IMPROVING TRAIN ENERGY EFFICIENCY BY ORGANIC RANKINE CYCLE (ORC) FOR RECOVERING WASTE HEAT FROM EXHAUST GAS

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ABSTRACT

In a context of energy cost increase, reducing engine fuel consumption has become a key issue for transportation industry. Many paths exist to achieve substantial fuel savings: downsizing, hybridization, energy recovery… IFPEN has carried out an analysis of heat losses showing that recovering exhaust heat energy is a promising solution for improving fuel economy. Thus, IFPEN and ENOGIA have co-developed an Organic Rankine Cycle (ORC) system for direct recovering energy from exhaust heat. This system has been designed in order to be implemented on a Diesel-electric regional train manufactured by ALSTOM TRANSPORT. The train has several Diesel engines that produce mechanical torque needed for generators used for train electric propulsion. The ORC recovers energy from the exhaust heat of the different Diesel engines.

The project funded by the French national agency for research (ANR) started with 0D simulations in order to identify the optimal ORC architecture as well as some promising working fluids. More than 100 fluids were evaluated and finally two fluids were retained for this application thanks to their safety features, eco-friendliness and thermodynamic potential. A pre-design study defined the main components (boiler, condenser, pump…) that answer to the major constraints: cost, compactness, efficiency. ENOGIA developed the "heart" of the ORC, a dedicated turbine coupled with a high-speed generator on the same axle. The objective is that the electricity produced by the turbo-generator is re-injected for the train electrical propulsion. An ORC prototype has been assembled with a special care for avoiding any organic fluid leaks. The prototype has then been tested in an engine bench with the same Diesel engine as in the regional train. At the engine bench, the electricity produced by the ORC is re-injected in the French grid by means of inverters and transformers.

Based on previous experiences, IFPEN has developed an advanced control system for this application, which allows transient control of ORC operation by regulating vapor superheating at evaporator outlet. The machine has been largely instrumented for monitoring Rankine cycle operation. At the time of paper writing, around 10kW of ORC electricity output power has been reached in stable conditions.

1. INTRODUCTION

In Europe, more than 50% of the railway network is not electrified. Thus, Diesel electric trains are widely used for regional passenger transportation. In these trains, the Diesel engines are linked to high-voltage generators to provide direct current (DC) to the electric train traction. Each regional train has several engines consuming each around 50l/100km of fuel. In a context of energy saving and global warming awareness, train manufacturers have been focusing their research and innovation efforts on the fuel consumption reduction of their engines. But despite all these improvements, engine efficiency is reaching an asymptote around 40-45%. At least 60% of the energy content of the fuel is lost in exhaust gas heat (~30%) and engine coolant (~30%). Many paths exist to achieve substantial fuel savings. Among these, hybrid concepts show significant efficiency improvements but with high cost. That's why some scientists are focusing their interest on how recovering energy from engine losses. Heat conversion to mechanical or electrical work can't only be reduced to energy consideration, then the concept of exergy derived from the second law of thermodynamics has to be introduced. It represents the part of the energy that can be really extracted for a thermodynamic closed system reversibly from its initial state to equilibrium. Exergy (Ex) variation between states 1 and 2 of a system in contact with its environment is defined as:

$$\Delta \mathrm{Ex}_{12} = (\mathrm{H}_2 - \mathrm{H}_1) - T_0 . (\mathrm{S}_2 - \mathrm{S}_1) \tag{1}$$

El Habchi (2010) shown that recovering energy from the exhaust presents higher potential than coolant energy recovery. As an example, over a specific mission profile (Artemis Motorway, for passenger car) for a 2L gasoline engine, exhaust gas exergy represents 26% of fuel lower heating value whereas coolant exergy is only 3%. Several technologies exist to convert exhaust heat into useful work such as turbo-compound, thermoelectric generator or thermo-acoustic engine and finally thermodynamic systems (Rankine, Stirling, Ericsson cycles). However, the complexity or the cost of some technologies is disproportionally high in comparison to the heat recovery potential: considering this, Rankine cycle seems to be the most promising approach. Heat recovery technology is already widely exploited in stationary equipment or for heavy ships. The implementation on mobile applications is challenging due to the transient behavior of the heat source. No serial production Rankine system exists yet for heavy-duty or train application.

Considering this context, IFPEN and ENOGIA have co-developed an Organic Rankine Cycle (ORC) system for recovering energy from exhaust heat from a Diesel-electric regional train made by ALSTOM TRANSPORT. The train has several Diesel engines developing more than 300kW max. power each. They have a two-stage turbocharging which limits even more exhaust gas temperature compared to a biogas spark-ignited stationary engine for example. The Rankine system produces work by the mean of a working fluid that exchanges heat between a hot source and a cold sink as described in figure 1. The working fluid is circulated and pressurized thanks to a volumetric pump. The fluid is then vaporized inside a boiler by exchanging heat with a hot source, exhaust gas in this case. This vapor at high pressure is then expanded in a turbine generator which produces electricity that is used for electric train propulsion. The working fluid is liquefied in a condenser by exchanging heat with a cold source before it is pumped again. The ORC works in a medium range of temperatures (100 to 200°C) compared to steam Rankine systems that operate at higher temperatures.

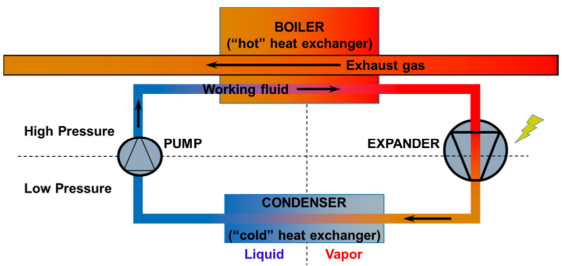

Figure 1: Rankine cycle principle

The project has followed different steps from blank sheet to a prototype: a ORC pre-sizing stage including selection of the ORC architecture and the working fluid, the ORC prototype conception and manufacturing, the testing in realistic conditions at engine bench.

2. SIZING THE ORC

2.1 Heat recovery potential on the train

The first step of this work is to evaluate the heat recovery potential of the train application depending on the hot source and cold sink. To achieve this study, a 0D dynamic low-frequency model of the train system propulsion has been made using the tool LMS Imagine Lab Amesim with IFPEN-Drive engine dedicated library. The IC engine, the generator and electrical load have been simulated using two real mission profiles given by the train manufacturer:

- Profile A: interurban route between two cities at high speed (average speed 120km/h) shown in figure 2.
- Profile B: one suburban route with a lot of stop & go (average speed 77km/h).

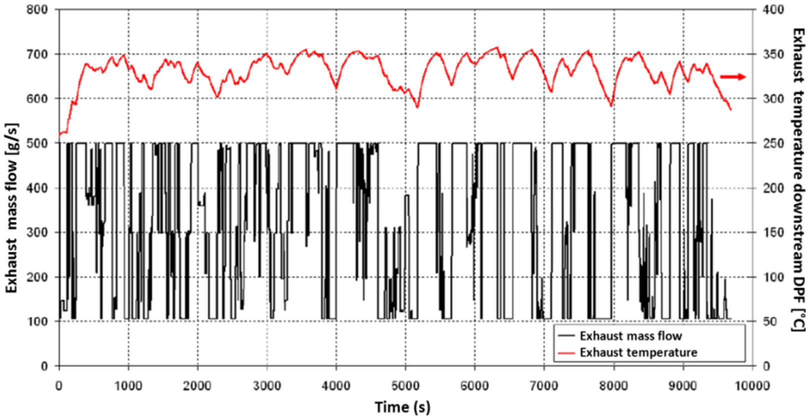

Figure 2: Exhaust mass flow and temperature evolution over mission profile A

The simulator evaluates the recoverable exergy along the chosen mission profiles by using input data of exhaust temperature and exhaust mass flow given by train manufacturer and the heat flow estimation evaluated thanks to REFPROP thermodynamic database of the NIST. Different ORC configurations have been simulated by varying 3 parameters in realistic conditions:

- The cold sink temperature: the ambient temperature impacts the cold sink temperature and thus the exergy recovery potential can be limited.
- The maximum working fluid temperature (for simulating thermo mechanical turbine constraint or limit before chemical degradation of the working fluid).
- The recovery system location: boiler position downstream the Diesel Particulate Filter (DPF).

Table 1: Heat recovery potential simulation results

ORC Configuration	1.	2.	4.	3.	5.
Cold sink T [°C]	50°C	50°C	25°C	50°C	50°C
Max. fluid T [°C]	No limitation	No limitation	200°C	200°C	150°C
Boiler position	Just after DPF	1m downstream DPF	Just after DPF	Just after DPF	Just after DPF
Exergy on profile A [% mech. energy]	48kW (14%)	24kW (7%)	42kW (13%)	39kW (12%)	36kW (12%)
Exergy on profile B [% mech. energy]	49kW (14%)	24kW (7%)	41kW (13%)	38kW (11%)	36kW (10%)

The assumption is that exhaust heat is recovered in both Exhaust Gas Recirculation (EGR) and exhaust line downstream DPF, that's why the levels of exergy are quite high (up to 14%). As EGR heat recovery is deeply intrusive in existent engine architecture and calibration, it has been abandoned at this stage of the project and energy will be recovered only on exhaust line. The main influence factor on recoverable exergy is the recovery system location: the results show that the boiler should be placed as closed as possible downstream DPF to maximize thermal exhaust energy. Then the maximum fluid temperature has a strong influence too: if the max. working fluid temperature is reduced by 50°C, the exergy potential is reduced by ~10%. Finally, the cold sink temperature has a medium influence on recoverable exergy especially when max. fluid temperature is already limited. Moreover, the 2 different mission profiles have minor impact on exergy potential. These results have to be moderated as the fuel consumption reduction will be different between the 2 mission profiles. Indeed, the ORC turbine has a variable efficiency depending on the operating conditions, especially at part load and during transient conditions, which is hard to be fully taken into account in the simulation.

2.2 Screening the working fluid

The working fluid plays a key role in a Rankine cycle. It is repeatedly vaporized, expanded and re-condensed. The work output for a given temperature gradient differs significantly for different fluids. That's why a screening of different working fluids is carried out to choose the most suitable fluid for this application according to specific criteria:

- Thermodynamic performance: high expansion work output. The pressure in the boiler should be as high as possible to increase the turbine expansion rate. Finally, the pressure downstream the condenser should be as closed as possible to atmospheric pressure also to increase the turbine expansion rate.
- Mollier's diagram shape (temperature versus entropy): the dry working fluids are more suitable as they don't liquefy during their expansion in the turbine. The need for superheating is then reduced and the risk of droplet generation during expansion (leading to turbine blade erosion) is avoided. For a mobile application with high space constraints, the fluid needs to have a high specific heat capacity and latent heat of vaporization to minimize flow rates and by the way the size of components especially the boiler and the required pumping power.
- Safety: inflammability (explosion protection due to critical flashpoint) and toxicity.
- Chemical stability: molecule decomposition under ageing or thermal effects.
- Environment aspects: GWP, ODP.
- Material compatibility: corrosiveness, lubricant properties of the turbine.
- Equilibrium pressure when ORC is stopped: if ORC is under atmospheric pressure when stopped, air can enter inside the circuit if leaks are present and thus degrading Rankine cycle efficiency.
- Low freezing point: compliance with train parking with cold conditions (-30°C).

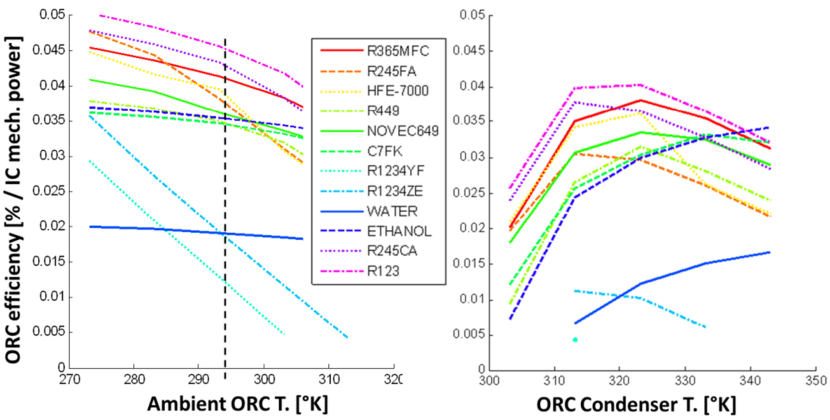

Figure 3: Global ORC efficiency simulated for different fluids for ambient and condenser T. variations

The fluid screening has been carried out with an ORC 0D steady-state model using Matlab platform. Different types of working fluids have been tested including water, ammonia, SO_2, hydrocarbons, alcohols and hydrofluorocarbons: more than 100 different fluids have been analyzed. The thermodynamic data of the fluids have been estimated thanks to the REFPROP V9.1 software of the NIST. The ORC efficiency is calculated for the engine point producing the maximum power (>300kW) taking into account realistic train conditions. Thus, every ORC component has been described by assumed realistic values of efficiencies for the turbine generator and the pump and using water as cold sink. This water circuit is cooled by an electric cooling fan. The fluid is superheated, its minimal pressure is above 1 bar, its maximum pressure is below 25bar and its maximum temperature is below 200°C. The Rankine circuit is also optionally composed of a regenerator that exchanges heat between vapor phase from downstream turbine and liquid phase from downstream pump.

Finally, about 500 000 simulations have been carried out in this project. In figure 3, the results show the maximum global ORC efficiency defined as the ratio between the electric output net power of the ORC over the mechanical engine power. This efficiency is between 3 to 5% depending on the conditions (ambient or condenser temperatures…). This global ORC efficiency decreases at low condensing temperatures as more energy is spent to cool the water (cold sink) than the gain in ORC thermal efficiency (Carnot theorem). Because of safety issues, hydrocarbons, alcohols and ammonia are disqualified for train application. Water is also not adapted as efficiencies are really low. Finally, HFC presents good trade-off with a 4% ORC efficiency potential combined with acceptable toxicity and environmental characteristics. Finally, the project has chosen two fluids for experimental testing :

- R245fa: high efficiency and long partner experience with this fluid but high GWP.
- Fluid B: high efficiency, not sensible to condenser water temperature variation, low GWP but high cost.

Table 2: Working fluid specifications

Fluid characteristic	Formula	Max. continuous T	Critical P/T	Inflammability NFPA / HMIS	Toxicity NFPA / HMIS	ODP GWP	Supplier Cost
R245fa	C3H3F5	154°C	154°C 36,5bar	1 / 1 Non flammable	2 / 2	0 950-1030	Honeywell Medium
Fluid B	Confiden tial	<300°C	<200°C <20bar	0 / 0 Non flammable	Low	0 <50	Confidential High

2.3 Expected performances

Finally, simulations allow to obtain the expected performances for the selected ORC architecture with the two different working fluids. The ORC efficiency expected is around 6 to 7% with both fluids meaning that 6 to 7% of the heat power received by the fluid in the boiler will be re-injected for the electric train traction.

Table 3: Predicted performances at steady-state max. power engine operating point

Fluid	R245fa	Fluid B
Heat power received by the fluid in the boiler	134 kW	122 kW
Heat power lost by the fluid in the condenser	117 kW	107 kW
Electrical power generated by the turbine	16 kW	14 kW
Electrical pump power consumption	1,8 kW	1,6 kW
Cooling power consumption	5,8 kW	3,6 kW
ORC efficiency (compared to heat on fluid)	6,3 %	7,2 %
Fluid mass flow	2150 kg/h	3600 kg/h
P / T in HP branch	25 bar / 167 °C	15 bar / 200 °C
P / T in LP branch	3,6 bar / 41°C	1,5 bar / 50 °C

3. ORC PROTOTYPE AND IMPLEMENTATION AT ENGINE BENCH

3.1 ORC architecture

After the first stage of pre-sizing, IFPEN and ENOGIA co-designed an ORC layout taking into account the previous recommendations in order to be tested at engine bench. The layout is displayed in figure 4. The heat is recovered in the exhaust line downstream the DPF in order to avoid the boiler clogging. The exhaust line has been modified by the implementation of two exhaust throttles allowing the exhaust gas going through the boiler or bypassing it, depending on exhaust thermal energy available. The expansion machine is a turbine that is coupled to a generator for electricity production. Among the conventional components of an ORC cycle, one can notice the presence of a regenerator to improve the cycle efficiency with an intermediate heat exchange in order to pre-heat the pressurized liquid with the vapor after expansion on the turbine. The ORC is instrumented with thermocouples, pressure sensors and flow meters in order to allow real-time monitoring of the ORC energy balance.

3.2 Component description

To pressurize the working fluid, an industrial volumetric pump self-lubricated has been chosen with a variable capacity between 80 to 1000L/min. It is driven by an electrical motor of 3 kW max power with a chain transmission. The boiler has been chosen with specific criteria for maximizing heat exchange with exhaust gas with the minimum pressure drop in exhaust gas (for no impact on engine fuel consumption) and with a reasonable cost. The chosen technology consists in a cross flow stainless steel exchanger mixing tubes (for fluid) and plates (for exhaust gas). Total surface plates (>50m²) is much greater than surfaces of tubes (>3m²) to compensate lower heat transfer coefficient of the gas compared to the liquid. The boiler has been sized to reach the expected performance shown in table 3. ENOGIA has designed and manufactured the expansion machine. It is an axial turbine coupled with a generator on the same axle. The shape of the turbine blades have been adapted to the 2 different fluids based on the experience and know-how of ENOGIA. The robust design of the turbine allows to operate the ORC in flexible operating conditions without any risk of damaging turbine blades and the smart design permits to reduce significantly maintenance intervals of the expander. The condenser and the regenerator are off-the-shelf plate exchangers for cost and planning reasons, taking into account weight and compactness for a further train integration.

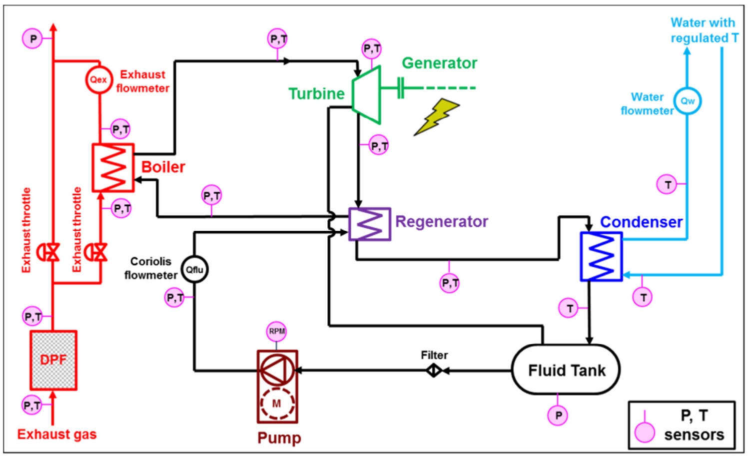

Figure 4: ORC prototype system layout with its measurement equipment for engine bench

3.3 Implementation at engine test bench

The design has taken into account a first level of constraints in terms of train integration. Train integration study has not been fully completed but has highlighted some general guidelines in order that the ORC prototype implemented at engine bench should become compatible with real train integration in the near future. A volume has been defined by the train manufacturer to implement the ORC on the train: it is represented in figure 5 by the tubular frame in blue. This constraint imposed to make a chain transmission between the electrical motor and the fluid pump. Moreover, the condenser and the regenerator had to be inclined to fit in the available room.

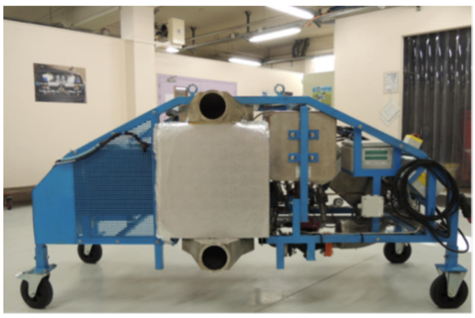

Figure 5: ORC prototype before entering in the test cell

The ORC has been manufactured with the dedicated pressure and temperature sensors. The prototype has been implemented at engine test cell and coupled up with the one Diesel engine identical to the ones used on the train as presented in figure 6. The exhaust throttles have been mounted: the chosen technology is a flap with an electrohydraulic actuator with position feedback. The electricity generated by the ORC is injected in the test facility grid by means of a smart inverter and a transformer. The smart inverter used in this application, provided by MAVEL, allows a turbine speed regulation and real-time monitoring of the electrical power produced. For each point of the ORC circuit, based on the measurements of pressure and temperature, the fluid and exhaust gas specific enthalpies are tabulated thanks to the thermodynamic data given by the NIST software: REFPROP V9.1. The fluid and exhaust gas heat power are obtained by introducing the measurement fluid mass flow and the enthalpy of a reference state for 20°C. The heat transfer efficiencies of each exchanger are evaluated: boiler, condenser and regenerator ; the turbine efficiency is estimated by making the difference between the isentropic expansion work and the real work measured.

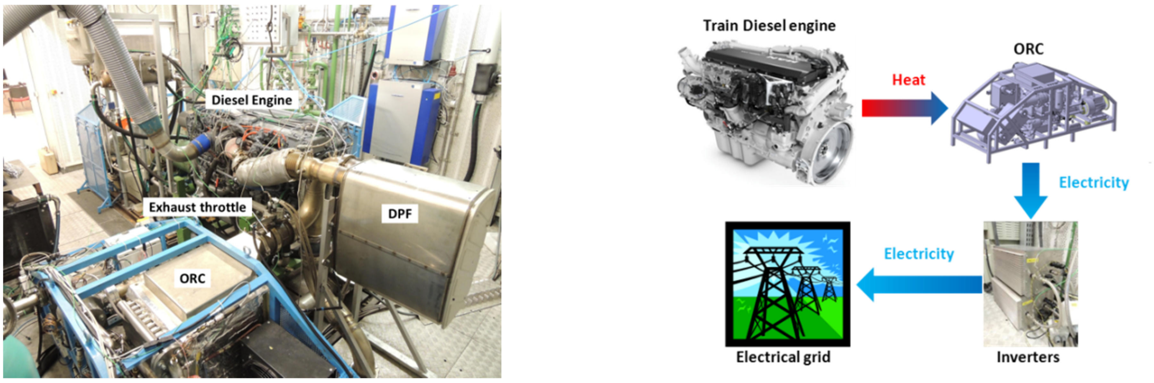

Figure 6: ORC prototype implementation at the engine bench

4. ORC CONTROL SYSTEM

One challenge of this project is to control dynamically the ORC which is a complex system evolving in transient conditions. The principle of the ORC control consists in dynamically adjusting the corner points of the thermodynamic cycle on the Mollier diagram (pressure vs. enthalpy) to ensure safe and efficient operation, with respect to changing external conditions. Ideally, one should be able to adapt both the high pressure (HP) point at evaporator outlet and the low pressure (LP) point at condenser outlet. However, this means being able to control four different thermodynamic variables (two for each point), which is in general unachievable due to the reduced number of available actuators and their lack of control authority. In practice, depending on the ORC configuration, only a few variables can be tightly controlled, and sometimes just one. All the different configurations tested during the project fall into the generic ORC layout shown in figure 7 with the inputs/outputs for control.

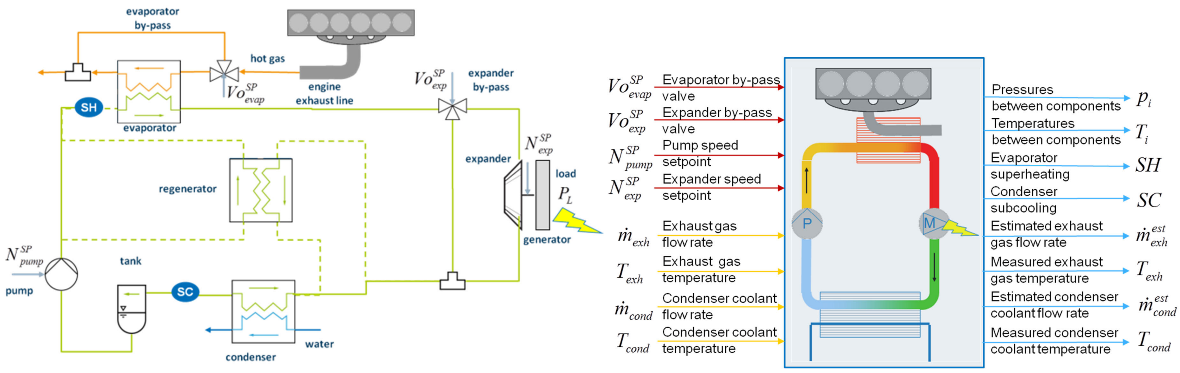

Figure 7: ORC control layout with I/O
(red: manipulated ; yellow: disturbance ; blue: measured/estimated variables)

No actuator is available for control purposes on the condenser side, which means that cooling conditions are entirely seen as an external disturbance. The turbine speed setpoint N_{exp}^{SP} sent to the inverter has little effect in the project conditions and can only be used to optimize turbine efficiency.

The turbine bypass Vo_{exp}^{SP}, which has been integrated in some configurations for safety reasons, cannot be used during nominal (power production) operation. The pump speed setpoint N_{pump}^{SP} is the only actuator with large enough control authority and can be used to control, for instance, the superheating SH at evaporator outlet, a variable which is meaningful both in terms of performance and safety. Thus, a main control loop acting on pump speed to regulate evaporator superheating can be designed, as described in Peralez et al., 2014, for a long-haul truck application. There is one last actuator available, the evaporator bypass Vo_{evap}^{SP}, which has a safety purpose too, but could in principle be used for slow regulation of another variable (HP pressure, for instance), as suggested in Peralez et al., 2014. However, contrary to long-haul truck applications, where ORC systems are most often designed for operation at roughly one third of engine full load (corresponding to flat highway conditions), see for instance Espinosa et al., 2010, the ORC system under investigation is optimized for use at engine full load. Thus, the usefulness of a control loop acting on the proportional evaporator bypass valve to regulate pressure at evaporator (fluid) outlet is very limited in this context.

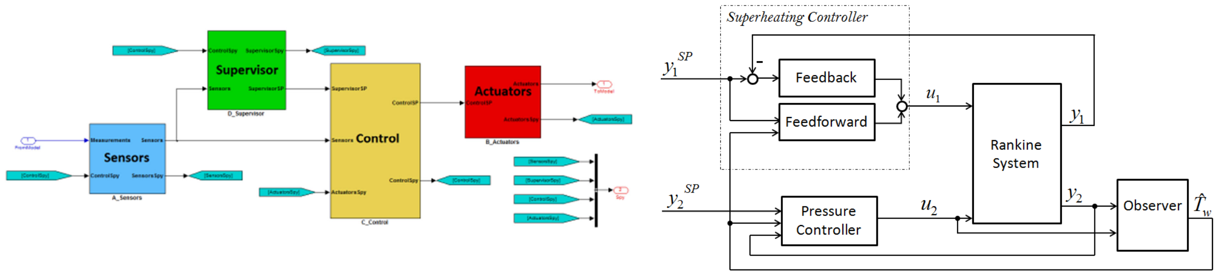

Figure 8: Global supervision and control system in Simulink (left) and decentralized control loops layout (right)

Based on these considerations, in the global supervision and control system in Simulink (figure 8), only the first decentralized control loop (the superheat controller of figure 8, where $u_1 = N_{pump}^{SP}$ and $y_1 = SH$) has been implemented so far. The superheat controller is made of two parts. The feedback part is a gain scheduled PI controller where for the feedforward part two solutions are available: a static feedforward, heuristically calibrated, and the model-based feedforward, presented in Peralez et al., 2013. A first calibration of the gain scheduled PI controller can be directly obtained using a dynamic ORC simulator, based on moving-boundary modeling of heat exchangers coded in Modelica/Dymola, coupled to the control system coded in Simulink. However, a thorough system identification campaign on several operating points is required to obtain an accurate representation of ORC dynamic behavior and finalize controller calibration.

5. EXPERIMENTAL RESULTS

5.1 Relevant results in steady-state conditions

Figure 9 presents the best results on the maximum power engine point (>300kW) for each ORC configuration tested. For confidentiality reasons, the heat power recovered from exhaust gases and the electric power produced at the output of the ORC turbine generator are normalized in reference to the first configuration using R245fa fluid without regenerator. The different bars of the graphs correspond to the different steps of the ORC improvements by the means of the fluid, extra exchanger, mass fluid and boiler optimizations.

The first level of optimization consisted in changing the working fluid from R245fa to fluid B and adding the regenerator. The turbine blades were changed and optimized for the use of fluid B. The chart shows a significant improvement (+22%) on the heat power recovered from the exhaust gases. Thanks to a special shape in its Mollier diagram, fluid B is specially adapted to run with an intermediate exchanger (regenerator) upstream the boiler. Indeed, this exchanger allows pre-heating the pressurized working fluid in liquid state upstream the boiler (the HP branch) with the hot working fluid in vapor state downstream the turbine (the LP branch). The drawbacks of using such exchanger are the extra mass of working fluid (cost issue) and the rising complexity of ORC control. In this project, we estimate the increase of the mass working fluid around 18% leading to an 15% extra cost of the total ORC fluid cost. This 15% increase cost has to be compared to the 40% ORC electricity production enhancement allowed by this intermediate exchanger and the use of this new fluid B.

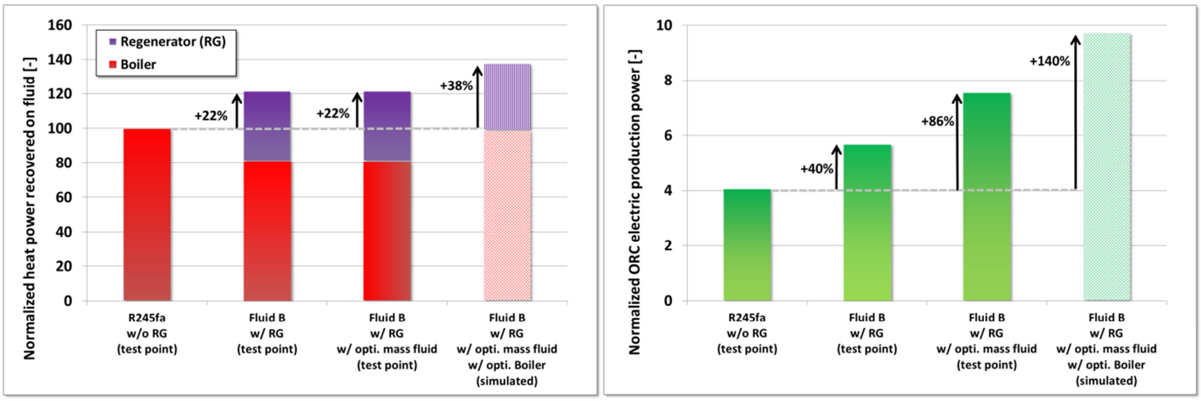

Figure 9: Tests results at max. power engine for different ORC configurations in terms of normalized heat power recovered on the fluid and ORC electric production power

The second step was to optimize the mass of working fluid inside the ORC. This operation is needed to avoid pump cavitation in case of fluid lacking or to avoid non optimized fluid liquefaction in the condenser in case of fluid overload. Furthermore, this optimized working mass fluid allows to maximize the thermodynamic efficiency of the cycle by establishing the optimized pressures in the LP and HP branches. The last step is still ongoing and the tests have not yet been done. Calculations have predicted that with an optimized boiler with higher exchange surface, exhaust gas heat recovering can be improved by 38% compared to the first configuration and ORC electric power output increased by 140%. The tests are still on-going and at the time of paper writing, more than 150hours of ORC operation have been carried out and 600 operating points (steady-state or transient) have been recorded. As a significant achievement, around 10kW of electricity power produced by the ORC turbine generator have been measured continuously in the last tests.

5.2 Boiler hunting

In this project, among all the technical challenges that have been taken up, the boiler has shown sometimes an unstable behavior in steady-state thermal conditions. Indeed, with stabilized constant exhaust gas and working fluid mass flows, temperature periodic oscillations can appear downstream the boiler. This phenomenon is well-known in refrigerating applications like described by Mithraratne et al., 2002, with diphasic exchangers and it has been called "boiler hunting". More recently, Yuh-Ren et al., 2014, faced the same problem with an ORC using R245fa. In this project, we observed the boiler hunting for both working fluids R245fa and fluid B (see figure 10) with the same boiler but with different signal properties. The signal period were respectively 40s and 17s whereas peak amplitude were respectively 8°C and 6°C for R245fa and fluid B. As a remark, temperature sensors accuracy is around ±0,5°C. Until now, no consistent scientific explanation exists justifying such behavior. Some scientists assume that the phenomenon depends on the working fluid characteristics and on the boiler internal geometry. This abnormal behavior must be avoided to ensure a robust and consistent ORC control in transient conditions.

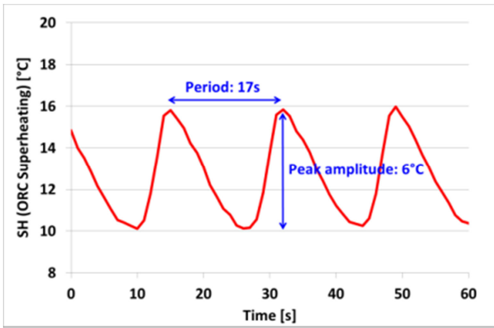

Figure 10: ORC superheating oscillations in steady-state conditions (T, P) after the boiler for fluid B

6. CONCLUSIONS

This pre-industrial project has succeeded in building an operational ORC prototype for a train application by merging the skills of IFPEN and ENOGIA. A pre-sizing study allowed to identify the exergy potential on a realistic train mission profile and the optimal recovery system location provided by ALSTOM TRANSPORT. Then, the screening fluid allowed to choose 2 suitable working fluids for this application considering all the safety, thermodynamic and cost constraints. The expected results were evaluated by simulation. The ORC prototype was built by ENOGIA by selecting the optimal components and respecting a limited volume for further train integration. The prototype has then been implemented at the test bench at IFPEN. An ORC control has been deployed using the know-how of IFPEN previous experiences on Rankine systems. These tools work with the help of exhaustive measures of temperature, pressure and mass flows allowing to evaluate in real-time conditions the energy balance of the whole ORC system. Experimental results showed the high increase of waste heat recovery and electric produced power after each improvement step along the project duration. The change of fluid and the addition of the regenerator increased the electric production by 86% compared to the first configuration. At the time of paper writing, around 10kW of ORC electricity output power has been reached in stable conditions and more than 150h of testing have been carried out. Further improvements should be attainable.

NOMENCLATURE

DPF	Diesel Particulate Filter
GWP / ODP	Greenhouse Warming Potential / Ozone Depleting Potential
IFPEN	IFP Energies nouvelles
NIST	US National Institute of Standards and Technology
ORC	Organic Rankine Cycle
SH/SC	SuperHeating/SubCooling
WHR	Waste Heat Recovery

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