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Overview of the Activities on Heavy Duty Diesel Engines Waste Heat Recovery with Organic Rankine Cycles (ORC) in the Frame of the ECCO-MATE EU FP7 Project

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Abstract

The ECCO-MATE Project is a European Union funded project aimed to develop a synergistic framework for cutting edge research on novel engine technologies for higher energy efficiency and lower emissions.
The project partners, Ricardo plc, an engineering consulting company, and the University of Trieste, focus the research attention on waste heat recovery systems, such as Organic Rankine Cycles (ORC), which are gaining increasing interest by engine manufacturers, vehicles and ships fleet operators, because of their potential for further increasing engine efficiency and decreasing fuel consumption. In particular, in the frame of the developed research activity, the 1-D Ricardo engine simulation software WAVE has been used in order to assess novel engine concepts, both in the commercial vehicles and marine sectors.
A combined engine-ORC system First and Second Law of Thermodynamics analysis has been proposed in order to study where system inefficiencies are concentrated and propose improvements, with particular focus on commercial vehicle heavy duty diesel engines. A thermo-economic analysis has been also considered.
Furthermore, in collaboration with the project partners National Technical University of Athens (NTUA) and Winterthur Gas & Diesel (WinGD), an innovative low pressure Exhaust Gas Recirculation (EGR) configuration for low speed 2-stroke ship propulsion units has also been studied with the aim of reducing NO_x in order to meet IMO Tier III emissions limits. ORC systems are, in this application also, a promising technology that can be used, in synergy with emission reduction systems, to recover, in particular, low temperature heat sources such as engine coolant and scavenging air, always with the aim of improving overall system efficiency while respecting new stringent emission reduction targets. The first results of the research activity show that a fuel consumption improvement up to 10% could be achieved both for commercial vehicles off-highway applications and in the marine sector, depending on the type of ORC and waste heat recovery architecture chosen and the engine considered.

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1. Introduction

This paper is meant to be a short overview to the work carried out, about waste heat recovery in marine and commercial vehicles heavy duty diesel engines, in the frame of the EU funded FP7 (Framework Package 7) ECCO-MATE Project (Experimental and Computational Tools for Combustion Optimization in Marine and Automotive Engines).

The main goal of the project is the study of cutting edge combustion strategies to be applied in heavy duty engines used for vehicles and ships propulsion. In parallel to these topics, Ricardo and the University of Trieste, in collaboration with the National Technical University of Athens (NTUA) and Winterthur Gas & Diesel (WinGD), focused the research activities on the analysis of different waste heat recovery concepts, such as, in particular, Organic Rankine Cycles (ORC), in order to exploit the engine waste heat with the final objective of decreasing fuel consumption, increasing overall powertrain efficiency, and reducing environmental pollution.

In the last decades, several institutions, such the EU, the American EPA (Environmental Protection Agency) and the IMO (International Maritime Organization), are introducing new stringent emissions limits in order to control pollutants and reduce the impact of transportation technologies on the environment. Some of these regulations are, for example, the Euro and Tier, in the on-off highway sectors, and the IMO Tier in the large ships marine sector [1]. Several methods are currently applied by engine manufactures and fleet owners in order to reduce pollutants, such as aftertreatment systems, new engine air management technologies, such as Exhaust Gas Recirculation (EGR), fleet operating strategies, and advanced technologies such as waste heat recovery systems.

In both commercial vehicles and marine heavy duty diesel engines, only around 40 - 50% of the energy introduced with the fuel is converted into mechanical energy at the brake, while the rest is usually wasted to the cooling and lubrication oil circuits, through friction processes, and to the environment through radiation, convection and exhaust gases. In Fig. 1, two typical heat balances, for full load conditions, have been reported: in Fig. 1(a) a 200 kW four stroke, single stage turbocharged, charge air cooled (CAC), direct injection, 6 cylinders engine for commercial vehicles applications, obtained from Ricardo WAVE calculations [2], while in Fig. 1(b) a 13.6 MW two-stroke, 6 cylinders, single stage turbocharged, scavenge air cooled (SAC), IMO Tier II compliant ship propulsion unit, calculated from the data obtained from the WinGD GTD software [3]. Actual technologies can reach slightly higher efficiencies compared to what reported for the two engines.

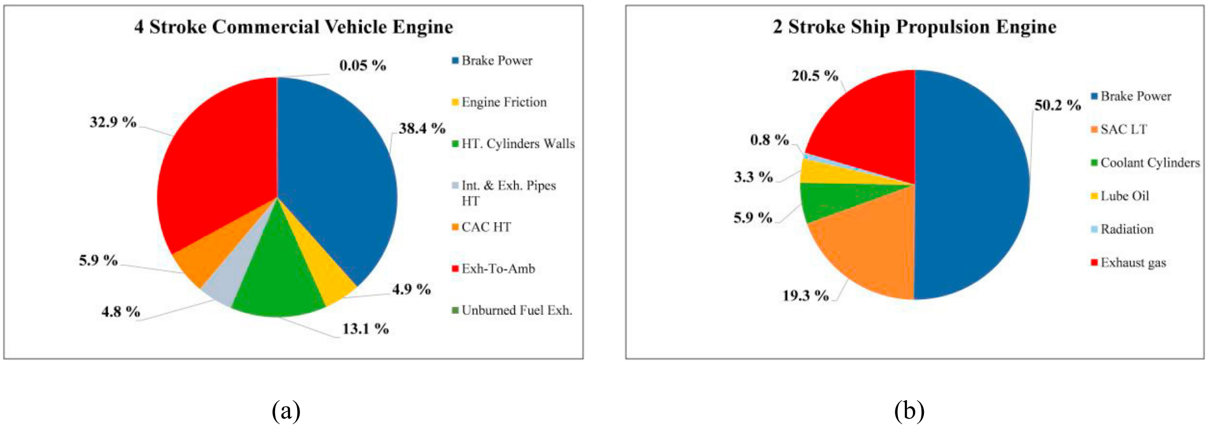

Fig. 1. Heat balances examples: (a) 200 kW commercial vehicle engine heat balance, (b) 13.6 MW ship propulsion engine

As it can be observed from the two charts reported above, a sensible amount of heat can be recovered from various possible heat sources such as exhaust gas, engine cooling circuit, Charge Air Cooler (CAC), Scavenge Air Cooler (SAC) and lubrication oil circuit. Additionally, when using EGR architectures, also an additional heat rejection source can be considered when analyzing waste heat recovery possibilities, in particular when considering cooled EGR, which, otherwise, would require to reject additional heat to the engine cooling circuit and then to the environment.

Particularly, when considering 4 stroke engines, exhaust gas and, eventually EGR, show a good potential for heat recovery, due to the higher temperatures at the engine cylinders' exhaust side. When considering large 2 stroke marine propulsion units, which have brake thermal efficiencies up to more than 50%, exhaust and EGR heat are still very promising heat sources, due to the combination of the medium temperature level and high volume flows of exhaust gases involved in the engine gas exchange processes. However, for both engines, the actual challenge is also the recovery of lower temperature heat sources, such as coolant and charge, or scavenge, air.

In this work some of the results obtained during the research activities in the frame of the ECCO-MATE project are reported, in particular, for typical marine applications and commercial vehicles, demonstrating the potential of the Organic Rankine Cycle (ORC) technology when applied to recover heat from heavy duty diesel engines.

Concerning marine applications, a 2 stroke IMO Tier II compliant marine diesel engine model has been developed, using Ricardo WAVE, and validated based on the data supplied by Winterthur Gas & Diesel (WinGD). A Low Pressure (LP) Exhaust Gas Recirculation (EGR) circuit has then been added with the scope of reducing NO_x emissions for IMO Tier III compliancy. The engine heat rejection boundary conditions have been extracted from the model in order to evaluate the benefits achievable when considering different ORC architectures, with the final goal of mitigating the fuel consumption adverse effect of adding the exhaust gas recirculation path.

Concerning commercial vehicles applications, especially targeting smaller size engines, a 4 stroke, 200 kW diesel engine model has been considered. A MATLAB-based post processing routine has been developed with the scope of assessing the engine First and Second Law of Thermodynamics balances for every operating point which can be simulated in Ricardo WAVE. The same approach has been considered also when adding an ORC waste heat recovery based model, with the scope of analyzing the overall benefits in terms of fuel consumption decrease and overall efficiency. A thermo-economic approach is currently under development in order to assess the concepts and operational strategies in terms of financial feasibility and economic performance, when considering the engine-ORC system as a combined powertrain rather than two different separated systems, as usually done in literature, thus evaluating also combined operational strategies including both ORC and engine parameters.

2. Marine applications

Due to IMO Tier III emissions legislations introduction, various emissions reduction strategies and technologies are currently developed and applied to both low and medium speed diesel engines used for ship propulsion and power generation. Some examples can be: Exhaust Gas Recirculation (EGR), Selective Catalytic Reduction (SCR), water injection, combustion optimization, alternative fuels (such as Liquefied Natural gas, LNG) and advances turbocharging strategies [4,5], while some operational strategies are also used in order to reduce fuel consumption, as for example slow steaming and weather routing [6]. Most of the technologies developed commonly lead to a reduced engine fuel efficiency, but decreased pollutants. For this reason, their combined use with waste heat recovery systems such as steam Rankine cycles, Organic Rankine Cycles (ORC) and more complicated systems, could lead to an improvement in the positive trade-off between fuel efficiency and engine pollution.

In the frame of the ECCO-MATE project, Michos *et al.* [7] analyzed the combined effect on engine performance and overall fuel consumption of installing an ORC boiler on the exhaust line of a 4 stroke turbocharged V12 engine used for marine auxiliary power generation. Different turbocharging strategies, such as Waste-Gate (WG) and Variable Turbine Geometry (VGT), have been investigated in order to counterbalance the detrimental effect of the increase exhaust line backpressure. Simple and recuperated ORC architectures have been investigated, through simulation, in order to assess the combined engine-ORC fuel economy improvement. A combined engine-ORC system using VGT turbine and acetone as ORC working fluid has been considered the most promising, leading to a possible improved fuel efficiency between 9.1 and 10.2%, depending on the ORC boiler engine backpressure.

In literature, several different publications and reports are available about the description of the working principles and performance of different emissions reduction strategies, however, to the author’s knowledge, none of them considers the effective potential that these kind of technologies could have in relation to the possible utilization of waste heat recovery systems, in order to propose combined more efficient and less polluting engines.

Following what reported in the Third IMO GHG Study [8], it is possible to evince how the most CO_2 polluting and fuel consuming ships are typically in the order: container ships, bulk carriers, oil tankers, general cargo ships and chemical tankers. The interesting outcome of this assessment is the observation that these types of ships are typically powered by low speed 2-stroke propulsion units, which are also between the main prime movers in the marine sector. Some of the emissions and fuel consumption can come partially also from typical 4-stroke auxiliary power units, used in ships to supply power for internal use or for diesel-electric propulsion architectures.

For the reasons reported above, in the frame of the ECCO-MATE collaboration, a 13.6 MW brake power 2 stroke diesel ship propulsion engine has been considered. A model has been developed in Ricardo WAVE and validated based on the data supplied by the project partner WinGD. The baseline model is representative of a IMO Tier II compliant engine. For the purpose of the study, a Low Pressure (LP) EGR architecture has been added to the model, in order to simulate IMO Tier III operations for NO_x emissions reduction. The impact on fuel consumption has been assessed based on the EGR targets suggested by WinGD for three different operating points: 100%, 75% and 50% loads. The 50% load can be considered as representative of a slow steaming operation.

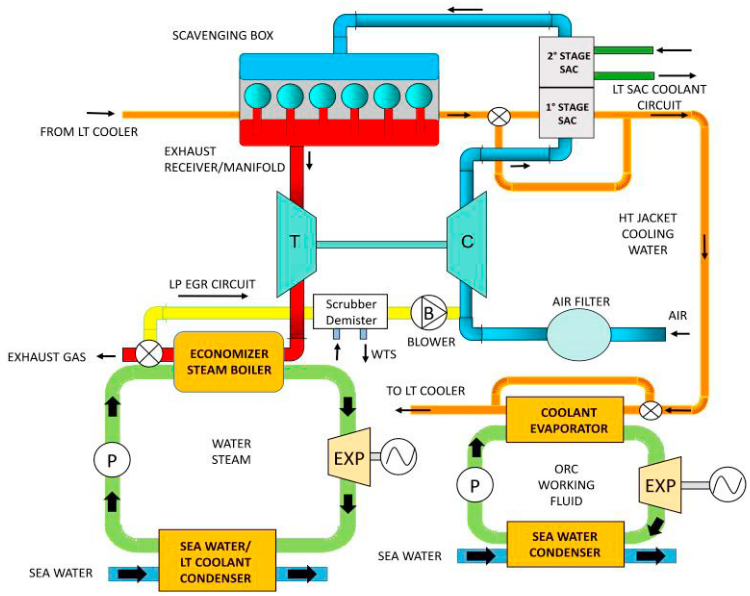

Fig. 2. 2 stroke, 6 cylinders inline, ship diesel engine and combined ORC systems used to recover exhaust gas and coolant/SAC heat

The boundary conditions, concerning heat rejection from Scavenge Air Cooler (SAC), engine block and exhaust economizer have been extracted and estimated with the scope of being used as inputs for different ORC architectures evaluated using a thermodynamic process simulation code developed in EES (Engineering Equations Solver, [9]). In particular, an ORC layout, not often studied in literature, considering the possibility of recovering both engine high temperature cooling circuit and scavenging air heat in a unique simple architecture, has been assessed. The configuration allows to increase the coolant temperature, and thus, ORC performance. The performance of the ORC system, combined with a traditional tailpipe steam Rankine cycle, have been evaluated both for Tier II (baseline) and Tier III (LP EGR) operations. The engine and ORC systems architectures have been reported in Fig. 2.

In particular, the proposed architecture benefits of the increased heat amount which can be recovered both from the tailpipe economizer and the first stage Scavenge Air Cooler (SAC) due to the use of EGR in Tier III operations, which tends to increase the overall engine line gas temperatures, thus leading to an increased power output achievable from the waste heat recovery system. This can help to mitigate the drawback of increased fuel consumption of the engine due to the recirculation of the exhaust gas to the intake in order to reduce NO_x emissions.

The ORC performance have been optimized using a combination of a Genetic Algorithm and a Nelder-Mead optimization algorithm, and the main considered variables controlled are the ORC fluid mass flow, the condensing pressure, the pump pressure ratio, the superheating degree and the cooling fluid mass flow. Fixed efficiencies have been used for the pump (60%), the expander (75%) and gearbox (98%), supposing to produce mechanical energy which could be re-inserted into the engine propeller shaft. The results for the ORC generated power are reported in Fig. 3, for the Tier II and Tier III operating modes (without and with LP EGR) and for the three different engine load points evaluated. The fluids considered are: water-steam for the exhaust line Rankine cycle and R1233zd(E) for the coolant/SAC ORC concept. All three main operating points have been evaluated: 100%, 75% and 50% load.

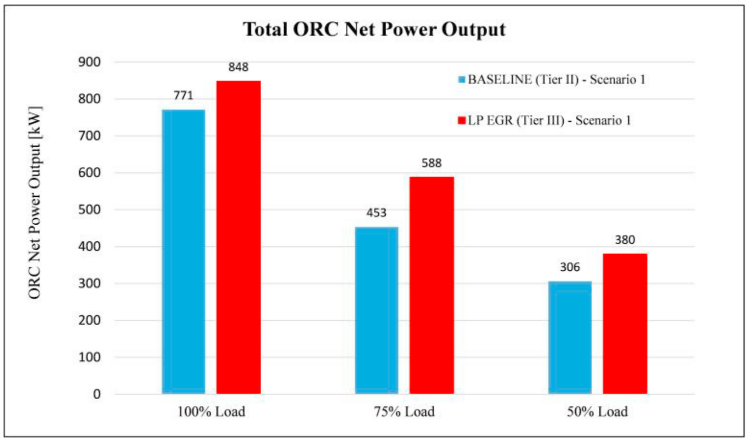

Fig. 3. ORC net generated power for 100, 75 and 50% load points and Tier II and Tier III operations

Table 1. Summary of the analysis results in Brake Specific Fuel Consumption, BSFC [g/kWh] percentage (%) difference due to IMO Tier III LP EGR operations and to the use of waste heat recovery systems based on ORC technology

Load	Baseline vs LP EGR	Baseline vs Baseline + ORC	LP EGR vs LP EGR + ORC
100	+ 1.3%	- 5.4%	- 5.9%
75	+ 6.1%	- 4.3%	- 5.5%
50	+ 3.4%	- 4.3%	- 5.3%

The use of waste heat recovery systems, such as Rankine cycles and ORCs can lead to fuel consumption improvements also when considering 2 stroke engines. In particular, when in the need of meeting new stringent IMO Tier III emission limits, the use of waste heat recovery systems can mitigate the drawback of increase fuel consumption, due, for example, to the use of EGR, as reported in the summarizing Table 1, while, at the same time improving performance in Tier II operational mode (baseline).

3. Commercial vehicles applications

In heavy duty on and off-highway commercial vehicles applications, ORC systems are still in a research and development phase, mostly due to the high cost of prototypes implementation, reliability and safety issues. Moreover, compared to stationary power generation and marine applications, in which the engine tends to run for many operational hours at steady-state stable speed and load points, in vehicles applications, the operating profile and, thus, the possible heat sources for an ORC-based waste heat recovery system, tends to show a more transitional behavior, which leads to the need to carefully design the recovery systems and effective controlling strategies.

However, between commercial vehicles, applications such as long-haul trucks and agricultural tractors and/or earth moving machines, show a more reasonably stable operating profile [10].

In particular, in the frame of the ECCO-MATE project, a typical agricultural tractor application has been evaluated. A 6 cylinders inline, 300 kW brake power, 2-stage turbocharged with HP EGR prime mover has been considered as baseline engine. A high load and high speed operating point has been chosen as design case, and two different ORC architectures evaluated: a simple evaporator on the exhaust line, and a parallel evaporators configuration recovering exhaust and EGR heat. Two different heat sink layouts have been also simulated: one using the engine high temperature cooling circuit and the other using an additional lower temperature cooling circuit only for the ORC. Ten working fluids have been simulated using a process simulation model and optimization techniques to find the best performance. A Brake Specific Fuel Consumption (BSFC) improvement up to 10% has been obtained using medium-high temperature suitable fluids such as water-steam, ethanol, methanol and acetone. A trade-off with cooling fan parasitic consumption has also been estimated. Indeed, especially in vehicles applications, the impact on the cooling system must be always considered when designing the waste heat recovery system. The whole results have been reported in [11].Most of the studies and prototypes reported in literature are, however, considering the engine and the ORC system as two completely different entities, almost not influencing each other. However, despite of the well-known effects of fitting the ORC system on the engine (e.g. cooling circuit impact and exhaust line backpressure, evaluated in [7,11]), a new approach should be proposed in order to consider a combined engine-ORC system, trying to optimize the performance of the overall powertrain, both acting on the ORC and engine sides. For this reason, a First and Second Law of Thermodynamics methodology has been applied in order to evaluate a combined concept, able of catching the thermodynamic effects of both systems. The approach can be useful when considering the design of the overall powertrain in the first phases of a project. Some preliminary results of the ongoing work have been reported in this paper. More detailed outcomes will be proposed in a future publication.

As baseline, a 200 kW medium duty diesel engine has been considered. The engine has a 6 cylinders inline, single stage turbocharged, charge air cooled architecture, and it is suitable for on-off highway applications, or small marine recreational applications. The Ricardo WAVE model for the engine has been obtained from the software validated examples, and it represents the operation of the engine over a wide spectrum of points of the speed-load diagram, thus being suitable to evaluate several operating points which can occur during a duty cycle.

A post-processing routine, based on MATLAB, has been developed in order to calculate precise energy and exergy balances for every operating point which can be simulated in WAVE. The boundary conditions, obtained from the topping engine simulation, have been then used as inputs for the bottoming ORC system evaluations. In particular, an example has been reported in this paper, considering a small marine application (e.g. recreational boat), but commercial vehicles applications are currently under study at the moment in which this paper is being written. Anyway, the methodology can be easily applied to any powertrain, given the right boundary conditions.

The engine model has been divided in several control volumes, and energy and exergy (or availability, A) balances have been applied for every control volume. The engine model scheme has been reported in Fig. 4.

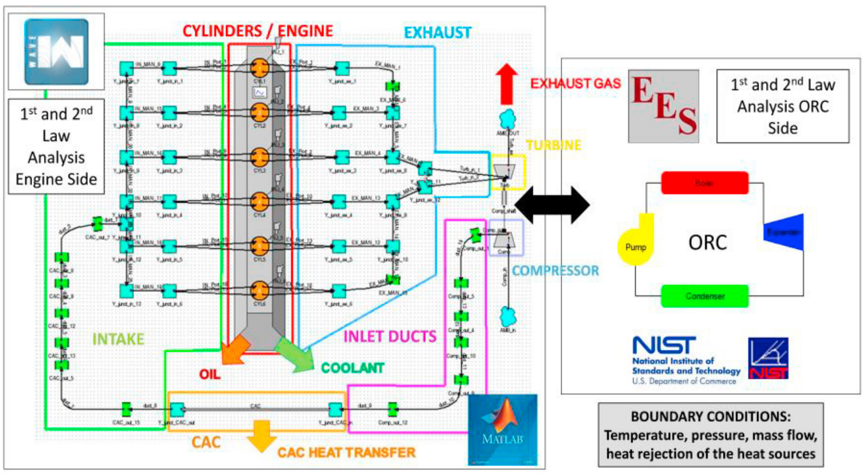

Fig. 4. Engine WAVE model divided in control volumes for First and Second Law calculations. Scheme of the analysis methodology approach

Both engine First and Second Law analysis calculations are based, for the engine, on accurate ideal gas based formulations, and on detailed energy and availability (exergy) balances. In the case of the availability balance, the following Eq. (1) [12] has been applied, for every control volume, on a crank angle degree step base (φ), and then integrated over an engine cycle. In Eq. (1) an example for the cylinders/engine control volume has been reported.

$$\frac{dA_{cyl}}{d\varphi} = \frac{m_{in}b_{in} - m_{out}b_{out}}{6N} - \frac{dA_{work,brake}}{d\varphi} - \frac{dA_{frict,loss}}{d\varphi} - \frac{dA_{HT,loss}}{d\varphi} + \frac{dA_{fuel,burned,ch}}{d\varphi} - \frac{dI_{cyl}}{d\varphi} \tag{1}$$

All contributions *A* are availabilities (J) of different terms composing the availability balance: e.g. brake work availability (*work, brake*), friction losses availability (*frict., loss*), heat transfer losses (*HT, loss*), chemical availability introduced with the diesel fuel (*fuel, burned, ch*). While, the terms $m_{in}b_{in}$ and $m_{out}b_{out}$ are related to the flow availabilities at the inlet and outlet of the control volume and calculated, as reported in [12], from WAVE available simulation outputs, and some additional routines developed in MATLAB. The only unknown of the equation is the irreversilibities term *I*, which can be calculated from the balance, and gives an indication of the wasted exergy (and thus the efficiency) of the control volume considered. In the design phase, the irreversibilities should be minimized when possible.

For the ORC side, the main components of the system (evaporator, condenser, pump and expander) have also been considered as control volumes and the energy and exergy balance formulations, according, for example, to Somayaji *et al.* [13], have been implemented in EES (or MATLAB) in order to calculate the irreversibilities and the availability terms.

Finally, the results for the combined engine-ORC system have been obtained, for the different load-speed operating points considered, both for what concerns First Law and Second Law parameters. In particular, in Fig. 5, it is possible to observe, for a high speed-high load point, how most of the irreversibilities concentrates in the cylinder/engine terms (combustion related irreversibilities) and in the ORC evaporator term. Improvements in combustion efficiency and in heat transfer process in the evaporator could lead to overall benefits for the combined system. Reducing heat transfer from the cylinders walls and from the exhaust manifolds could also increase the availability in the exhaust gas, which can, in turns, be recovered through the use of the bottoming cycle (Low Heat Rejection concept). Different ORC layouts and combined engine-ORC operational strategies can be investigated, using the proposed approach, in order to improve the overall efficiency, but considering the mutual effects of both engine and ORC operational parameters. Moreover, more detailed expanders performance investigations (in particular for scroll and piston types) are currently being considered, in order to assess off-design operating points and have a more precise evaluation of the possible system benefits. Engine increased backpressure effect can be also considered with the proposed methodology.

As a last step of the analysis, a thermo-economic approach is being currently studied in order to assess the combined engine-ORC concepts from an economic perspective, with the scope to understand which concept is more feasible from the financial point of view. In this case, cost correlations from literature (e.g. [14,15]) and/or from Ricardo experience, are currently assessed, because essential for reliable systems comparisons.

Conclusions

The scope of the paper is to propose an overview of the research activities, developed, and under development, during the ECCO-MATE EU funded project, about the study of ORC-based waste heat recovery systems for both heavy duty marine and commercial vehicles applications. In the proposed work, the main interest has been focused on the study of combined engine-ORC systems, with the scope of increasing overall powertrain efficiency, rather than considering engine and ORC as two separated entities.

The methodology proposed for the 200 kW size engine can be easily extended to any kind of engine architecture which can be simulated in WAVE, while the 2 stroke study shows the potential available in these kind of applications, which is not yet fully exploited. The overall outcome of the work is that it is possible to use ORC systems in order to improve fuel consumption up to 5 - 10%, in the proposed applications, when considering the right choice of heat sources, recovery system layouts and working fluids.

In particular, both in marine low and medium speed 2 and 4 stroke engines, and in on-off highway 4 stroke applications, the use of ORC systems, combined with overall powertrain optimization, can lead to sensible efficiency gain and, thus, to cost saving and environmental benefits, especially when considering high fuel consuming, and polluting, applications such ships and on-off highway vehicles.

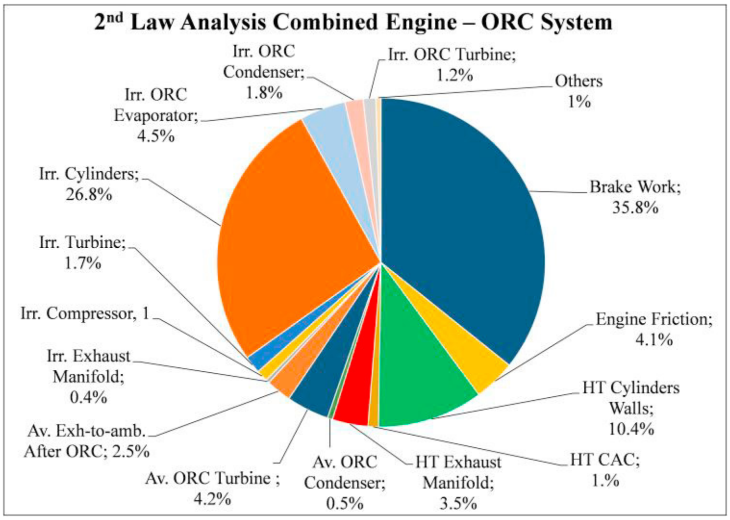

Fig. 5. Second Law analysis chart of the combined engine-ORC system

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