

Experimental Analysis of an Organic Rankine Cycle Plant Bottoming a Heavy-Duty Engine Using Axial Turbine as Prime Mover

Davide Di Battista and Roberto Cipollone
Universita degli Studi dell'Aquila

ABSTRACT

The use of reciprocating internal combustion engines (ICE) dominates the sector of the on-road transportation, both for passengers and freight. CO₂ reduction is the present technological driver, considering the major worldwide greenhouse reduction targets committed by most governments in the western world. In the near future (2020) these targets will require a significant reduction with respect to today's goals, reinforcing the importance of reducing fuel consumption. In ICEs more than one third of the fuel energy used is rejected into the environment as thermal waste through exhaust gases. Therefore, a greater fuel economy could be achieved if this energy is recovered and converted into useful mechanical or electrical power on board. For long haul vehicles, which run for hundreds of thousands of miles per year at relatively steady conditions, this recovery appears especially worthy of attention.

In this paper, an Organic Rankine Cycle power unit was tested on a heavy duty diesel engine with an axial single stage turbine as the prime mover. Key differences appear between theoretical predictions and measured performances, and this invites toward an experimental real verification of the assumptions made by predictions. The most critical aspects are certainly represented by the behavior of the expander machine in mechanical power range of 2-7 kW. In the unit tested, the single stage impulse axial turbine was operated driving an electric variable speed generator and an AC/DC converter. The experimental activity gave also the possibility to go deep inside the need of reducing the thermal power to be exchanged at low temperature (by means of a radiator) and inside the management of transients conditions of the recovery unit.

An overall net efficiency of the power unit was around 2-3 %, with mechanical power production equal to 2.5 kW, when the thermal power transferred from the ICE exhaust gases is 55 kW.

CITATION: Di Battista, D. and Cipollone, R., "Experimental Analysis of an Organic Rankine Cycle Plant Bottoming a Heavy-Duty Engine Using Axial Turbine as Prime Mover," *SAE Int. J. Engines* 10(4):2017, doi:10.4271/2017-01-9279.

1. INTRODUCTION

Internal combustion engines (ICE) are the major choice powertrain for road transport applications. This is expected to remain as such for at least a couple of decades, even though alternative powertrains are becoming more common and market expectations are increasing. Concerning the energy balance, up to 60-65 % of the input energy of ICEs is lost to the environment, the major part of this energy being lost in exhaust gases (typical value of the loss is around 30-35 % of the fuel energy). These gases have a pressure and temperature greater than ambient values, thus they can be used for energy recovery which is an obvious method of improving the overall efficiency of the engine and of the vehicle. The possibility to have this recovery into mechanical or electrical form makes the recovery more or less complex and requires technological choices which can limit the recovery effectiveness itself.

Engine turbocharging is a noble way to recover energy (universally used in diesel engines), but the compression of the inlet air requires an energy which is less than the available heat (energy) that enters in the turbine. Hence, part of the gas is bypassed (wasting energy in

terms of gas flow rate), or the turbine is throttled by an inlet-guided vane stage which increases gas speed and improves the performances of the turbocharger. In any case, throttling is a loss and, even though the dynamic performance of the turbine improves, part of available energy of the exhaust gas is not recovered. In order to avoid this energy loss, throttling can be substituted with a flow control. An additional turbine can be operated in parallel to the main one feeding it by part of the exhaust gas by passing from the one which drives the compressor [1]. If this additional turbine operates on the same turbo-compressor shaft, the presence of an alternator (which recovers energy into mechanical form) could behave as an electric motor, improving the dynamic performances of the turbo-compressor (e-turbocharger) [2]. Alternately, the additional turbine can be operated with its shaft, driving a generator or producing mechanical energy (as in the Volvo D13 engine) [3][4]. In both cases, the high revolution speed of the dynamic machines prevents a massive introduction of this technology on the market: if direct mechanical energy is used for propulsion, a gear is required in order to match turbine and engine speed, while if the recovery is electrical, alternators are not conventional and their performances are lower. A potentially

more successful alternative is represented by energy recovery via an Organic Rankine Cycle (ORC)-based power unit. Namely: heat is transferred into a fluid which vaporizes and is also slightly superheated. At this stage, it can expand converting thermodynamic energy into mechanical energy. Then, the fluid is condensed and re-pressurized, thus realizing a thermodynamic cycle. The reference cycle is the Rankine one, even though a slight superheating is always considered (Hirn cycle).

This recovery concept is not at all new also when a low or medium grade thermal energy sources is considered [5, 6, 7]. However, in the last decade, many studies have been presented focusing the attention on the road transportation sector, considering all the thermal losses from the engine as potential medium or high temperature sources [8].

In this specific application, there are many aspects that prevent or make the development of a unit at industrial level difficult, in particular: (a) the expander technology linked in part to the fluid choice and its operating conditions, (b) the size and weight of the unit reduce the limits of applicability due to on-board limitations and propulsion power increase, (c) the discharge of the thermal energy at lower temperature, and (d) the interaction of the unit with the engine (back pressure). The first aspect is a technological problem for which reliability, operational flexibility, sensitivity to inlet conditions, final use of the mechanical energy recovered, and control strategies are still the most important concerns; the last three aspects produce limitations to the heat recovery and more generally, on the real net benefits of the heat recovery.

Limiting the attention of the expander technology, it has been extensively treated for many decades [9, 10]. A number of different design concepts have been considered depending on the cycle conditions, on the fluid selected, and on the size of the power unit. Considering the energy recovery in ICE on the road sector [11], both dynamic and volumetric machines have been examined: the first are characterized by a continuous flow rate throughout the machine, while the second ones elaborate finite volumes, resulting in a pulsating flow rate. Positive displacement machines seem to be the most used for these applications: scroll [12] and screw [13] expanders have been reported as among the most suitable solutions for micro and small scale applications. Rotary vane expanders also have good potential, in particular for manageability, simplicity of maintenance, compactness and cost [14]. They showed an isentropic efficiency of about 50-60% with recovered power up to 2 kW [15]. Gerotor machines have been tested for low grade energy recovery and showed a peak isentropic efficiency of 85% [16], but it decreases in smaller applications. More recently, among the volumetric machines, swash-plate expanders were introduced with isentropic efficiency of about 35-40% and volumetric efficiency in the range of 10-35% [17]. Piston expanders can run at low speed (1000÷3000 RPM) [18, 19] matching the requirements of conventional low cost electric generators, while dynamic machines run at high revolution speeds (50÷200 kRPM) [20, 21, 22], thus allowing a reduced size and weight. Both types of expanders have been widely used inside the ORC-based power unit, regardless of the mechanical power produced (< 10kW). Moreover, it is known that dynamic machines are more conventional and suitable for greater mechanical powers (> 100 kW).

In reality, the expander choice should consider also other aspects which make the choice less univocal as it could appear. Dynamic machines (axial and radial turbines) are characterized by a very low weight to power ratio, particularly beneficial in the mobile sector. They also have a potential overall efficiency greater than other machines, being the mechanical and volumetric efficiency higher than the corresponding volumetric machines. In the radial (centripetal) version, they also gain operative flexibility concerning the inlet and outlet thermo-fluid dynamic conditions and, more generally, they could benefit from turbocharger technology. Axial machines, moreover, demonstrate a potentially higher global efficiency (also with respect to the radial types), and for them a technological effort should be expected. Moreover, the lower volumetric and mechanical efficiency of the volumetric machines (with respect to dynamic ones) would require: a) a development effort to improve filling volumes during the intake phase and to reduce leakages: across vanes and closing planes in rotary machine [22] and across piston and cylinder in reciprocating ones [23]; b) reduce relative speed among components in relative motion which reduces friction power.

In an effort to synthesize, the expander technology is still an open question, even though volumetric machines, probably rotary ones, seem to have a wider future [25, 26]. Some additional aspects should be considered too, as well as the transient operation of the expander and its capability to take the load: dynamic behavior, size, compactness, weight and cost (also considering return on investment).

The analysis of the specific literature on ORC-based power units fed by ICEs exhaust gases also shows the need of some additional research efforts not yet fully exploited and which deserve further attention:

- a. when heat is recovered by the exhaust gases and transferred to a working fluid, only a small amount of it is recovered in terms of net mechanical energy (5-10%). The remaining part must “remain” inside the fluid and must be exchanged outside, either through an engine cooling fluid or directly into the air. In both cases, this heat is reversed into the atmosphere through a radiator. The expected power to be exchanged at lower temperature is significant: for a 5 kW mechanical power unit, about 50-60 kW at low temperature must be exchanged. The temperature difference between external air and working fluid - or an intermediate additional cooling fluid - being low (20-40 °C), the size of the radiator tends to increase, representing a limiting factor. Therefore, the reduction of this thermal energy represents a key factor when a given mechanical power is requested in terms of recovery. Therefore, the idea of maximizing the mechanical power recovered which implies maximum recovery from the evaporator (maximum working fluid flow rate) and a thermodynamic cycle with maximum work even though desirable could not be suitable because it can interfere with other constraints (weight increase, aerodynamic performances, space on board);
- b. not only is the expander choice still an open question, but so is the final use of the mechanical energy recovered. The conversion into an electrical one provides wider flexibility, but the overall conversion chain till to the final energy (DC 12-24V for automotive battery) has to be considered;

- c. reliability of waste heat recovery systems are still one of the most limiting factors: although great engine efficiency improvement has been demonstrated, components should also present characteristic of easy of management and maintenance, particularly critical in the transportation sector [27].

In this paper, the authors discuss the performances of an ORC-based power unit conceived for heat recovery of a heavy duty turbocharged diesel engine. The engine was run at fixed speed on a test bench varying the load from 40% to 100% of the rated value. A single stage axial turbine was operated in the unit whose most relevant operating variables were measured. The expander was connected to a variable speed alternator and the AC produced was rectified in order to store it in a battery. The overall conversion chain till to the charge of a 24 V DC battery has been studied. The limits of the turbine and of the overall electrical conversion were outlined and justified in a power range of the turbine of about 2-5 kW. Real performances of the turbine were identified, in particular mechanical and electrical efficiencies, not limiting the analysis on the adiabatic-isentropic efficiency. Thanks to the thermodynamic data of the working fluid (R245fa), the real cycle has been reconstructed.

In order to contribute to reduce the heat reversed into the atmosphere (low temperature side), which requires a radiator, the effect of a regeneration stage was evaluated. Part of the heat of the fluid leaving the turbine can be recovered, thus reducing the heat recovered from the exhaust gas, but still maintaining the same mechanical power produced. According to this, in fact, the cycle efficiency increases, and the heat recovered decreases as well as the heat to be reversed into the atmosphere.

2. EXPERIMENTAL CAMPAIGN

Usual components of an ORC-based power plant are a heat exchanger on the hot source (Heat Recovery Vapor Generator, HRVG), an expander machine which converts heat in mechanical energy, a condenser in order to restore the liquid properties and the pump which pressurizes the fluid. The ORC system has been designed in the framework of EU project "No-Waste", and it was tested in the laboratory of the University of L'Aquila [28]. The HRVG unit is a stainless steel finned coil heat exchanger which guarantees high effectiveness and great permeability on the gas side, minimizing the detrimental effect of the engine backpressure [29, 30]. Pump technology is of internal gear type with a rated mass flow rate of 250 g/s at 1800 RPM; it is coupled with a variable speed DC brushless motor with a magnetic clutch in order to keep separate the working fluid (WF) side from the actuation side. The condenser instead is a plate heat exchanger cooled by tap water. In a vehicle application, this can be easily done with a secondary water circuit operating at low temperature (40-50°C) [31, 32]. This concept is not new in medium and heavy duty engines in which the idea to split the cooling circuit (in two parts) could have additional and different effects: efficiency increase of the conditioning unit [33, 34] (and eventually of a refrigerating unit on board which is functional to specific transportation needs of the freights), overcooling of the engine intake air (volumetric efficiency increase), thermal optimization of the engine cooling according to operating points. The expansion process is done inside a single stage impulse axial turbine:

rated mechanical power is about 7 kW at 80000 RPM. The performances of this machine technology and operational limits have been observed and discerned, following the overall conversion chain, from thermodynamic energy to mechanical and definitively to DC electrical battery storage, through electrical conditioning due to the variable frequency current produced by the electric generator.

This choice was also due to:

- propose an expander of a dynamic machine type which could be simply scaled to operate at higher mechanical power for higher thermal sources for similar ICE recoveries. There are a number of off-road applications which could be characterized by higher mechanical power and require high power density to dimension ratio in which dynamic machines are more suitable;
- evaluate the performance of an electrical generator running at variable speed, which generates a variable frequency voltage and an electronic circuit able to charge at a fixed DC level (24 V) battery on board. This system link would also include a mechanical gear;
- evaluate the resilience of operational conditions such as transient management of the power unit, expander start up, time to reach steady operating conditions, and operating engineering parameters like presence of vibrations, noise, and oil needs to support expander behavior.

2.1. Hot Source Characterization

The hot source is represented by an IVECO N67 engine operating at 1500 RPM with a rated power of 118 kW. Table 1 shows the main characteristics of the ICE considered.

Table 1. ICE specifications

Engine model	NEF67 TM2.1
Number cylinders	6
Firing order	1-5-3-6-2-4
Cylinder arrangement	In line
Valves per cylinder	2
Cycle	Diesel 4 Strokes
Injection system	Direct
Induction System	Turbocharged after cooled
Bore	104 mm
Stroke	132 mm
Total displacement	6.7 liters
Peak Power	118 kW@1500 RPM

Figure 1 shows the experimental values of temperature and mass flow rate of the exhaust gases of the ICE considered. Temperature is measured with K-Thermocouple, air mass flow rate with the data coming from the hot flow meter linked to the ECU and fuel rate is also known by ECU data. Exhaust gas variables are taken just after the catalyst, in order to recover only the real thermal losses. The ICE is operated at different load conditions and 1500 RPM: the load value affects the gas temperature, while the exhaust mass flow rate variations is due to turbocharging, which changes with load.

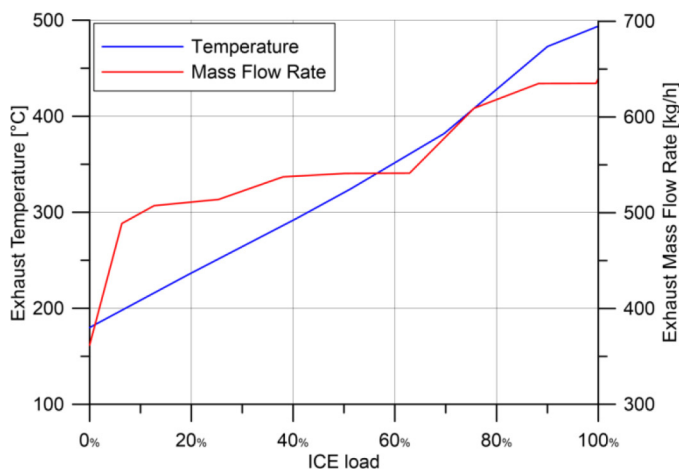


Figure 1. ICE exhaust gas characterization

2.2. Experimental Set-Up

Figure 2 shows the experimental setup realized in order to assess the potential of an ORC-based heat recovery system bottoming a heavy duty engine.

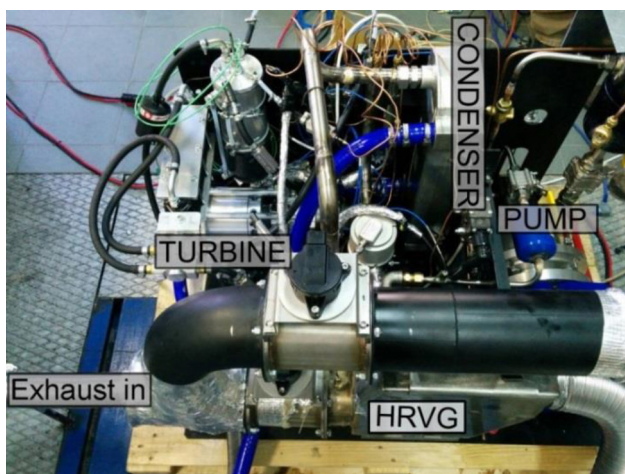


Figure 2. ORC test bench

In Figure 3 the position of the sensors is also shown along the circuits: pressure transducers (uncertainty: ± 0.2 bar) and thermocouples type T (uncertainty: $\pm 1^\circ\text{C}$) are placed in the 1-2-3-4 thermodynamic cycle points. Working fluid mass flow rate is measured by the rotational speed of the volumetric pump, a speed sensor is used to measure revolution speed of the turbine (uncertainty: 0.05%) and a Hall effect LEM sensor (uncertainty $\pm 1\%$) to measure the DC current (at 24 V) provided by the electric device after the generator. Exhaust gas temperatures at inlet and outlet of the evaporator are measured with K-thermocouples (uncertainty: $\pm 2.2^\circ\text{C}$) while exhaust mass flow rate is given by engine ECU data (steady conditions). Heat removed in the condenser is measured thanks to T-thermocouples placed on the tap water circuit at the inlet and the outlet of the condenser and a turbine effect water flow meter (uncertainty: ± 1 l/min). Tap water is

continuously refrigerated by an external cooling tower, so it always enters in the condenser at room temperature. The water flow rate was limited to 15-20 l/min in order to have a condensing temperature in the range of 40-60°C. This condensing temperature can eventually be coupled with an on-board cooling circuit, which operates at 40°C with a flow rate of about 40-50 l/min. Hence, in an on-board application, the condenser coolant circulates at higher temperatures but also with a higher flow rate: this would result in a lower mean temperature difference between the two fluids in the condenser and, therefore, the condensing temperature could not be much higher than the one obtained in the tests here performed.

The electrical load is realized thanks to a parallel of electrical resistances able to adjust the load according to the turbine revolution speed. A turbine bypass valve is positioned in a parallel branch of the circuit in order to avoid two-phase flow at the turbine inlet: during warming up of the ORC-plant; in fact, the evaporator is unable to superheat the working fluid, and a two-phase flow would damage the turbine blades. Therefore, in these conditions, the bypass valve (which has an internal ejector which creates a pressure drop between evaporating and condensing sections) is open and the fluid reaches the condenser without passing through the turbine. Only when the fluid is completely superheated the bypass is closed, and the flow can pass through the turbine. This represents a serious drawback when an axial dynamic machine is used: the exposition of the turbine blades at saturated liquid droplets is able to drastically reduce turbine efficiency and its mechanical integrity.

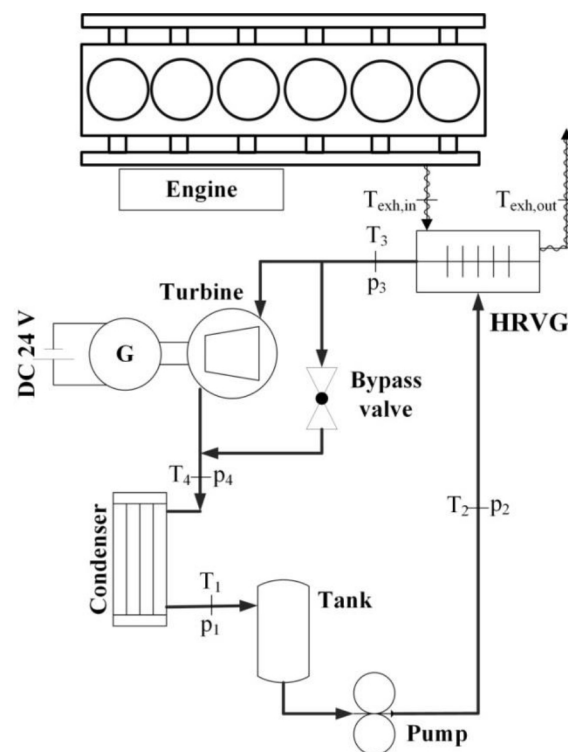


Figure 3. ORC plant test bench