used to drive the engine for the present system. Since the vehicle weight of the heavy duty truck is 9800 kg , the ORC system added weight is much smaller than the truck weight. Therefore, the effects of the ORC system added weight on the acceleration performance of the engine and the truck were not considered. The acceleration performance of the engine with and without the ORC system was analyzed according to Fig. 12 and Fig. 13.

Fig. 12 presents the variation of the engine speed for the engine integrated with and without the ORC system. The engine speed increases significantly when the cycle fuel injection quantity was increased to 198.8 mm³/c. The accelerating times of the engine in the speed range from 1600 r/min to 2100 r/min for the diesel engine with and without ORC are 103.582 s and 103.574 s respectively, and the engine with ORC has a slight delay of 0.008 s. So the ORC system has minimal effects on the engine acceleration performance.

Fig. 12 Speed of the engine with and without ORC

The power output of the engine integrated with and without the ORC system is presented in Fig. 13. The power output of the engine without ORC is 165.46 kW when the engine operates at 1600 r/min, and the power output of the engine in the combined system is 165.26 kW which decreased a little due to the increased backpressure, while the power output of the combined system is 168.24 kW. Therefore, the ORC system has increased the power output of the combined system. With the increment of the cycle fuel injection quantity, the power output increases gradually, and the difference of the power output of the engine with and without the ORC system is more obvious. When the engine speed is 2100 r/min, the power output of the combined system is 220.24 kW which has increased by 4.13 kW than that of the engine without

1 ORC. Therefore, the engine acceleration performance can be improved for the engine integrated
 2 with the ORC system if the ORC power output is used to drive the engine.

Fig. 13 Power output of the engine with and without ORC

4.2 Transient performance during the start-stop process of the expander

The transient performance of the engine with ORC in the start-stop process of the expander is evaluated to discuss the effects of the ORC system operating conditions on the engine performance. The engine was operated at the speed of 2000 r/min with the cycle fuel injection quantity of 185.4 mm³/c. The initial speed of the expander was 1400 r/min, and the expander speed at different time is presented in Table 3.

Table 3 Rotating speed of the expander

Time(s)	Speed(r/min)	Stage	Process
0-50	1400	A	Running
50-55	1400-0	B	Closing
55-60	0	C	Closed
60-65	0-1400	D	Starting
65-80	1400	E	Running

The variations of the backpressure and temperature of exhaust gas are described in Fig. 14. In the start-stop process of the expander, the backpressure and temperature of exhaust gas have obvious changes. The mass flow rate of working fluid decreases when the expander was suddenly closed and restarted in stage B, C and D, and the average temperature of exhaust gas

1 increases and the density decreases. Hence the volume flow rate and backpressure of exhaust
 2 gas increases. Therefore, the mass flow rate of engine air input decreases and the temperature
 3 of exhaust gas increases.

4
 5 Fig. 14 Transient backpressure and exhaust gas temperature of the engine with and without ORC

6 Fig. 15 presents the transient output power of the diesel engine with and without ORC system
 7 in the process of start-stop of the expander. The engine integrated with the ORC system has
 8 higher power output when the expander is working. The power output of the engine with ORC
 9 decreases gradually in the closing process (Stage B) when the expander speed was decreased
 10 from 1400 r/min to 0 r/min. The transient output power of the engine with ORC system has a
 11 fluctuating change in stage D, and gradually decreases to a steady value when the expander
 12 speed was increased to 1400 r/min in stage E. In the closed process (Stage C) of the expander,
 13 the power output of the ORC system is zero, and the power output of the engine in the combined
 14 system has a slight decrease due to the increased backpressure. The maximum reduction of the
 15 engine power output is 0.063 kW. Therefore, exhaust gas should be released through the by-
 16 pass exhaust pipe by adjusting the control strategy when the expander is closed and the ORC
 17 system is not working.

Fig. 15 Transient power output of the engine with and without the ORC system

6. Conclusions

In this paper, the steady and transient performance of a diesel engine with and without an ORC system were evaluated. Based on the present simulation and analysis, the main conclusions are listed as following:

The maximum increment of net output power of the diesel engine integrated with the ORC system is 4.13 kW. Coupled with the ORC system has increased the engine thermal efficiency by 0.66 % and decreased the engine BSFC by 3.61 g/(kW·h).

The increased engine backpressure caused by the ORC system delays the acceleration time of the engine for 0.008 s in the speed range of 1600 r/min to 2100 r/min when the ORC system power output is not used to drive the engine. The acceleration performance of the engine with ORC can be improved if the increased power output is used to drive the engine.

The backpressure and exhaust gas temperature of the engine with ORC have obvious changes in the start-stop process of the expander. The power output of the engine with ORC decreases when the expander is closed, and the exhaust gas should pass through the by-pass exhaust pipe when the ORC system isn't working.

1 Nomenclature

	$\dot{E}$	Exergy (kW)
	h	Enthalpy (kJ/kg)
	$\dot{m}$	Mass flow rate (kg/s)
	P	Pressure (kPa)
	$\dot{Q}$	Heat energy (kW)
	s	Entropy (kJ/kg·K)
	T	Temperature (K)
	$\dot{W}$	Power (kW)
<i>Greek letters</i>		
	η	Efficiency (%)
<i>Subscript</i>		
	amb	Ambient
	back	Backpressure
	bw	Backpressure of the engine with ORC
	bwo	Backpressure of the engine without ORC
	e	Engine without ORC
	en	Energy
	eva	Evaporator
	ew	The combined system of the engine and the ORC system
	exp	Expander
	fu	Fuel
	n	Net power output increment
	pu	Pump
	we	The engine in the combined system
<i>Acronyms</i>		
	BSFC	Brake Specific Fuel Consumption
	ORC	Organic Rankine Cycle
	WHR	Waste Heat Recovery

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9

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1 **Figure captions**

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