Energy xxx (2014) 1–10

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Development and experimental study on organic Rankine cycle system with single-screw expander for waste heat recovery from exhaust of diesel engine

Ye-Qiang Zhang [a], Yu-Ting Wu [a,*], Guo-Dong Xia [a], Chong-Fang Ma [a], Wei-Ning Ji [a], Shan-Wei Liu [a], Kai Yang [a], Fu-Bin Yang [b]

[a] Key Laboratory of Enhanced Heat Transfer and Energy Conservation, Ministry of Education, Beijing University of Technology, No. 100 Pingleyuan, Chaoyang District, Beijing, China
[b] School of Mechanical and Power Engineering, North University of China, Xueyuan Road, No.3, 030051 Taiyuan, China

ARTICLE INFO

Article history:
Received 28 March 2014
Received in revised form
3 August 2014
Accepted 12 September 2014
Available online xxx

Keywords:
Exhaust
Waste heat recovery
ORC (Organic Rankine Cycle)
Single-screw expander

ABSTRACT

A single-screw expander with 155 mm diameter screw has been developed. A spiral-tube type evaporator and an aluminum multi-channel parallel type condenser have also been developed with weight of 147 kg and 78 kg, respectively. Based on the development of above components, an ORC (organic Rankine cycle) system prototype was assembled and tested for waste heat recovery from diesel engine exhaust. An experimental system was built for this ORC system, and experiments were conducted for different expander torque and diesel engine loads. Influences of expander torque and diesel engine loads on the performances of ORC system were studied. The results indicated that the maximum of the power output is 10.38 kW and the biggest ORC efficiency and overall system efficiency are respectively 6.48% and 43.8%, which are achieved at 250 kW of diesel engine output. Meanwhile the biggest improvement of overall system efficiency is 1.53%. The maximums of volume efficiency, adiabatic efficiency and total efficiency of single-screw expander are 90.73%, 73.25% and 57.88%, respectively.

1. Introduction

Over the past century, the diesel engine has been a primary power source for automobiles, long-haul trucks, locomotives, and ships, and is the main oil consumption machinery. Under ideal case, around 30% ~ 40% of fuel energy is available as shaft work, while other is lost as waste heat through coolant and exhaust [1]. In driving conditions, energy lost is close to 80% [2]. Improving the utilization of low-grade energy can significantly increase the overall energy efficiency and remarkably reduce the oil consumption, so it is a promising path of energy saving and oil consumption reduction for diesel engines [3]. Of interest, many researchers have recognized that WHR (waste heat recovery) from engine exhaust has the potential for decreasing fuel consumption without increasing emissions, and recent technological advancements have made these systems viable and cost effective [4].

The ORC (Organic Rankine Cycle) 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 generations. 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 [5].

Besides ORC, there are alternative thermodynamic cycles for WHR, such as Brayton cycle, Kalina cycle, Stirling cycle and carbon dioxide trans-critical cycle. Relevant studies have revealed that Brayton cycle requires a longer payback time [6] and it is less attractive for low to medium temperatures WHR [7]. Stirling cycle is not economically attractive and fails to match performances of ORC [8]. Kalina cycle can efficiently recover waste heat in engine exhaust temperature range, and research has focused primarily on large-scale facilities [9–13]. Carbon dioxide trans-critical cycle would not be feasible for WHR because of practical restrictions on maximum cycle pressure [14].

On the research about ORC for internal combustion engine waste heat recovery, in order to achieve the highest efficiency, researchers pay much attention to comparison and selection of

* Corresponding author. Tel.: +86 10 67396662x8323; fax: +86 10 67392774.
E-mail addresses: wuyuting@bjut.edu.cn, wuyuting1970@126.com (Y.-T. Wu).

http://dx.doi.org/10.1016/j.energy.2014.09.034
0360-5442/

working fluid [4,15–22]. The studies on different heat sources-exhaust gas, coolant, charge air cooler, exhaust gas recirculation, and their combination [23–25] -are another primary research topic, as well the analysis of performance of ORC under different driving conditions [26,27].

Besides the previous works, there are a few of papers about the study on the performance of ORC with diesel engines [28–30]. Oomori and Ogina developed an organic Rankine cycle system using waste heat from the engine coolant in a passenger car in 1993 [31]. In this system, R123 was used as working fluid and a scroll machine was used as the expander. The test demonstrated that a 3% gain for an ambient temperature of 25 °C was gotten. There are a lot of experimental studies on organic Rankine cycle for low-medium temperatures and small scale waste heat recovery, which are the references for analysis of waste heat recovery with diesel engines. In these studies, turbines [32–35], as well as scroll expanders [36–38] and screw expander were used as the expander.

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 [39].

Turbine expander has many advantages [40], but it is generally applied in power cycles with power output greater than 50 kW, because its efficiency would be unacceptable in small scale power cycles [41]. Turbine expander is suitable for superheated vapor. With saturated steam, the problems of using turbine expander are water erosion to blades and low overall efficiency of the unit [42]. 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 [43].

Recently, scroll expander has been gaining some interests as the expanders in small scale ORC. 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 [44]. Compared with other volume-type expanders, scroll expander has the most complicated geometry and it may be applied in a very small scale power system, such as 0.1 ~ 2 kW [42,45].

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-resistance 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 [46]. 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. A. Desideri et al. described experimental results of a small scale ORC system which utilizes a single-screw expander modified from a single-screw compressor [47]. 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 1 MW, and scroll expander is suitable for that with diesel engine power output less than 100 kW. For the power output of ORC for waste heat recovery from exhaust of 100 kW ~ 1 MW diesel engine is generally from 1 kW to 10 s 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 336 hp 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. This single-screw expander is CP type, and the reference of its 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 was used as the shaft seal. The balance hole which connects high pressure leakage room with low pressure discharge volume of this expander was drilled on the shell which is different to that drilled on the screw or main shaft. The curve on the shell for enlarging air intake to compressor was canceled. 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. Fig. 2 shows the photograph and configuration of the spiral-tube type evaporator. In the evaporator, a spiral titanium tube was placed in a cylinder and baffles were also inserted in the cylinder to enhance heat transfer in the evaporator. In order to reduce the weight of this evaporator, titanium tube was used instead of stainless steel tube. Heat is transferred from

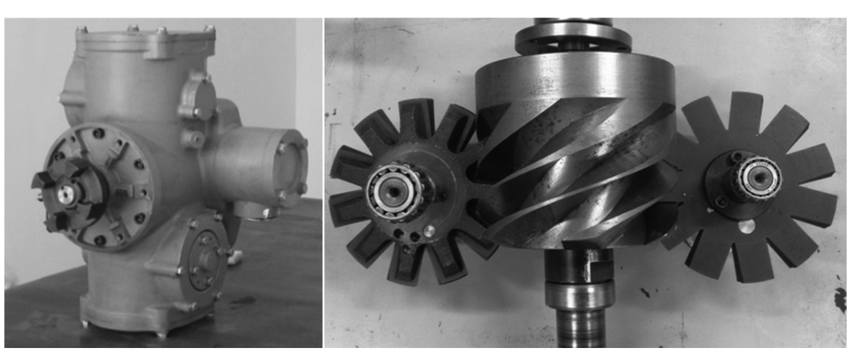

Fig. 1. Photograph of the single-screw expander.

Please cite this article in press as: Zhang Y-Q, et al., Development and experimental study on organic Rankine cycle system with single-screw expander for waste heat recovery from exhaust of diesel engine, Energy (2014), http://dx.doi.org/10.1016/j.energy.2014.09.034