EXPERIMENTAL STUDY ON ORGANIC RANKINE CYCLE SYSTEM WITH SINGLE-SCREW EXPANDER FOR WASTE HEAT RECOVERY FROM DIESEL ENGINE EXHAUST

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ABSTRACT

A single-screw expander prototype with 155 mm diameter screw was developed. An ORC (organic Rankine cycle) experimental system for waste heat recovery from diesel engine exhaust was built. Experiments were conducted for different expander torque and diesel engine loads. The experimental results indicated:(1) Single-screw expander is suitable for small/medium scale ORC system, and it can obtain good performance at low-medium rotational speed. The maximums of power output 10.38 kW andshaft efficiency 57.88% are achieved at 1538 rpm.(2) The maximums of volumetric efficiency, adiabatic efficiency and expansion ratio of single-screw expander are 90.73%, 73.25% and 4.6, respectively.(3) The performance of ORC system is affected not only by the working case of diesel, but also by the torque of single-screw expander. The biggest ORC efficiency is 6.48%, which is gotten at 250 kW diesel power output and 64.43 Nm of single-screw expander.(4) With ORC system, the specific fuel consumption of diesel is effectively decreased. When the power output of diesel is 250 kW, the specific fuel consumption is decreased by 3.5%, and the overall system efficiency is 43.8%, which is increased by 1.53%.(5) With the reducing of mass flow rate pumped into evaporator, the dryness of vapor is accelerated, and heat exchange quantity almost linearly decreases. Volumetric flow rate of vapor into single-screw expander increases with increase of inlet vapor dryness but volumetric efficiency decreases with that. The rising of expansion rate is due to increase of inlet pressure and decease of outlet pressure with the increase of inlet vapor dryness and the biggest expansion ratio is 4.7. With the increase of inlet vapor dryness, torques and power outputs of single-screw expander are rising.

1. INTRODUCTION

Over the past century,the diesel engine has been a primary power source for automobiles, long-haul trucks, locomotives, and ships. The efficiency of a modern diesel engine is about 30%~40% in an ideal case,Theother energy dissipated is lost bytransmission to the environment through exhaust gas,cooling water, lubrication oil and radiation.In driving conditions, energylost is even close to 80%. Improving the utilization of low temperature energy can significantlyincrease the integrated energy efficiency and remarkablyreduce the fuel consumption, so it is apromising path forenergy saving and consumption reducing for diesel engine.Of interest, manyresearchers recognize that waste heat recovery (WHR) fromengine exhaust has the potential to decrease fuel consumptionwithout increasing emissions, and recent technological advancementshave made these systems viable and cost effective (Chammas et al., 2005).

The ORC is a Rankine cycle in which an organic substance is used instead of water-vapor. ORC system is an environmentally friendly system with no emissions of exhaust gases such as CO, CO_2, NO_X, SO_X and other atmospheric pollutants. The most important feature for an ORC is its capability of utilizing various kinds of low-grade heat sources for power generation. Most studies choose ORC for WHR due to its simplicity and ability to operate with low to moderate temperature differences. Another primary advantage of ORC is the use of widely available and affordable components.

In an ORC system, there are two main types of expanders: the velocity-type expanders, such as axial turbine expander, and the volume-type expanders, such as screw expander, scroll expander and reciprocal piston expander (Qiu et al., 2011).Turbine expander has many advantages, but it is generally applied in power cycles with power output greater than 50kW, because its efficiency would be unacceptable in small scale power cycles (Peterson et al., 2008). Turbine expander is suitable for superheated vapor. With saturated steam, the problems of using turbine expander are water erosion to blades and low shaft efficiency of the unit. In addition, turbine has faster rotational speed, and an excess gear box is indispensable if it is utilized in a small scale ORC. Compared with the velocity-type expanders, volume-type expanders are suitable for the ORC-based waste heat recovery because they are characterized by lower flow rates, higher expansion ratios and much lower rotational speeds.

Recently, scroll expander has been gaining some interests as the expanders in small scale ORC(Peterson et al., 2008, Lemort et al.,2009). This device does not require inlet or exhaust valves which reduces noise and improves the durability of the unit. Another advantage is that the rolling contacts provide a seal such that large volumes of oil used as a sealant are not required and the leakage is reduced. Compared with other volume-type expanders, scroll expander may be applied in a very small scale power system, such as 0.1~10kW.

There are two types of screw expanders: twin-screw expander and single-screw expander. Twin-screw expander has been widely used in Rankine cycle system, especially for geothermal and waste heat applications. Twin-screw expander depends on precise numerically-controlled machining to achieve a leak-resistant fit. Compared with twin-screw expander, the single-screw expander has a lot of advantages, such as long service life, balanced loading of the main screw, high volumetric efficiency, low noise, low leakage, low vibration and simple configuration, and so on. Single-screw expander can realize 1-200 kW range of power output, and it is more suitable for low temperature and small scale of ORC system for waste heat recovery. Recent studies have reported the performance of in-house built single screwexpander for low power capacity. Wang et al. (2011) presented a 5 kWe machine with an isentropic efficiency of up to59%. He et al. (2013) built and tested a 22 kWe single screw expander reaching a maximum isentropic efficiency of55% at 2800 rpm. Wang et al. (2013) analyzed the influence of the gaterotor/shell and the screw/shell gap by buildingand testing three different single screw expanders.Desideri et al (2013) described experimental results of a small scale ORC system which utilizes a single-screw expander modified from a single-screw compressor. In total, 120 steady-state experimental data points have been measured and the adiabatic efficiency of expander is from 27.3% to 56.35%.

According to the power output of different type of expanders, turbine is suitable for waste heat recovery from exhaust of diesel engine which power output is more than 1MW, and scroll expander is suitable for that with diesel engine power output less than 100kW. For the power output of ORC for waste heat recovery from exhaust of 100kW~1MW diesel engine is generally from 1kW to 10’s of kW, single-screw expander is the most appropriate candidate.

In this paper, an ORC experimental system with single-screw expander was developed for waste heat recovery from exhaust of a 336hp diesel engine. Experiments were carried out to investigate the influence of engine condition and expander torque on the performance of ORC system and overall engine system with ORC.

2. DEVELOPMENT OF ORC SYSTEM

2.1 The single-screw expander

A single-screw expander has been developed by our team, as shown by fig.1. The reference of this prototype’s design is a single-screw compressor. Then the arrangement of screw and gaterotors, the installment of bearings, and the apparent structure are similar to a single-screw compressor. In order to simplify the construction and reduce the friction resistance, packing seal with PTFE is used as the shaft seal. The balance hole which connects high pressure leakage room with low pressure discharge volume of this expander is drilled on the shell which is different to that drilled on the screw or main shaft. The parameters of this single-screw expander used in the test are shown in table 1.

2.2 Evaporator

A spiral-tube type evaporator has been developed for the waste heat recovery system. In the evaporator, a spiral titanium tube is placed in a cylinder and baffles are also inserted in the cylinder to enhance heat transfer in the evaporator.In order to reduce the weight of this evaporator, titanium tube is used instead of stainless steel tube. Heat is transferred from exhaust to spiral titanium tube, and working fluid is heated by spiral titanium tube and is evaporated in the tube. The design temperature is 550℃, and the design capacity is 150kW. The design pressures of organic substance side and the gas side are 2.5MPa and 0.1MPa, respectively. Because the organic substance volume continuously increases for being heated, the cross section area needs to increase correspondingly. The evaporating process is divided into 5 tube sides. The first and second tube sides both have 8 tubes, the third tube side has 16 tubes, the forth tube side has 24 tubes and the fifth tube side has 32 tube. The length of each tube is 6.8m and the wall thickness is 1.2mm. The parameters of the evaporator are shown in Table. 2.

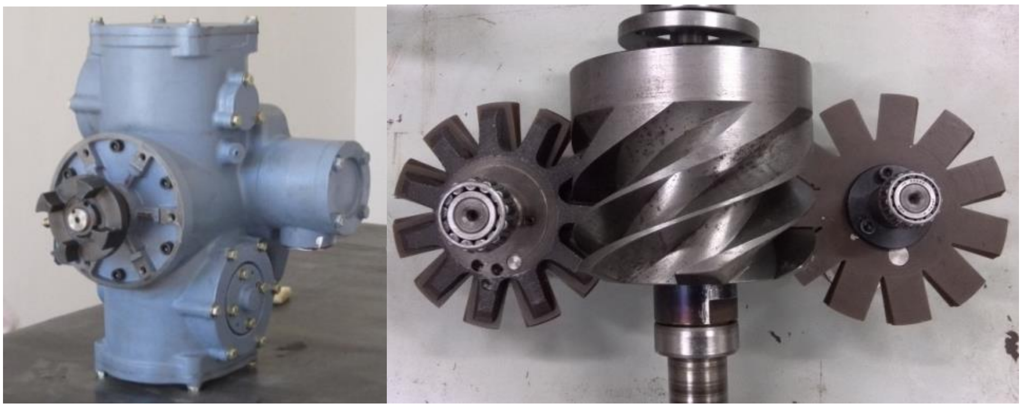


Fig.1: Photograph of the single-screw expander

Table.1: The parameter of single-screw expander

Parameters	Value	Parameters	Value
Diameter of screw(mm)	155	Diameter of gaterotor(mm)	155
Groove number of screw	6	Tooth number of gaterotor	11
Center distance(mm)	124		

Table.2: The parameter of the spiral-tube evaporator

parameters	value	parameters	value
Diameter of spiral tube(mm)	16	Wall thickness of shell (mm)	4
Wall thickness of spiral tube(mm)	1.2	Evaporator weight (kg)	147
Shell diameter (mm)	500	Heat exchange area (m^2)	12
Shell length (mm)	1500	Heat input capacity (kW)	142

2.3 Condenser

An aluminum multi-channel parallel type condenser has been developed for the waste heat recovery system. In order to enhance the heat transfer on air side, high performance louvered fins are used. While, the application of aluminum multi-channel tubes strengthens the ability of heat transfer from working fluid to air. Fig.3 shows the photograph and configuration of the aluminum multi-channel parallel type condenser. The working fluid enters the header and flows through tubes. It is important to reduce the flow resistance because of the significanteffect on the power output of single-screw expander. In the design, parallel structure of dual-condenser is used and the total flow process is divided into two tube sides. The working fluid is averaged to 70 tubes in each first tube side, and then averaged to 48 tubes in each second tube side after working fluid condensation from the first tube sides. The calculation results that the total flow resistance is less than 0.1MPa. A fan is used to enhance the air flow and the bending type construction of the condenser would improve its utilization. The parameters of the evaporator are listed in Table. 3.

Table.3: The parameter of the parallel type condenser

parameters	value	parameters	value
Tube width (mm)	25.47	Heat transfer area in air side (m^2)	1.02
Tube thickness (mm)	2	Size of condenser (mm)	980×980×1255
Fins spacing (mm)	1.4	Condenser weight (kg)	78
Fins height (mm)	6.85	Heat rejection capacity (kW)	150
Louvered angle(℃)	27	Fan size (m)	φ860×64

2.4 Pump

The pump is a multistage centrifugal pump called CR5-32 and is provided by GRUNDFOS. The pump was running at rated speed. In order to adjust the flow rate of working fluid, a throttling bypass valvewas installed between the pump and the storage tank of working fluid. The parameters of the pump are shown in Table. 4.

Table.4: The parameter of the pump

parameters	value	parameters	value
Rotational speed (rpm)	2919	Stages	32
Designed volume flow (m^3/h)	2.98	Net weight (kg)	81.9
Designed head (m)	205		

2.5 Configuration of the ORC system

The prototype of ORC system for WHR is shown in fig.2. The ORC system included a single-screw expander, an evaporator, a condenser, a storage tank of working fluid, a multistage centrifugal pump, etc. R123 was used as the working fluid because of its outstanding ability to improve the ORC performance. R123 was first heated to vapor by exhaust waste heat of engine in the evaporator, and then the vapor expanded and generated power output in the single-screw expander. The vapor from expander was condensed into liquid by ambient air in the condenser. The R123 liquid in condenser was pumped to the evaporator. There wasa storage tank in the ORC system for supplying working fluid.

Fig.2: ORC system prototype

3. EXPERIMENTAL APPARATUS AND DATA DERIVATION

3.1 Experimental system

Fig.3 illustrates the concept of experiment. Heat source is the exhaust of a diesel engine whose power output can reach 336 horsepower. Operations start at the firing of the diesel engine. Pump begins to work when the power output of engine rises to 40 kW, then working fluid is circling in the system. It does not directly flow into the expander because a bypass is opened. When the power output of engine is over 80 kW, valves at inlet and outlet of the expander are opened, while a valve at the bypass is closed and the fan of condenser is switched on to start the working cycle. Working fluid passes through the expander, and the expander rotates. The power output of diesel engine increases gradually to the preset point. After the temperature of exhaust at inlet of the evaporator becomes steady, different torque of expander is adjusted, and experimental data are collected until the end of experiment. Pump in ORC system rotates at rated speed. In order to adjust the flow rate of working fluid into evaporator, a throttling bypass valve is installed. In the test, by adjusting the excitation of an eddy current dynamometer linked with the shaft of single-screw expander, the torque of single-screw expander can be changed.

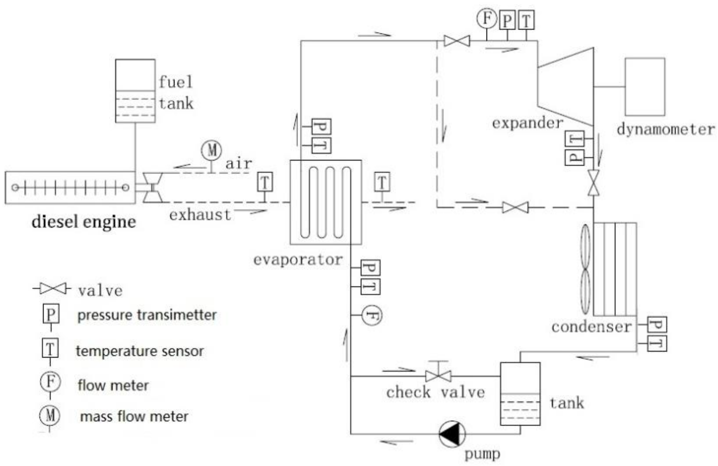


Fig.3: ORC system diagram

The power output and rotational speed of the single-screw expander are recorded by the dynamometer.Temperature probes and pressure transducers were installed on the organic substance side at inlet and outlet of the evaporator, expander, and outlet of condenser to determine the state of the working fluid. Temperature probes were installed on the exhaust side of the inlet and outlet of evaporator to determine the temperature of the exhaust. Temperature probes use PT100 with an accuracy of ±0.5℃ besides the temperature probes on the exhaust side which are N-type thermocouple with an accuracy of ±1.5℃. The pressure sensors of SMP131 with an accuracy of ±0.5%FS and measurement range of 0~2MPa were used to measure the working fluid pressure, and a pressure sensor of SMP121 is used to measure the exhaust pressure with an accuracy of ±0.2%FS and measurement range of 0~0.1MPa. These temperature probes and pressure sensors are provided by Shanghai Leeg Instruments CO., LTD. The mass flow rates of working fluid were measured using a rotameter(model H250) with an accuracy of ±1.0%FS which was installed on the organic substance side at inlet of evaporator and a vortex flow meter (model VFM4070G) with the accuracy of ±0.5%FS installed at inlet of expander. These two instruments are manufactured by KROHNE. The exhaust mass flow is calculated by the fuel consumption meter of FC2210 with the accuracy of ±0.4%FS supplied by Hunan xiangyi dynamic test instrument CO., LTD and the air mass flow measured by thermal gas mass flow meter of 20N150 with the accuracy of ±1%FS provided by Shanghai ToCeil Engine Testing Equipment CO., LTD installed at inlet of engine. In order to measure the rotational speed and power output of expander, an eddy current dynamometer of GW40 supplied by Hunan xiangyi dynamic test instrument CO., LTD. was installed. The maximum measurement of torque and rotational speed are 160N·m with an accuracy of ±0.2%FS and 10000rpm with an accuracy of

±1rpm,respectively. All the output signals of experimental data weretransported to a computer and stored as a function of time there.

3.2Dataderivation

(1)Power output: this indicates the ability of single-screw expander to output power, and is defined as

$$Pe = \frac{N \cdot \omega}{1000} \tag{1}$$

(2)Dryness is defined as the fraction of the total mixture which is vapor, based on mass. That is

$$x = \frac{\dot{m}''}{\dot{m}} = \frac{\dot{m}''}{\dot{m}' + \dot{m}''} \tag{2}$$

(3)Shaft efficiency of single-screw expander: this is the ratio of power output to enthalpy drop of working fluid in an ideal adiabatic process, which is defined as

$$\eta_{\exp} = \frac{Pe_{\exp} \times 3.6}{\dot{m}_{R123} \Delta h_{s,\exp}} \times 100\% \tag{3}$$

(4)The effect of leakage in expansion process can be evaluated by volumetric efficiency, which is defined by

$$\eta_V = \frac{V_i}{V_m} \tag{4}$$

(5)ORC efficiency: this is the ratio of available energy to overall energy obtained from thermal source, and is expressed as

$$\eta_{ORC} = \frac{(Pe_{\exp} - Pe_{pump}) \times 3.6}{\dot{m}_e (h_{e,in} - h_{e,out})} \times 100\% \tag{5}$$

(6)Specific fuel consumption: this indicates the economic performance of engine, which is defined by

$$d = \frac{\dot{m}_{fuel}}{(Pe_{\exp} + Pe_{engine})} \times 10^3 \tag{6}$$

(7)Overall system efficiency

$$\eta_{t,system} = \frac{3.6 \times (Pe_{\exp} + Pe_{engine} - Pe_{pump})}{\dot{m}_{oil} \times H_{oil}} \times 100\% \tag{7}$$

4. EXPERIMENTAL PERFORMANCE ANALYSES

In the test, temperature and mass flow of exhaust werevaried by changingin the power output and the rotational speed of diesel engine. Table 5 lists detailed specification and temperature and mass flow for different conditions of diesel engine (denoted as different cases), and table 6 gives the influences of the ORC system to diesel engine.

Table.5: Parameters of different conditions of diesel engine

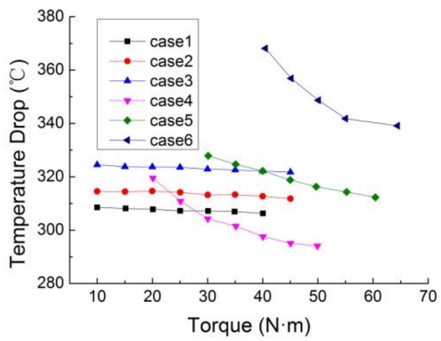
item	Unit	Case1	Case2	Case3	Case4	Case5	Case6
Power output	kW	140	160	180	200	220	250
Rotational speed	rpm	1800	1800	1800	1900	1900	1900
Temperature of exhaust	℃	417	430	448	425	451	485
Mass flow of exhaust	kg/h	958	1024	1092	1205	1272	1315

Table.6: Influences of the ORC system to diesel engine

Case	Power output	Rotational speed	Specificoil consumption without ORC	Specificoil consumption with ORC	Increment of specific oil consumption	Exhaust overpressure without ORC	Exhaust overpressure with ORC	Increment of exhaust overpressure
	kW	rpm	kg/h	kg/h	%	kPa	kPa	%
1	140	1800	28.7	29	1.05	6.4	7.3	14.06
2	160	1800	32.2	32.8	1.86	7.3	8.6	17.81
3	180	1800	36.6	37.1	1.37	8.3	9.8	18.07
4	200	1900	39.4	40	1.52	9	10.7	18.89
5	220	1900	43.3	44	1.62	10.2	12.7	24.51
6	248	1900	49.5	50.1	1.21	11.6	13.3	14.65

Note: in case 6the power output of diesel engine is 250kW with ORC system.

Fig.4 shows the changes of temperature drop of exhaust with torque of single-screw expander. In the first three cases, the temperature drop decrease linearly and the changes are very small; however, the changes of temperature drop in the other cases are much larger.It is obvious that the temperature drop does not increase with the increase of diesel power output. In case 4 and case 5, some points are lower than ones in the first three cases. The influence ofexpander's torque onthe heat quantity absorbed from exhaust is shown in fig.5. The decreases of the quantity of exchanged heat are too little to consider in the first three cases, while it decreases obviously in cases 4 through 6 with the increase of torque of single-screw expander. Because the mass flow of exhaust keeps steady at a case, the quantity of exchanged heat is mainly affected by temperature drop. From this figure, it is shown that the quantity of exchanged heat increases with the increase of the power output of diesel engine also.Although the temperature drop does not increase with the increase of diesel power output, the quantity of exchanged heat keeps increasing due to the increase of the mass flow of exhaust.



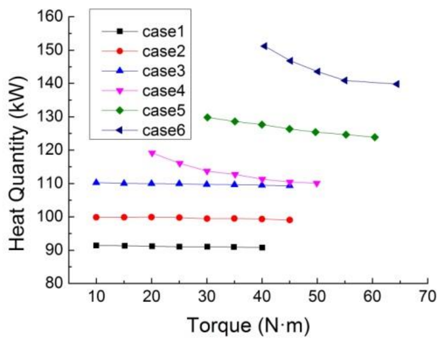
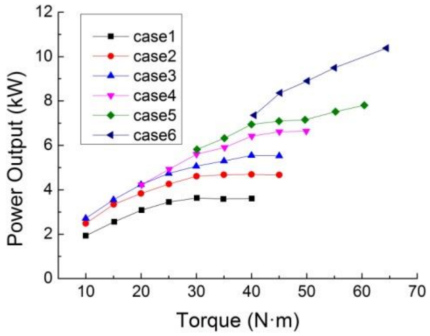


Fig.4: Temperature of exhaust gas vs. torque**Fig.5:**Quantity of exchanged heat vs. torque

Power output of single-screw expander can be calculated and its changes with the torque are shown in fig.6. It is shown that the power output of single-screw expander increased in the form of a parabola with rising expander torque. In the first four cases of experiments, when the torques of the expander are 30N·m, 40N·m, 40N·m and 50N·m, the maximums of power output of the expander are 3.63kW, 4.69kW, 5.55kW and 6.64kW, respectively. In case 5 and case 6 the maximums of power output of the expander are not achieved due to the restriction of the experimental conditions. But the increase of the power output becomes slow with the increase of the torque, and the maximums obtained are 7.81kW and 10.38kW, respectively.

Fig.7 shows the change of the shaft efficiency of the single-screw expander. From the figure, there are maximums of the shaft efficiency in every group of data in the first five cases, they are 41.45%, 46.73%, 47.59%, 49.90 and 49.93%, respectively. The shaft efficiency increases with the torque of expander in case 6, and the maximum is 57.88% at 64.43N·m of torque. The inflection point of the shaft efficiency in case 6 doesn't occur, because the increase of lubricating oil's temperature is too fast and it soon exceeds 105℃, then the engine could not go on working.



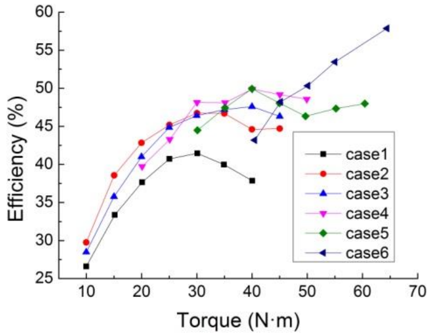
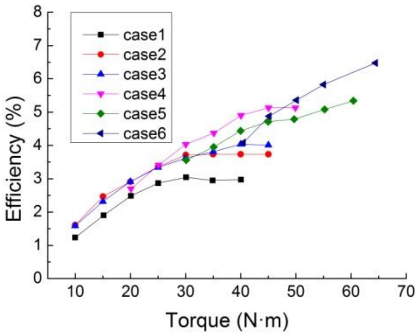


Fig.6:Power output vs. torque**Fig.7**:Total efficiency vs. torque

Fig.8 shows the variation of ORC efficiency. From this figure, the maximums of ORC efficiency are obtained in the first four cases; they are 3.04%, 3.74%, 4.04% and 5.13%, respectively, corresponding to the expander's torque of 35Nm, 40Nm, 40Nm and 50Nm. In case 5 and case 6, the power output of the single-screw expander increases with the torque while the quantity of exchanged heat decreases with the torque, so, the ORC efficiency increases with the torque, and the maximums obtained in the test are 5.34% and 6.48%, respectively.

The overall system efficiency of diesel engine with ORC is an improvement over that of diesel engine without ORC, as shown in fig.9. From the figure, the smallest improvement is 0.81% at 140kW, and the biggest improvement is 1.53% at 250kW. It is obvious that 43.80% is the highest overall system efficiency with ORC system when the power output of diesel engine is 250kW.



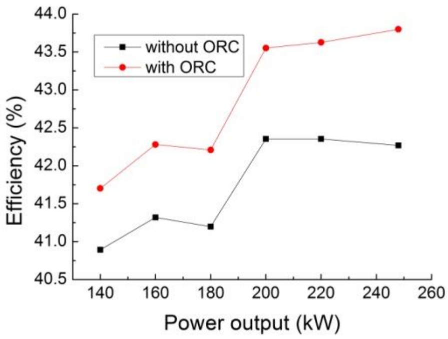
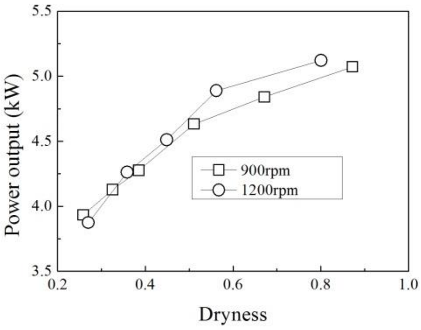


Fig.8: ORC efficiency vs. torqueFig.9: Overall system efficiency vs. power output of

diesel engine

Power output indicates the performance of work output for single-screw expanders. Fig.10 shows that power output increases with dryness. The increase is faster at low dryness than it is at high dryness. But there is little difference between the values of power output for different rotational speed at the same dryness, and the biggest power output is 5.12kW, which is shown in fig.10.

Although the power output increases with the increase of inlet vapor dryness, the shaft efficiency of single-screw expander decreases with the increase of dryness, and the maximum is 7%~8% bigger than the minimum, as shown in fig.11. From this figure, it can also be observed that the shaft efficiency at 1200rpm is bigger than that at 900rpm, and the biggest efficiency is nearly 50%.



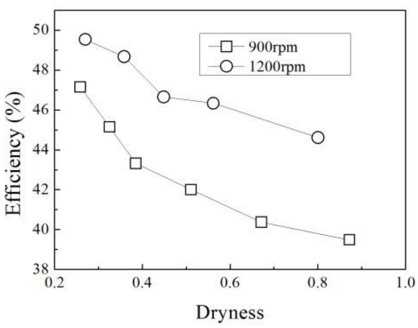


Fig.10: Power output versus inlet vapor dryness**Fig.11**:Shaft efficiency versus inlet vapor dryness

5. CONCLUSION

In this study, the influence of torque of single-screw expander on the performance of ORC used in waste heat recovery is obtained for different conditions of diesel engine. The effects on performance indices of single-screw expander and heat-work conversion efficiency are investigated. Based on the present analysis, the following results are concluded:

(1) Single-screw expander is suitable for small/medium scale ORC system, and it can obtain good performance at low-medium rotational speed. The maximums of power output 10.38kW and shaft efficiency 57.88% are gotten at 1538rpm.

(2)The maximums of volumetric efficiency, adiabatic efficiency and expansion ratio of single-screw expander are 90.73%, 63.46% and 4.6, respectively.

(3) The performance of ORC system is affected not only by the working case of diesel, but also by the torque of single-screw expander. The biggest ORC efficiency is 6.48%, which is gotten at 250kW diesel power output and 64.43N.m of single-screw expander.

(4) With ORC system, the specific fuel consumption of diesel is effectively decreased. When the power output of diesel is 250kW, the specific fuel consumption is decreased by 3.5%, and the overall system efficiency is 43.8%, which is increased by 1.53%.

(5)With the increase of inlet vapor dryness, torque and power output of single-screw expander are rising and the biggest power output is 5.5kW, but the shaftefficiencyof single-screw expanderis decreased by 7%~8%.

In summary, the results of test basically reach the expectation. Meanwhile, it also has great room for improvement. On the one hand, increasing the rotational speed to 2800~3000rpm and decreasing the outlet pressure of the single-screw expander can obtain more power output. On the other hand, optimizing the layout of system and decreasing the weight of main equipment can realize the compact and lightweight design for utilization in a truck. With the continuous improvement of equipment and testing, the system for waste heat recovery from exhaust of fixed and moving internal combustion engine would have great prospects in saving fuel and improving overall system efficiency.

Nomenclature

Variables		Subscripts	
d :	specific oil consumption [kg/(kW·h)]	e :	exhaust gases
h :	specific enthalpy [kJ/kg]	$engine$:	diesel engine
H :	heating value [kJ/kg]	$\exp$:	expander
$\dot{m}$:	mass flow rate [kg/h]	i	ideal
N :	torque [N·m]	in :	inlet
P :	pressure [bar]	is :	isentropic

Pe:	power [kW]	m	measurement
t:	time [s]	oil:	diesel oil
V:	volume flow rate [m^3/h]	ORC:	ORC system
x	vapor dryness	out:	outlet
ε:	expansion ratio [-]	$pump$:	pump in ORC system
η:	efficiency [-]	$R123$:	R123
Δ:	difference [-]	sys:	system
ω:	angular velocity [rad/s]	$total$:	total

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