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Experimental study of a small scale organic Rankine cycle waste heat recovery system for a heavy duty diesel engine with focus on the radial inflow turbine expander performance

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HIGHLIGHTS

- An advanced ORC system, tested on a 200 kW – class off-highway diesel engine.
- A radial ORC turbine expander with novel back-swept blading tested experimentally.
- A state-of-the-art molecularly-complex working fluid was tested.
- Integrated generator electrical system power and efficiency measured.
- Maximum 4.3% ORC system efficiency at 40% load on NRTC cycle at 1700 rpm (80 kW).

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ABSTRACT

The purpose of this work is to experimentally evaluate the effect on fuel efficiency of a small scale organic Rankine cycle (ORC) as a waste heat recovery system (WHRS) in a heavy duty diesel engine that operates at steady state conditions. The WHRS consists of two operating loops, namely a thermal oil loop that extracts heat from the engine exhaust gases, and the working fluid loop which is the ORC system. The expansion machine of the ORC system is a radial inflow turbine with a novel back-swept blading that was designed from scratch and manufactured specifically for this WHR application. The engine test conditions include a partial engine load and speed operating point where various operating conditions of the ORC unit were tested and the maximum thermal efficiency of the ORC was defined close to 4.3%. Simultaneously, the maximum generated power was 6.3 kW at 20,000 rpm and pressure ratio of 5.9. The isentropic efficiency reached its peak of 35.2% at 20,000 rpm and 27% at 15,000 rpm. The experimental results were compared with the CFD results using the same off-design conditions, and the results were in good agreement with a maximum deviation of 1.15% in the total efficiency. Last but not least, the engine-WHRS energy balance is also discussed and presented.

1. Introduction

State of the art internal combustion engines (ICE) waste a substantial amount of fuel energy in the form of exhaust gases and engine coolant heat loss. Modern commercial road and off-road heavy-duty diesel engines present a maximum brake thermal efficiency value of approximately 45% at their optimum operating point [1], while gasoline engine maximum thermal efficiency is typically between 30% and 40% [2]. Engine wasted heat is not only a waste of fuel but also a matter of significant global warming and environmental pollution concerns. CO_2 emissions from the transportation sector have increased by 45% between 1990 and 2007, making this sector responsible for nearly one third of the world's CO_2 emissions. Therefore, manufacturers of ICEs are increasingly forced to look at the feasibility of adopting

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Nomenclature

Variables

h	enthalpy [kJ/kg]
$\dot{m}$	mass flow rate [kg/s]
P	pressure [bar]
P_e	electrical power [kW]
W	power output [kW]

Subscripts

0	total thermodynamic properties
1–2	stations within the cycle
s	isentropic
to	thermal oil
w_f	working fluid

Greek letters

η	efficiency [%]
τ	torque [N.m]

Acronyms

ASIC	Application Specific Integrated Circuit
BSFC	brake specific fuel consumption
ICE	internal combustion engine
ORC	organic Rankine cycle
rms	root mean square
TC	turbo-compounding
WHR	waste heat recovery

technologies such as waste heat recovery systems in order to reduce fuel consumption and CO_2 emissions.

Waste heat recovery technologies depend upon tapping into main heat sources in ICEs such as exhaust gas, EGR and/or engine coolant to be recovered. One such technology in use is Turbo-Compounding (TC) either in its mechanical or electrical forms. Depending on the engine load, TC can reduce the average BSFC by 3–6% with the ability of further reduction of 6.5% with highly efficient TC configurations [3]. In addition, combination of TC and steam injection could result in reduction of BSFC by 6.0–11.2% over different speeds [4]. However, it is worth mentioning that the utilization of TC in ICEs is limited due to the high exhaust backpressure caused by such technology and eventually higher pumping losses [5]. Another significant waste heat recovery technology proposition is thermoelectric generation. Experimental studies have shown that fuel savings of 3.9 up to 4.7% could be achieved by using thermo-electric generation [6–8]. However, this technology is currently too expensive and faced with a longer development time [9]. In addition, it still presents very poor efficiency (typically less than 4%). Therefore, it is of essence to investigate a more efficient and cheaper technology.

Organic Rankine Cycles (ORCs) have become popular in re-using wasted heat since they operate efficiently and use relatively simple standard components. Moreover, ORCs can take indirect advantage of the heat rather than the direct exhaust gas supply thus allow a much higher degree of freedom in optimising the expander. Using ORCs in mobile applications is not a new idea. A first concept on a train had already been commercialized in the 1920s, taking advantage of the price difference between diesel and coal [10]. Unfortunately, this system quickly became uncompetitive because that difference stopped being profitable [11]. Later, several systems were developed, mostly for trucks or marine applications, and then this interest disappeared until the 2000s, when automotive manufacturers started being interested in that technology again [11] largely due to regulatory pressure. Patel and Doyle [12] built a prototype of an ORC that was used as a bottoming cycle in a Mack 676 diesel engine. The authors stated that at the peak power condition, 36 additional horsepower was produced resulting in a gain of 13% in power without additional fuel. Recently, wide theoretical investigations have been conducted on ORC applications in ICEs [13–21]. The results indicate that the BSFC improvements of up to 10% can be obtained. However, these theoretical studies usually neglect electro-mechanical losses along the turbo-generator power transmission route and heat transfer to the environment. Realistic expectations are limited to approximately 50% of the above BSFC figures [22].

Selection of the appropriate expansion machines is of great importance when utilizing ORC systems since these machines are responsible for power conversion and subsequent production usually by direct coupling to a generator [22–25]. In addition, the type of expansion machine has significant effects on the overall cycle performance, size and cost [26,27]. Expanders can be classified into two main groups, namely, positive displacement expanders (Screw, Scroll, Piston and Rotary Vane) and turbo-machines (Axial or Radial). The selection of the appropriate expander depends on the application. Moreover, other important factors should be considered when selecting expanders such as high isentropic efficiency, pressure ratio, power output, lubrication requirements, complexity, rotational speed, dynamic balance, reliability, cost, working temperatures and pressures, leakage, noise and safety [28,29]. Turbo-expanders are preferred when to convert the extracted power to electricity while reciprocating expanders, due to their flexibility of operation, are preferred when the extracted power is coupled directly to the crankshaft [30]. Moreover, displacement expanders could be used at low output powers due to the limitation of their rotational speed [31], whereas turbo-expanders operate at higher rotational speed and hence higher power. However, for waste heat recovery applications, scroll expanders and radial turbines are the most common solutions to be found in literature [32,33]. Since ORC efficiency increases at high pressure ratios, radial turbines appear more suitable for vehicular applications where mass flow rates are in the low-to-medium range and pressure ratios are in the medium-to-high range.

Nowadays, ORC systems as WHR technologies are gaining attention in both academic and industrial sectors. Several recent studies have investigated ORC technology and show promise in solar systems [34–38], biomass [39–44] and geothermal applications [45–48]. In recent years, studies concentrating on ICE applications have increased. Zhang et al. [49] evaluated the wasted heat in the engine exhaust, intake air, and coolant of a vehicular light-duty diesel engine. It is worth mentioning that the performance map of the light-duty diesel engine was created using an engine test bench while the study of the coupled system (engine + ORC) was conducted using a simulation study. The results of the simulation study showed that the ORC output power improved from 14% to 16% in the peak effective thermal efficiency region and from 38% to 43% in the small load region. Furukawa et al. [50] conducted an experimental test on the ORC that was used to recover the heat of the engine coolant with Hydro-fluoro-ether as the working fluid. The fuel consumption decreased by 7.5%. Recently, Wang et al. [51] conducted a recent study on recovering the wasted heat of the exhaust gas and coolant of a CNG machine using a supercritical-subcritical dual-loop organic Rankine cycle. R1233zd and R1234yf were used as the working fluids. The engine point with 600 N.m and 1600 rpm was selected as the case study since CNG engine usually operates at low to middle speed and torque for bus applications. Similar to Zhang et al. [51], the engine map was obtained experimentally while the results of the integrated system (engine + ORC) were obtained using the simulation study. The simulations showed that fuel efficiency could be improved by more than 8% in most of the engine's