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Energy Procedia 129 (2017) 740–745

Energy Procedia

www.elsevier.com/locate/procedia

IV International Seminar on ORC Power Systems, ORC2017
13-15 September 2017, Milano, Italy

Cost to benefit ratio of an exhaust heat recovery system on a long haul truck

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Abstract

Nearly 30 percent of the fuel energy in an internal combustion engine is lost as waste heat in the form of hot exhaust gases. Nowadays it seems clear that the heavy duty manufacturers will implement bottoming Rankine cycles to recover the exhaust heat on their long haul trucks in the 2020s as an answer to future stringent regulations and the still increasing customer pressure for reductions in operating costs. Though the potential of exhaust heat recovery is clear, the technology has to prove the business, durability and safety cases to be widely spread in the next decade. This paper focuses on the business case of such a technology.

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Peer-review under responsibility of the scientific committee of the IV International Seminar on ORC Power Systems.

Keywords: "Heavy duty trucks, exhaust heat recovery, piston expander, fuel saving, cost, business case"

1. Introduction

To date, emission regulations focusing on local pollutants have not focused on the efficiency of internal combustion engines (ICE). However, future regulations will focus on CO_2 emissions, requiring high efficiency increase of the whole drivetrain. The best efficiency of a modern ICE will remain below 42% and research projects tend to increase it up to 50 or 55%. Electrification of ancillaries and hybridization seem to lead to little fuel savings on Heavy Commercial Vehicles (HCVs) and, at least, would be too expensive to reach future CO_2 emissions regulation compared to air drag reduction and waste heat recovery (WHR). While HCVs aerodynamic is mostly constrained by regulation and also depends on trailer manufacturers, WHR appears as essential in the future innovation panel for HCVs. Though the potential of WHR is clear, the technology has to prove the business,

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Peer-review under responsibility of the scientific committee of the IV International Seminar on ORC Power Systems.
10.1016/j.egypro.2017.09.108

durability and safety cases to be launched in mass production. This paper is dedicated to assess the business case of such a system through the calculation of the cost of the system and of its payback time. We try to go deeper in details than previous papers did [1].

Nomenclature

EAT	Exhaust After Treatment
HCV	Heavy Commercial Vehicle
ICE	Internal Combustion Engine
ORC	Organic Rankine Cycle
SCR	Selective Catalytic Reduction
WHR	Waste Heat Recovery

2. ORC architecture

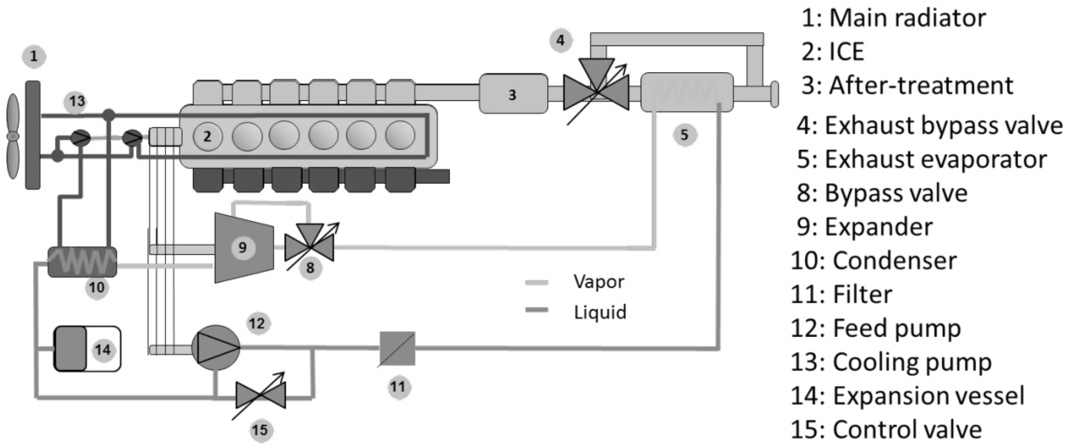


Fig. 1. ORC system considered for this business case (turbocharger is not shown)

The truck engine architecture chosen is a so-called “SCR- only” exhaust after-treatment system. Though it is not the best configuration for WHR [2], it has been chosen based on our current development of a demonstration truck. The waste heat is only recovered from the tailpipe as there is no EGR on this engine. The Organic Rankine Cycle (ORC) recovers the heat from the exhaust gases to convert it into mechanical power re-injected on the driveline. In the scheme considered (Fig. 1), there is no electric component: only pneumatic valves for the three of them and mechanical coupling for the two pumps and the expander. The working fluid, which is a mixture containing mostly ethanol, is moved to an evaporator (5) by means of a pump (12). The pump is assumed to be a gear pump. The flow is controlled by means of a liquid bypass valve (15) that re-circulates part of the liquid to achieve the desire superheating at the evaporator outlet. The vapor circulates from the evaporator to the expander (9) that will expand it and will re-inject torque. The expander considered is based on a swashplate architecture counting three pistons cumulating around 240 cm^3. This device is coupled to the ICE though the gear of an engine PTO. We assume a simple passive freewheel and a damping system between the expander shaft and the PTO gear. A vapor bypass valve (8) may help the warm-up the expander or the stop of the ORC. The vapor at low pressure goes to a condenser (10) that is cooled in parallel of the existing engine cooling loop. The additional cooling pump is mechanically linked to the engine. The working fluid which has been condensed is pumped back to the evaporator. The evaporator and the condenser are assumed to be plate heat exchanger in stainless steel for temperature and corrosion issues. A gas bypass valve (4) is used to control the load on the ORC and reduce the cooling needs on the radiator to favor the cooling of the main engine.

Though the purpose of the paper is not to detail the fuel savings, we have to make an assumption to assess the payback time. According to [3] with a similar ORC architecture but with a very large evaporator, the fuel saving in a real driving cycle may be assumed to range between 2.6 to 2.9% with possible improvements. On the other hand, a simple static calculation on a design point (in table 1) assuming an evaporator effectiveness of 75% and a pump and expander net isentropic efficiencies of 36% and 55% respectively, gives 3.4% fuel saving. From several papers, we know that the dynamics of the system may reduce this potential by a factor up to 2 [4]. We will then assume 3% ±0.5% fuel savings for the payback time estimation.

Table 1. Nominal design point and assumption for fuel savings calculation.

	Value	Unit
Engine power	108	kW
Exhaust massflow	179	g/s
Exhaust temperature	331	°C
Exhaust gases specific heat	1.066	kJ/kg/K
Vapor pressure	20	bar
Vapor superheat	30	°C
Condensing pressure	1	bar
Required pump NPSH	300	mbar

3. Costing method

To assess the cost of such a system we first need an assumption on the yearly sales in order to figure out the type of manufacturing process, from an integrated approach with machining in-house and a fully automated assembly line to an out-sourced strategy coupled to a manual assembly line. The following sales scenario that gives a cumulated number of 250,000 pieces over 8 years will direct us to the second strategy. The forecast volumes are too low to justify a high level of integration and automation.

Table 2. Sales scenario.

	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8
Sales per year (unit/y)	5 000	10 000	15 000	25 000	32 500	42 500	52 500	67 500
Cumulated sales (units)	5 000	15 000	30 000	55 000	87 500	130 000	182 500	250 000

The costing method will then consist in detailing all the parts of each component and calculate a cost for each. The sum of it will give the “purchased parts and services”. Some details of the cost breakdown can be found in Appendix A. They are sum up in table 2. The cost calculation method of the parts may vary from a rough estimation based on our experience or from a quotation from suppliers, to a calculation based on the weight and the material cost of the part. For instance, the latter pattern is applied for the plates of the heat exchangers that are in stainless steel. We assume 3.6€/kg for the material. The weight is calculated based on the size of the part and the density of the material. Last, we add an extra factor of 1.4 to cover all expenses related to material wastes, machine rate, etc.

In addition to this cost, we add the tooling and assembly investment costs. Regarding the plates of the heat exchanger we assume a process of stamping with a tool at 300,000€. The plates are then manually assembled to form a stack which is pressed while the fittings are positioned by an assembly machine. Then the stack is brazed in a furnace, before being tested under pressure. This process gives us three assembly machines which costs are gathered into the 1,000,000€. These investment costs are divided by the cumulated number of sales over 8 years to form the cost added per part.

The labor to assemble the components is accounted as follow. We take a rate of 40€/h plus a 1.2 factor to account for the overheads. We multiply this rate by an estimation of the assembly duration. The cost includes all commodities: buildings, electricity…

A ratio of 30% on the sum of all previous costs is taken to account for the SG&A and the profit that should cover the R&D costs as well as the expected return on investment.

The sum of all these costs gives the manufacturing cost of the components. Then we add the margin of the OEM to integrate the system and cover the R&D costs. The margin is accounted as a percentage of +80%±20% based on the component costs.

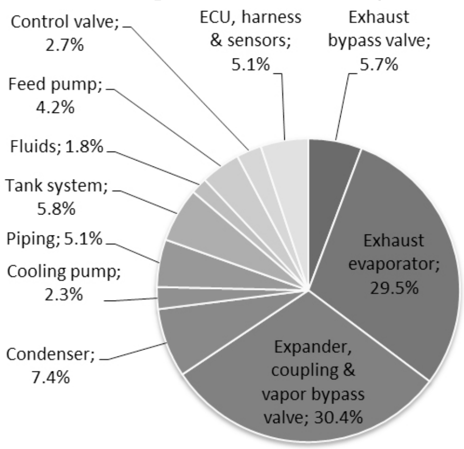
4. System cost

It can be seen that the total weight of the system is estimated at ~110kg, the half of which is coming from the exhaust evaporator (including the extra weight of the caning of the EAT).

Table 3. Component costs.

Component	Weight [kg]	Main material (if applicable)	Purchase parts and services	Total Toolings	Total Assembly investments	Assembly labor	SG&A & profit	Total
Exhaust bypass valve	4.2	Stainless steel	56.83 €	600,000 €	500,000 €	4 €	19.57 €	**84.80 €**
Exhaust evaporator	46.6	Stainless steel	321.78 €	600,000 €	1,000,000 €	8 €	99.65 €	**431.84 €**
Expander, coupling & vapor bypass valve	15.3	Cast iron / Steel	315.00 €	1,800,000 €	2,000,000 €	16 €	100.26 €	**434.46 €**
Condenser	13.8	Stainless steel	69.52 €	600,000 €	1,000,000 €	8 €	23.98 €	**103.90 €**
Cooling pump	0.4	Cast iron / Steel	19.00 €	600,000 €	300,000 €	4 €	7.98 €	**34.58 €**
Piping	15.4	-	52.82 €	250,000 €	0 €	4 €	17.35 €	**75.17 €**
Tank system	2.6	Plastic	56.00 €	300,000 €	300,000 €	8 €	18.72 €	**81.12 €**
Fluids	8.6	-	20.00 €	0 €	0 €	0 €	7.20 €	**31.20 €**
Feed pump	0.4	Plastic / Steel	41.00 €	300,000 €	500,000 €	4 €	14.46 €	**62.66 €**
Control valve	0.2	Plastic / Steel / Copper	22.00 €	600,000 €	500,000 €	4 €	9.12 €	**39.52 €**
ECU, harness & sensors	2.5	-	58.00 €	0 €	0 €	0 €	18.60 €	**80.60 €**
Total	**110 kg**	-	1,032 €	5,650,000 €	6,100,000 €	60 €	342 €	**1,481€**

In Fig. 2 (left), a pie chart illustrates the cost breakdown showing that 60% of the cost is resulting from the evaporator and the expander costs. Adding the OEM margin, it gives us a total system cost around 2,666€ ±296€.



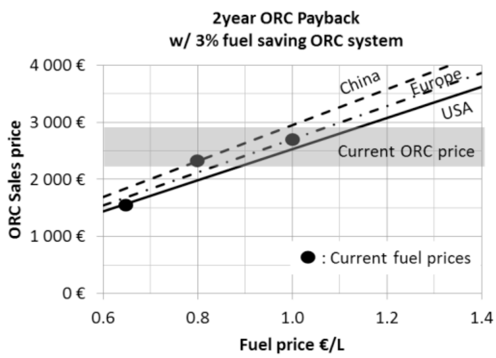


Fig. 2. Left: ORC manufacturing cost breakdown. Right: Requirements for a payback time of two years in different world regions

5. Payback time estimation

To assess the payback time, we defined three regions with homogenous parameter in terms of truck use: Europe, the USA and China. These parameters are gathered in table 3. The figure for the Chinese truck consumption is a forecast after the implementation of the “China 6” regulation that should be set up between 2019 and 2025. The mileage for Chinese truck is an average between express delivery, coal delivery or refrigeration trucks. For the USA trucks, we took the class 8 truck averages for mileage and consumption coming from the U.S. department of Energy [5]. Other figures come from our customer feedbacks.

Table 4. Assumptions for payback time calculation.

	Europe	USA	China	Unit
Mileage	130,000	110,000	150,000	km/y
Fuel	1	0.65	0.8	€/L
Consumption	35	44	35*	L/100km
ORC Maintenance	100	100	100	€/y

*: projected in 2025 with new regulation implementation

In Fig 2 (right), we plot the line that allows reaching a 2 year payback period on the ORC given its sales prices and its associated fuel savings.

As a result, it can be seen that the business case of the system can be met in Europe or in China whereas in the USA the diesel price makes it very difficult. There, only a CO_2 regulation, for example the Phase 2 Greenhouse Gas Emissions and Fuel Efficiency Standards set by the EPA and NHTSA [6], could help the market penetration.

6. Conclusion

Waste heat recovery on long haul trucks is the future technology to reduce fuel consumption. This paper tries to establish that such systems can meet the stringent requirements to make a strong business case. It has been proved that though a 2 year payback time may be considered, future improvements are requested to decrease costs and increase efficiency at least for the USA market. As an expander developer, the Exoès company answers this challenge in two folds. First is to design cost effective solutions integrating functions, reducing the quantity of parts and reducing the use of expensive materials in the expander. Second is to improve the expander efficiency, which is key in the system performance, with the target to reach 65-70% effective isentropic efficiency.

Acknowledgements

I would like to warmly thank Laurent Joly who educated me to this costing method and took the time to give me some advice based on his experience in comparable sectors.

References

[1] Walter, L., “Definition, design and thermal integration of a WHR system “,ICPC 2013 – 3.4

[2] Dingel, O., Arnold, T., Töpfer, T., Seebod, J., “Influence of EAT Concepts on Efficiency and Economy of an Organic Rankine Cycle System”, MTZ worldwide 10/2016

[3] Glensvig, M., Schreier, H., Tizianel, M., Theissl, H. et al., "Testing of a Long Haul Demonstrator Vehicle with a Waste Heat Recovery System on Public Road," SAE Technical Paper 2016-01-8057, 2016, doi:10.4271/2016-01-8057

[4] Grelet, V., Reiche, T., Lemort, V., Dufour, P., Nadri, M., “Performance assessement of waste heat recovery Rankine cycle based system for heavy duty trucks”, 3rd Engine ORC Consortium Workshop, Belfast, 2016

[5] http://www.afdc.energy.gov/data/

[6] https://www.epa.gov/regulations-emissions-vehicles-and-engines/final-rule-greenhouse-gas-emissions-and-fuel-efficiency

Appendix A. Detailed sub-components costs and characteristics

Category	Parts	Qty	Main material	Weight [kg]	Tooling [€]	Unit cost [€]	Total Cost [€]	Total weight [kg]
Exhaust evaporator	Fitting IN tube	1	stainless steel	0.1		0.4	**0.4 €**	**0.1**
Exhaust evaporator	Fitting OUT tube	1	stainless steel	0.1		0.4	**0.4 €**	**0.1**
Exhaust evaporator	Plate 300x200mm	60	stainless steel + clad	0.5	300 000	3.4	**203.2 €**	**28.8**
Exhaust evaporator	Fin 300x200mm	30	stainless steel + clad	0.5	300 000	3.4	**101.6 €**	**14.4**
Exhaust evaporator	Extra caning EATS 300x200x200mm	1	stainless steel	3.2		16.1	**16.1 €**	**3.2**
Exhaust bypass valve	Flap D100	1	stainless steel	0.5	300 000	2.5	**2.5 €**	**0.5**
Exhaust bypass valve	Axle	1	stainless steel	0.0		0.1	**0.1 €**	**0.0**
Exhaust bypass valve	Bushing	2	carbone	0.1		2.0	**4.0 €**	**0.1**
Exhaust bypass valve	Pneumatic actuator with position sensor	1	-	0.3		20.0	**20.0 €**	**0.3**
Exhaust bypass valve	Lever	1	stainless steel	0.0		0.1	**0.1 €**	**0.0**
Exhaust bypass valve	Pin	1	stainless steel	0.0		0.1	**0.1 €**	**0.0**
Exhaust bypass valve	Seat D100	1	stainless steel	3.0	300 000	15.1	**15.1 €**	**3.0**
Exhaust bypass valve	Pneumatic solenoid valve	1	copper	0.3		15.0	**15.0 €**	**0.3**
Cooling pump	Casing	1	cast iron	0.4	300 000	10.0	**10.0 €**	**0.4**
Cooling pump	Wheel	1	cast iron		300 000	3.0	**3.0 €**	**0.0**
Cooling pump	Axle	1	steel			2.0	**2.0 €**	**0.0**
Cooling pump	Bearing	1	steel			2.0	**2.0 €**	**0.0**
Cooling pump	Shaft seal	1	elastomer			2.0	**2.0 €**	**0.0**
Condenser	Front / back plate	1	stainless steel	0.7	300 000	3.6	**3.6 €**	**0.7**
Condenser	Plate 100x200mm	50	stainless steel	0.2	300 000	1.2	**60.5 €**	**12.0**
Condenser	Fitting tube in D35	1	stainless steel	0.2		1.3	**1.3 €**	**0.2**
Condenser	Fitting tube out D12	1	stainless steel	0.0		0.2	**0.2 €**	**0.0**
Condenser	Fitting tube cooling D50	2	stainless steel	0.4		2.0	**4.0 €**	**0.8**
Feed pump	Casing	1	Aluminum	0.4	300 000	10.0	**10.0 €**	**0.4**
Feed pump	Gear	2	cast iron			5.0	**10.0 €**	**0.0**
Feed pump	Axle	2	steel			2.0	**4.0 €**	**0.0**
Feed pump	Bearing	4	steel			3.0	**12.0 €**	**0.0**
Feed pump	Shaft seal	1	elastomer			5.0	**5.0 €**	**0.0**
Control valve	Coil	1	Copper	0.2	300 000	7.0	**7.0 €**	**0.2**
Control valve	Body	1	Plastic		300 000	2.0	**2.0 €**	**0.0**
Control valve	Cover	1	Steel			3.0	**3.0 €**	**0.0**
Control valve	Needle	1	Steel			5.0	**5.0 €**	**0.0**
Control valve	Spring	1	Steel			1.0	**1.0 €**	**0.0**
Control valve	Sealing	1	elastomer			1.0	**1.0 €**	**0.0**
Control valve	Bushing	1	Steel			3.0	**3.0 €**	**0.0**
Piping	HP HT 3m pipe + flexible hose + 2 fittings	1	Stainless steel	1.4	50 000	7.2	**7.2 €**	**1.4**
Piping	HP LT 1m pipe + nipples	1	Elastomer	0.3	50 000	5.0	**5.0 €**	**0.3**
Piping	LP LT 3m pipe + nipples	1	Elastomer	0.3	50 000	5.0	**5.0 €**	**0.3**
Piping	LP HT 0.5m pipe	1	Elastomer	0.3	50 000	10.0	**10.0 €**	**0.3**
Piping	Cooling D50 iron tube 5m	1	Steel	13.1	50 000	25.6	**25.6 €**	**13.1**
ECU, harness & sensors	Pressure + temperature sensor	2	-	0.3		6.0	**12.0 €**	**0.6**
ECU, harness & sensors	Temperature sensor	4	-	0.1		4.0	**16.0 €**	**0.4**
ECU, harness & sensors	Harness	1	-	1.0		15.0	**15.0 €**	**1.0**
ECU, harness & sensors	ECU	1	-	0.5		15.0	**15.0 €**	**0.5**
Tank system	Low pressure relief valve	1	Aluminum	0.1		7.0	**7.0 €**	**0.1**
Tank system	Low pressure + safety tank	2	Plastic	1.0	300 000	15.0	**30.0 €**	**2.0**
Tank system	Diaphragm	1	Elastomer	0.2		4.0	**4.0 €**	**0.2**
Tank system	Pressure control solenoid valve	1	-	0.3		15.0	**15.0 €**	**0.3**
Fluids	Ethanol96% + Denaturant 10L	1	-	8.0		15.0	**15.0 €**	**8.0**
Fluids	Lubricant 500mL	1	-	0.6		5.0	**5.0 €**	**0.6**
Expander, coupling & vapor bypass valve	Expander + bypass valve + coupling	1	-	15.0	1 800 000	300.0	**300.0 €**	**15.0**
Expander, coupling & vapor bypass valve	Pressure control solenoid valve	1	-	0.3		15.0	**15.0 €**	**0.3**