STUDY OF A VOLUMETRIC EXPANDER SUITABLE FOR WASTE HEAT RECOVERY FROM AN AUTOMOTIVE IC ENGINE USING AN ORC WITH ETHANOL

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ABSTRACT

Waste Heat Recovery in exhaust gas flow of automotive engines has proved to be a path to increase the overall efficiency of automotive vehicles. Recovery potential of up to 7% are shown in several works in the literature. However, most of them are theoretical estimations. Some of them presents results from prototypes fed by steady flow generated in an auxiliary gas tank and not with actual engine exhaust gases.
This paper deals with the simulation model of a volumetric expander, integrated in an ORC mock-up, coupled to a 2 l turbocharged gasoline engine and using ethanol as working fluid. An experimental facility of an ethanol ORC using a swash-plate expander coupled to an Ecoboost 2.0 engine has then been used to correlate it.
The target is to understand the physical phenomena which are not predictable by simulation and can only be observed by experimentation and secondly, to carry out some parametric studies showing the potential for optimizing different elements of the expander machine.

1. INTRODUCTION

In the last years, the interest in improving energy efficiency in reciprocating internal combustion (ICE) engines of vehicles has increased, together with the entry into force of ever more stringent anti-pollution regulations. Many of these works are focused on the development of new technologies to recover waste heat from IC engines. Saidur et al. (2012) propose four different groups to classify these technologies: the thermoelectric generators (TEG) (Yang, 2005), organic Rankine cycles (ORC) (Apostol et al., 2015), six-stroke cycle IC engine (Conklin & Szybist, 2010) and new developments on turbocharger technology (Dolz et al., 2012) and (Serrano et al., 2012). The turbocharging technology has been deeply developed for vehicle IC engines in recent decades. In fact, turbochargers are used in practically all Diesel engines used in automotive vehicles. Regarding other present technologies and considering this classification, ORC technology is one of the most promising because of its implementation in the near future engines. ORC technology to recover low-grade heat sources has been wildly developed in biomass, geothermal or solar power plants and also in combined heat and power (CHP) in industrial processes. There are many studies about these facilities, both theoretical and experimental. Some of these theoretical studies describe mathematical models in different ORC facilities for the recovery of these low temperature heat sources. Table 1 presents a summary of several studies with the main characteristics of the described models.

Table 1: Summary of papers about ORC modeling

Reference	Model features	Software	Max. Power	Working fluid
(Bracco et al., 2013)	ORC with a scroll expander	AMESim	1.5kW (mechanical)	R245fa
(Lecompte et al., 2013)	ORC for CHP with a volumetric expander	Matlab with RefProp	207kW (output)	R152a, R1234yf, R245fa
(Manente et al., 2013)	Dynamic ORC model with a turbine	Matlab (Simulink)	8MW (net power)	Isobutene and R134a
(Quoilin et al., 2010)	ORC with a scroll expander	EES	1.8kW (mechanical)	HCFC-123
(Wei et al., 2008)	Dynamic ORC model with a turbine	Modelica and Dymola	100kW	R245fa
(Ziviani et al., 2014)	ORC with a scroll expander	AMESim	2.16kW (mechanical)	R245fa
(Carlos et al., 2014)	scroll expander	-	260W (mechanical)	air and ammonia
(Cipollone et al., 2014)	sliding vane rotary expander	-	2kW (mechanical)	R236fa
(Ferrara et al., 2013)	reciprocating expander	WAVE and EES	2.26kW (output)	water
(Giuffrida, 2014)	scroll expander	Matlab with Refprop	2kW (mechanical)	several fluids
(Lemort et al., 2009)	scroll expander	-	1.8kW (mechanical)	HCFC-123
(Wenzhi et al., 2013)	reciprocating expander	Matlab (Simulink)	11.5kW (output)	water

At present, some studies try to adapt this technology to waste heat recovery (WHR) on vehicle IC engines. In these engines, space and weight restrictions are higher than in industrial installations, which greatly hinders their adaptation. On the other hand, the thermal power available in these engines for WHR is lower than in industrial processes. So the optimized expander, mass flows and working fluids for heat recovery in IC engines can be different than the options considered in other applications. Typically, the expanders used in industrial ORC facilities are turbines, screws, scrolls or rotary vane expanders (Qiu et al., 2011). However, ORC design for automotive engines generally presents a reciprocating machine as the optimal solution to recover waste heat energy into mechanical energy, due to low working fluid flow, high values in expansion ratios and space restrictions.

Regarding the working fluids, ethanol is considered by several authors as a promising fluid due to its good features in the temperature range of a vehicle application (450ºC-100ºC). Although ethanol is positively evaluated taking into account environmental, thermo-physical properties and cost features, it has been classified as serious hazard by NFPA due to its high flammability. (Seher et al., 2012) concluded that ethanol is one of the most favorable solution when a reciprocating machine is used as expander. (Howell & Gibble, 2011) selected ethanol as the best working fluid for a successful ORC for a HD truck.

Despite of these theoretical studies, where the ethanol has proven to be the most suitable working fluid for this type of installations, experimental ORC works with this fluid have not been published due to the flammability properties. Therefore, it is necessary to take safety measures to prevent accidents arising from the use of this fluid.

In previous studies, some methodologies to design these cycles for vehicle IC engines have been proposed (Macián et al., 2013) and applied to define the main characteristics of an ORC facility for WHR in automotive IC engines. This experimental facility has been assembled and tested in order to estimate the viability of this technology. This installation uses a swash-plate reciprocating expander to recover heat losses into mechanical energy and ethanol as working fluid. The main objective of this paper will consist in describing and validating a model in AMESim of this facility in order to evaluate the main thermo-physical magnitudes of these cycles.

2. SYSTEM LAYOUT

As the expander is the most innovative element of these cycles the description of this system layout has been divided in two parts: first part, where a general ORC layout is described and a second part, where the expander is characterized.

2.1 Organic Rankine Cycle layout

In order to perform an experimental evaluation of this system, an ORC test bench was designed and built at CMT-Motores Térmicos in Universitat Politècnica de València (
Figure 1) in a research project with the companies Valeo Systèmes Thermiques and Exoès. This facility can be coupled to different types of automotive combustion engines (an automotive diesel engine, a Heavy Duty diesel engine and an automotive petrol engine). The test bench recovers energy from exhaust gases of a turbocharged 2 l gasoline engine and exchanges thermal energy to the ethanol side.

Figure 1: ORC mock-up

Figure 2 shows the most relevant components of the ORC mock-up. The running principle is as follows: engine exhaust gases pass through the boiler to the working fluid, in this case, ethanol. Then, it is pumped into the high pressure loop and then is evaporated in the boiler and slightly superheated. Thus, working fluid under high temperature and high pressure is generated. After that, the vapor flows into the expander where enthalpy is converted into effective work measured by a torque measuring unit. Low pressure vapor is extracted from the expander and flows to the condenser, reducing its temperature by cooling water and producing condensed ethanol. Therefore, the cycle starts again. The ORC cycle contains as main elements: a boiler, a swash-plate expander, a condenser, a fluid receiver, a subcooler, an expansion vessel and a pump. The main elements have been carefully insulated to avoid heat losses to the ambient. The thermodynamic properties of the ethanol (pressure and temperature) have been measured upstream and downstream of all components, verifying energy balances and power estimations. Table 2 synthesizes the absolute uncertainties of all the sensors installed in the ORC mock-up.

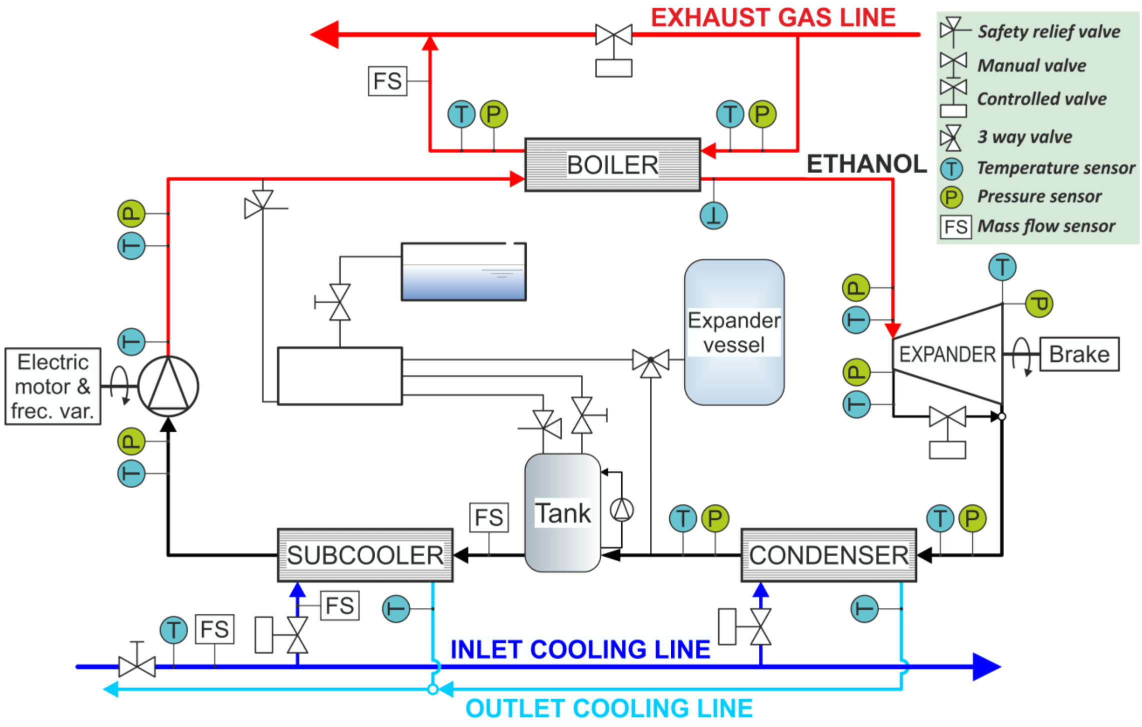

Figure 2: ORC scheme

Table 2: Range and accuracy of sensors

	Measurement principle	Range	Accuracy
Exhaust gas pressure	Piezoresistive	0-2 bar	0.05% FS
Ethanol high pressure loop	Piezoresistive	0-50 bar	0.05% FS
Ethanol low pressure loop	Piezoresistive	0-5 bar	0.05% FS
Temperatures	K-type thermocouples (Class 2)	(-270)-(1,372)K	±2.5°C
Ethanol flow meter	Coriolis flow meter	0-2,720 kg/h	±0.1%
Water flow meter	Electromagnetic flow sensor	0.3-1 m/s	±0.5% of rate
Expander rotational speed	Optical tachymeter	0-20,000 rpm	±1 rpm
Expander torque meter	Strain gauges	0-200 Nm	0.05%FS

2.2 Swash-plate expander layout

The expander machine used in this installation is a Swash-plate expander. Lower flow rates and higher expansion ratios could be reached in this machine, thus displacement expanders are considered the main technology for recovering waste heat from low temperature sources and low expander power in vehicle applications. The geometrical features of the expander are listed in Table 3 and
Figure 3 shows a picture of the Swash-plate expander delivered by Exoès.

Table 3: Swash-plate characteristics

Swash-plate characteristics		
Pistons number	3	
Bore	40	mm
Stroke	31	mm
Maximum expander speed	4500	rpm

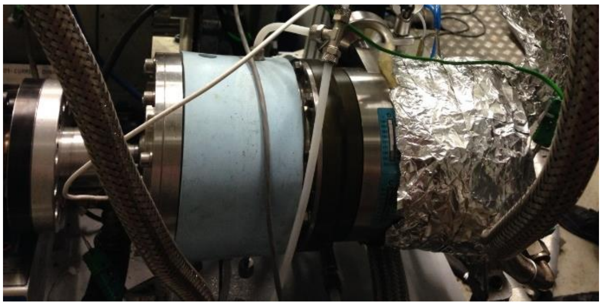

Figure 3: Swash-plate expander delivered by Exoès

The expander performance has been characterized through the calculation of the indicated diagram (P-V). One AVL GU13P piezoelectric pressure sensor was placed on the chamber of one of the pistons to evaluate the pressure variations. It allows tracking pressure variations during filling and emptying processes. The piezoelectric transducer was connected to a Kistler 5015 charge amplifier. The pressure-volume diagram is used to describe changes of volume and pressure of a system. A swash-plate expander is a positive displacement machine. It works as a two stroke machine, which means that during one revolution, with a piston movement from the Top Dead Centre to the Bottom Dead Centre and back again, one working cycle is completed. The superheated steam flows through the intake valve into the cylinder whose piston is near top dead center. Moving the piston downwards, the steam expands and lead out by exhaust ports in the cylinder (slits) situated near the bottom dead center. Finally, the upmoving piston closes the exhaust ports and compresses the steam remained in the cylinder and the cycle starts again. Furthermore, a TDC sensor is used to know the position of the BDC. TDC is an eddy current-Sensor which delivers a signal correlating to the distance between sensor and the swashplate. The piezoelectric pressure signal has been referenced using low frequency measurement (piezoresistive sensor). The analysis of P-V diagrams in different expanders could be very convenient to evaluate possible irreversibilities and improvements in the expansion machine. All the signals were recorded with a sampling frequency of 50 kHz and processed with Labview program. Each cycle was obtained as an average of at least 30 cycles to avoid dispersion in measurements.

3. MODELLING

A comprehensive theoretical model of both the Organic Rankine Cycle and the Swash-plate expander has been developed by the authors using AMESim®. The software package provides a 1D simulation suite to model and analyze multi-domain intelligent systems, and to predict their multi-disciplinary performances. This software consists of available object-oriented libraries, where the user should connect them properly and fix the parameters. The purpose of these models will be: Firstly, it should be used to help the understanding of those physical phenomena which are difficult to observe by means experimentation and secondly, in order to estimate the behavior of the cycle without the need for experimental tests under operating conditions that may cause danger to the installation and / or people. Both models have been validated using tests measured in the mock-up.

3.1 Organic Rankine Cycle model

A simple layout of the ORC consisting of a boiler, a positive displacement pump, a volumetric expander, a fluid receiver, a condenser and an expansion vessel is considered in this model.

Figure 4 shows the AMESim® model of the cycle based on the ORC installation. A detailed description for modelling each component will be presented in the following subsections.

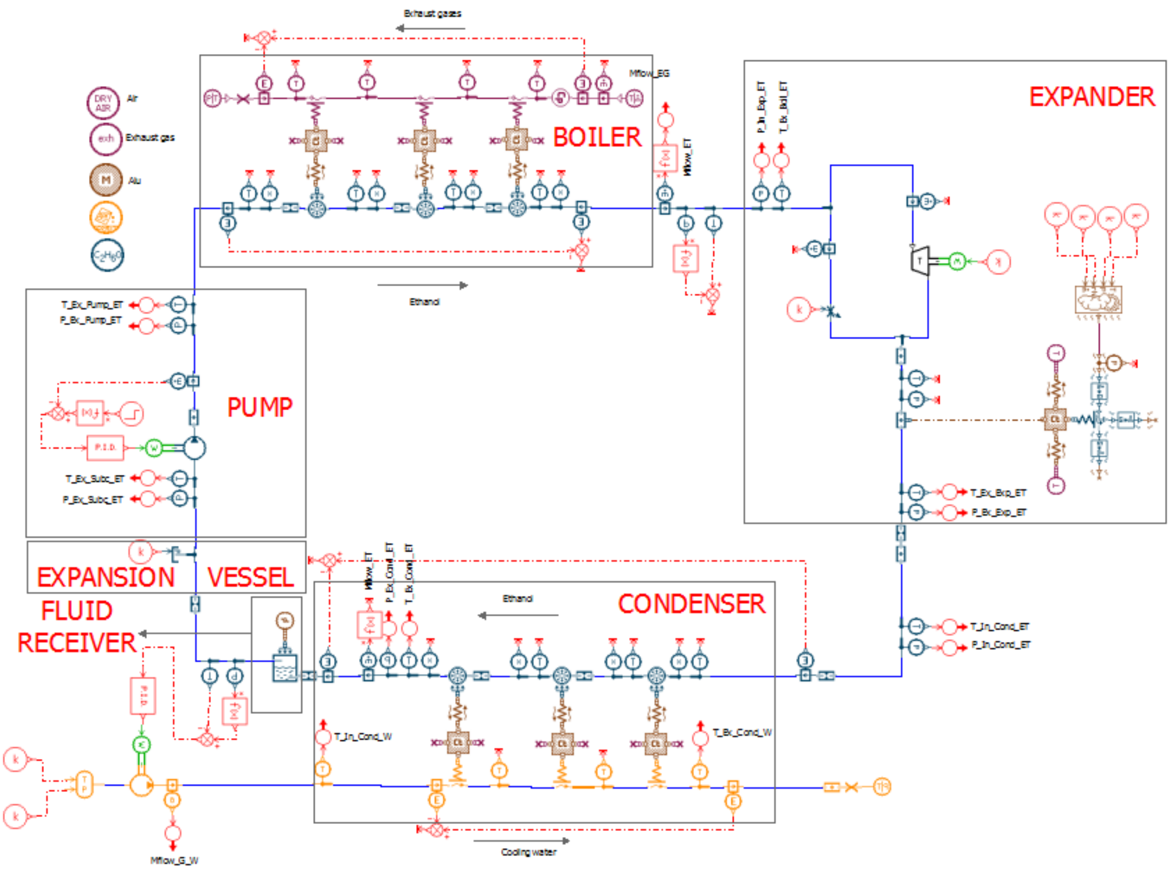

Figure 4: Organic Rankine Cycle model

3.1.1 Working fluid: In the modelling of a particular working fluid it is crucial to be able to reproduce both the thermodynamic and transport properties of the working fluid. AMESim® provides built-in physical-thermo property data of different fluids. In this case the working fluid is ethanol, which is considered by several authors as a promising fluid due to its great features in energy recovery aspect in the temperature range of a vehicle application. Table 4 summarizes the main characteristics of the working fluid.

Table 4: Properties of Ethanol

Chemical structure		C_2H_6O	
Critical Temperature	T_c	240.9	°C
Critical pressure	P_c	61.4	bar
Atmospheric boiling point	T_b	78.3	°C
Ozone depletion potential	ODP	0	-
Global Warming Potential	GWP	n/a	-
NFPA health hazard	H	2	-
NFPA flammability hazard	F	3	-
Auto ignition temperature	T_{ign}	363	°C

3.1.2 Heat Exchangers: The boiler ensures the heat transfer from exhaust gases to working fluid, based on plate and fin technology. A prototype was specifically designed for this application supplied by Valeo Systèmes Thermiques. The condenser and the subcooler are plate and fin heat exchangers chosen among industrial residential products. Plate and fin technology is preferred by the vast majority of the applications due to its compactness and high level of efficiency.

A 2D discretization model of both elements (boiler and condenser) is represented by a two-counter flow streams. In the case of the boiler, the exhaust gases and the ethanol represents the hot and cold source respectively. In the case of the condenser, the ethanol and the refrigerant (water) represent the hot and cold source respectively. In each element the volume has been divided in 3 small volumes, which in global terms exchanges the net thermal power of the global element. The heat exchange process takes into account both convective and conducting (just in longitudinal direction) process. Depending on the process (boiling or condensation) different correlations implemented in AMESim® have been taken into account.

3.1.3 Volumetric expander: The Swash-plate expander is the main element of the ORC system because it has a great impact in the overall system efficiency. Several tests have been done using turbines and expanders, most of them corresponds to scroll expanders and rotary vane ones. Between reciprocating machines, swash-plate expanders are increasingly taking into account due to its versatility and compactness. Swash-plate expanders could work with high pressure ratios, low flow regimes, lower rotational speeds and could tolerate fluid drops during its expansion. The expander model uses three parameters to characterize the performance of the expander, i.e. isentropic efficiency in Equation (1), mechanical efficiency in Equation (2) and volumetric efficiency in Equation (3).

$$\eta_{iso} = \frac{P_{ind}}{P_{iso}} \tag{1}$$

$$\eta_{mec} = \frac{P_s}{P_{ind}} \tag{2}$$

$$\eta_{vol} = \frac{\dot{m}_{ET}}{\rho_{ET} * N_{Exp} * Disp} \tag{3}$$

$$P_{iso} = \dot{m}_{ET} * \left(h_{in\_Exp\_ET} - h_{out\_Exp\_ET\_iso}\right) \tag{4}$$

$$P_{ind} = W_{cyl} * n_{cyl} * N_{Exp} * \frac{1}{60} \tag{5}$$

$$P_s = T_{Exp} * N_{Exp} \tag{6}$$

Where P_{iso} , P_{ind} and P_s are isentropic, indicated and shaft power respectively. They have been calculated using Equation (4), (5) and (6) respectively, where $\dot{m}_{ET}$ is the mass flow through the expander, $h_{in\_Exp\_ET}$ is the enthalpy at the inlet of the expander (calculated by using temperature and pressure at the inlet), $h_{out_Exp_ET_{iso}}$is the isentropic enthalpy at the outlet of the expander (calculated by using pressure at the outlet and entropy at the inlet), W_{cyl} is the energy extracted from the system (calculated by integrating P-V diagram), N_{Exp} is the expander speed and n_{cyl} the number of cylinders of the expander. Regarding the volumetric efficiency, ρ_{ET} is the density of the ethanol at the inlet of the expander and Disp is the volume displaced by the expander.
No leakages and internal pressure drops have been taken into account in this expander model. Thermal conduction with internal walls of the swash-plate expander is considered to consider heat losses to the ambient.

3.1.4 Pump: A fixed displacement pump is used in this model. The mass flow rate is obtained from volumetric efficiency. The enthalpy increase is defined by the mechanical and isentropic efficiency and the swept volume. No correlations have been considered for efficiencies. Instead, some fixed values were specified for the points simulated.

3.1.5 Pipes and pressure drops: Internal piping losses in the system have been taken into account using hydraulic resistances. The transformation process is pretended to be isenthalpic. Using these elements both enthalpy and mass flow are computed.
Pressure drops in the system have been calculated using correlations available in AMESim®. The hydraulic diameter and the cross-sectional area were used to model different cross-sectional geometries. The pressure drops are regular and the friction factor depends on the flow regime and the relative roughness of the duct. Depending on the state of the fluid different correlations were applied: In a single phase flow (liquid or vapour) the Churchill (Churchill, 1977) correlation is used, while in a two phase flow correlation the user can choose between Mac Adams (McAdams, W.H., Woods, W.K., and Bryan, 1942), Cichitti (Cicchitti, Lombardi, Silvestri, Soldaini, & Zavattarelli, 1959), Dukler (Dukler, A.E., Wicks, M., and Cleveland, 1964), Friedel (Friedel, 1979) and Muller-Steinhagen-Heck (Müller-Steinhagen & Heck, 1986). In this case the Mac Adams correlation was implemented.

3.1.6 Expansion vessel: The expansion vessel is modelled using a tank with modulated pressure and constant specific enthalpy. The user must specify the low pressure value with a constant.

3.2 Swash-plate expander model

As shown in section 3, the volumetric expander tested in this installation is a Swash-plate expander. Although in the global ORC model an AMESim® submodel of the TPF library was used for modelling the expander using volumetric, isentropic and mechanical efficiencies, the need for a physical model of the expander has led to the development of a specific model for just the Swash-plate expander. Figure 5 shows the particular model of the Swash-plate expander in AMESim®. This model could be used as a design and optimization tool in future developments.

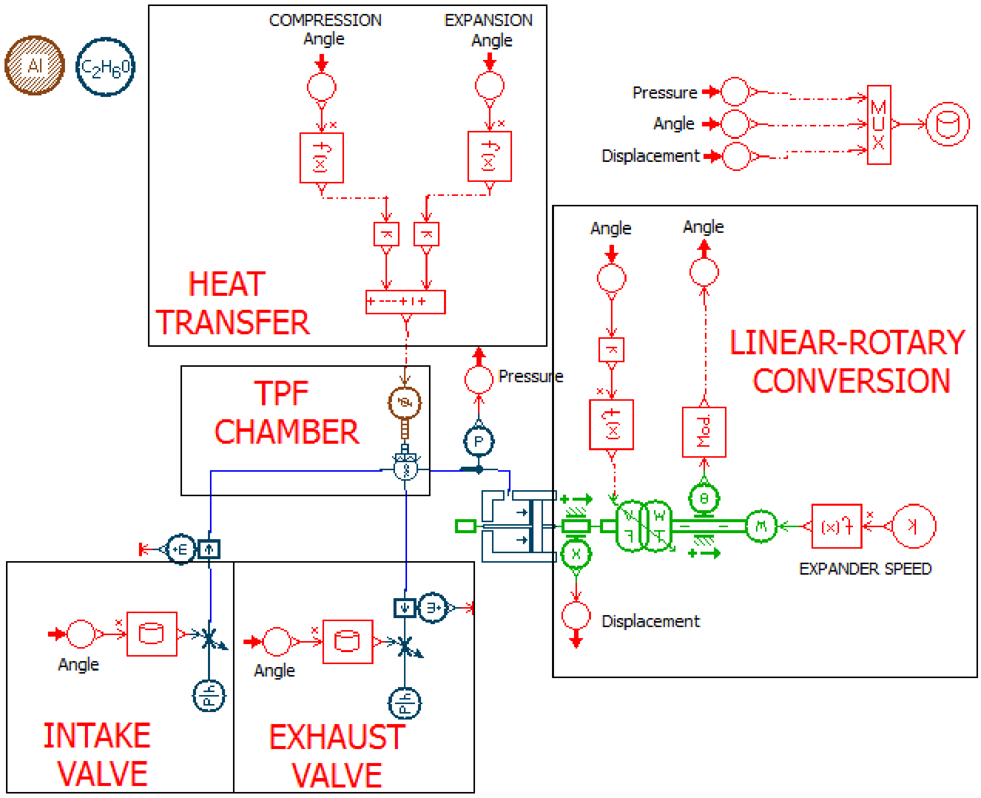

Figure 5: Swash-plate expander model

The fluid dynamic behavior of the Swash-plate was modelled using AMESim® and validated with the experimental tests developed in the expander. The comparison between P-V diagrams (simulated and tested) was used to quantify the error and accuracy of the model.

The main part of the model consists of a two phase flow chamber with variable volume and pressure and temperature dynamics. This submodel was modified respect the original model of the AMESim® library to take into account heat transfer during compression and expansion. The filling (Intake) and emptying (Exhaust) valves provide the mass and pressure exchanges during the process. The angle signal (obtained from the expander speed) is used in three parts of the model:

- In the heat transfer element: Although the expander was insulated, the expansion and compression process never follows an adiabatic law. The transformation is rather polytropic with a heat exchange between the working fluid and the expander walls due to friction, temperature differences and possible condensation effects in the piston chamber. Therefore, the angle signal was used to consider the angles of compression and expansion and to apply for each process a heat transfer coefficient.
- In the valves: The angle was considered to take into account the discharge coefficient for the intake and the exhaust valve at each particular angle. Thus, the valves were modeled as orifices with constant area and variable discharge coefficient.
- In the rotary-linear transformer: It was considered to calculate the absolute displacement in Equation (7) and therefore the volume variation in Equation (8) of the piston as a function of the Swash-plate angle.

$$X(\Phi) = R_{sw} * (1 - \cos(\Phi)) * tan(\alpha_{sw}) \tag{7}$$

$$V(\Phi) = V_d + \pi * \frac{A^2}{4} * X(\Phi) \tag{8}$$

Where R_{sw} is the radius of Swash Plate (m), α_{sw} is the swash plate angle (°),Φ is the angle covered by the piston, V_d is the dead volume (m^3), A is the bore (m), $X(\Phi)$ is the displacement of the piston (m) and $V(\Phi)$ is the volume of the piston (m^3). No leakages effects have been modelled.

4. RESULTS

4.1 Organic Rankine Cycle results

In order to characterize the ORC system three points have been tested at different steady working conditions of the ORC system. The points presented in this study aims to show the recovery features at different expander operating points. In these tests, the system has been controlled commanding three parameters: the speed of the pump, in order to control the mass flow of ethanol flowing through the installation, the balloon pressure of the expansion vessel, in order to control the outlet pressure of the expander, and the expander speed, in order to control the high pressure at the inlet of the expander.

These points correspond to a heat exchange in the boiler of 25 kW and three conditions of expander (expander speed of 2000, 2500 and 3000 rpm). Table 5 shows the inputs of the ORC model. For each point (P1, P2 and P3), the mass flow of the expander, the pressure at the inlet of the pump, the expander speed, the temperature at the inlet of the boiler at the EG side, the pressure at the boiler at the EG side, the mass flow of the EG and the temperature at the inlet of the condenser at the water side were fixed.

Table 5: Inputs of the ORC model

	P1	P2	P3	Units
Mf_ET	73.85	75.99	74.79	kg/h
P_in_P_ET	1.571	1.899	1.589	bar
N_Exp	2001	2502	3003	rpm
T_in_B_EG	749.48	740.28	748.92	°C
P_out_B_EG	1.018	1.024	1.018	bar
Mf_EG	154.98	159.47	155.25	kg/h
T_in_C_W	48.42	49.01	47.58	°C

Table 6 shows the volumetric, the isentropic, the mechanical efficiency (calculated using Equation (1),(2) and (3)) and the global efficiency of the expander (defined by the isentropic efficiency times the mechanical efficiency). They have been fixed in the model.

Table 6: Experimental efficiencies of the Swash-plate expander

	P1	P2	P3	Units
P_ind	1739	2007	1874	W
P_mec	1649	1543	1531	W
P_iso	3431	3413	3338	W
η_vol	19.37%	17.21%	14.54%	-
η_iso	50.68%	58.81%	56.14%	-
η_mec	94.81%	76.90%	81.72%	-
η_glob	48.05%	45.22%	45.88%	-

Table 7 presents the outputs of the model for the three points tested. For each point three columns are presented, the first one, called "P_i Exper.", corresponds to the experimental values, the second one, called P_i Sim., corresponds to the simulation values and the last one, called Error, corresponds the absolute error between both values. Temperatures are given in ºC, pressures in bar, torque in Nm and pump speed in rpm. As regards temperatures, the maximum deviation corresponds to the temperature at the inlet of the expander at medium expander speed (2500 rpm), with a value of 3.28%. The remainder temperatures of the cycle are obtained with an error lower than 3%. Regarding pressures, the maximum deviation corresponds to the pressure at the inlet of the condenser, with a value of 4.48%. The remainder pressures in the system are calculated with an error of 3%. The last two simulation parameters are the torque and the pump speed, in which the maximum deviation is 5%.

Table 7: Outputs of the ORC model

	P1 Exper.	P1 Sim.	Error	P2 Exper.	P2 Sim.	Error	P3 Exper.	P3 Sim.	Error
T_out_P_ET	47.39	46.39	0.31%	47.13	46.33	0.25%	48.60	46.33	0.70%
T_out_B_ET	210.23	208.65	0.33%	215.14	199.12	3.28%	208.29	201.34	1.44%
T_out_Exp_ET	104.74	116.21	3.04%	109.14	107.23	0.50%	111.05	109.89	0.30%
T_in_C_ET	103.79	102.55	0.33%	103.41	99.06	1.16%	102.26	97.12	1.37%
T_out_C_ET	48.27	48.58	0.10%	47.95	48.51	0.17%	47.88	48.60	0.22%
T_in_P_ET	46.67	45.76	0.28%	46.51	45.76	0.23%	47.47	45.76	0.53%
T_out_C_W	73.85	71.39	0.71%	67.25	69.03	0.52%	72.88	71.55	0.38%
P_out_P_ET	34.26	34.26	0.01%	31.01	31.48	1.51%	31.77	31.16	1.92%
P_in_Exp_ET	28.65	29.57	3.20%	27.00	26.53	1.74%	26.01	26.36	1.33%
P_in_C_ET	1.89	1.89	0.20%	2.01	2.10	4.48%	1.90	1.88	0.95%
T	7.81	7.98	2.18%	5.86	5.59	4.47%	4.87	4.96	1.85%
N_P	300	312	3.81%	305	321	5.14%	301	316	4.94%

4.2 Swash-plate expander results

The simulated and experimental curves of the pressure variation inside the expander chamber as a function of the volume were compared for the three points tested in previous sections.
Figure 6,
Figure 7 and

Figure 8 show the comparison carried out with the three expander speeds of 3000 rpm, 2500 rpm and 2000 rpm. Red and green crosses indicate the intake and exhaust valve closing angle (or volume) respectively. Red and green circles indicate the intake and exhaust valve opening angle (or volume) respectively. It was found a quite good agreement between experimental and simulation results in terms of indicated power delivered by the expander. In the right corner of these diagrams both the indicated power and the expander speed were added. Slight differences could be found in these simulations due to pressure drop in the valves and effects of pulsating flow, which cannot be modelled in AMESim® with the Two-Phase flow library.

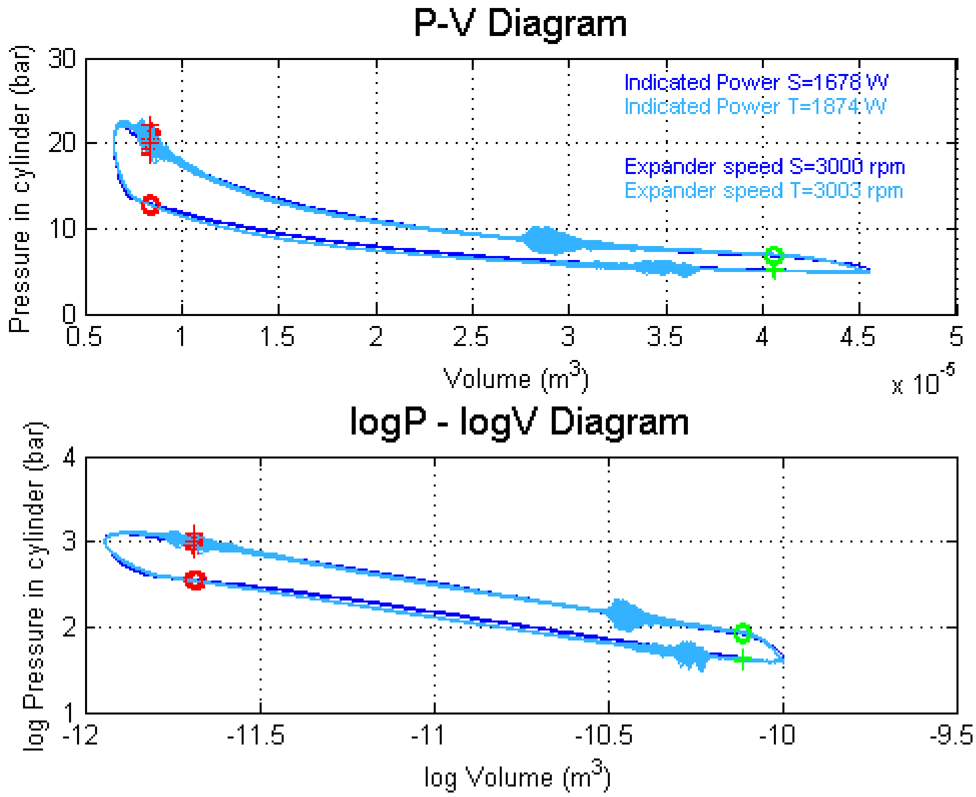

Figure 6: P-V and logP-logV Diagram 3000 rpm

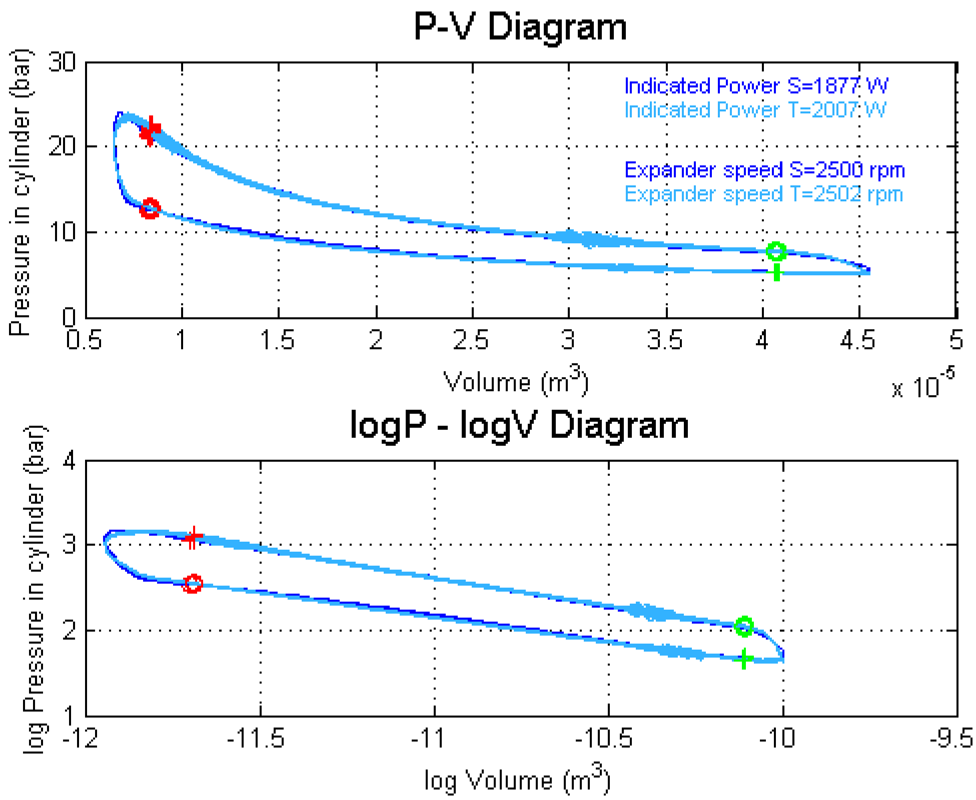

Figure 7: P-V and logP-logV Diagram 2500 rpm

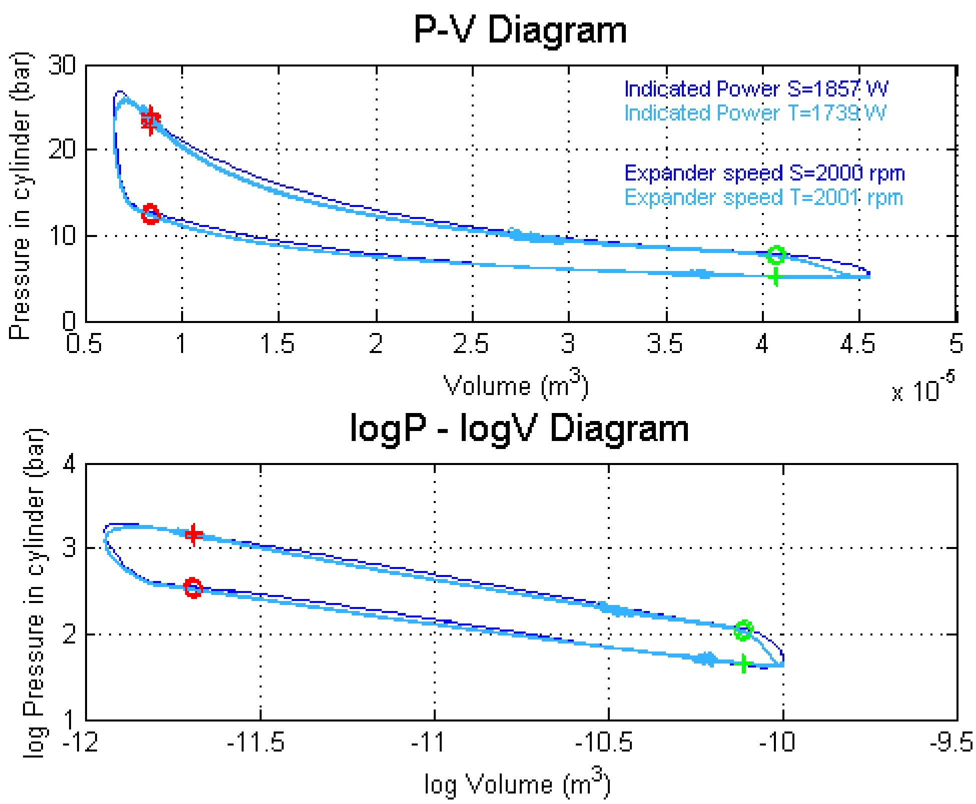

Figure 8: P-V and logP-logV Diagram 2000 rpm

Table 8 summarizes the results of the simulation. The inputs of the model were obtained from pressure measurements at the inlet of the expander and expander speed. In order to take into account differences between heat transferred in the three points, the coefficients of compression and expansion were modified. In this model the higher the expander speed is, the higher heat transfer rate should be imposed in the model. The maximum deviation of the model from measurements corresponds to 10% in the point of 3000 rpm, which is considered acceptable to predict flow behavior. Besides, the model predicts properly the filling and emptying processes as it can be seen in
Figure 6,
Figure 7 and
Figure 8.

Table 8: Results of the Swash-plate model

	P1	P2	P3	Units	I/O
P_B	25	25	25	kW	-
P_in_Exp_ET	28.65	27.00	26.01	bar	Input
N_Exp	2001	2502	3003	rpm	Input
P_ind_T	1739	2007	1874	W	-
P_ind_S	1857	1877	1678	W	Output
Error (%)	6.79%	6.48%	10.46%	-	-

5. CONCLUSIONS

The presented work describes and analyzes two models based on an experimental ORC installation installed in a turbocharged 2.0 l gasoline engine to recover waste heat in exhaust gases. These models correspond on one side to the global ORC cycle and on the other side the dynamic of the Swash-plate expander. The comparison of performance parameters have been made in three points by means of changing the inputs and obtaining the outputs of the model. The results are summarized in the following points:

- An ORC model is developed using the software AMESim®. This model allows to simulate the main parameters measured in the cycle. Comparing the three steady operating points, a maximum deviation of 4% regarding pressures and temperatures and a value of 5% regarding torque was attained.
- A Swash-plate expander model is presented using the software AMESim®. This model represents the fluid dynamic behavior of the Swash-plate using discharge coefficients, displacement laws and heat transfer coefficients. The P-V diagram was measured by a piezoelectric pressure sensor and compared to the simulation. Maximum deviation of 10% was achieved at point of 3000 rpm.

Waste heat recovery technologies seem to assume an essential role in the new regulations of the forthcoming decade. Therefore, ORC will be considered in increasingly growing markets to solve some of the actually environmental challenges, among which it can be pointed out ICEs. In these systems a large number of features should be contemplated, i.e. working fluid, heat exchangers, volumetric machine, pressure and temperature levels, etc….Thus, in order to optimize and improve these systems it is crucial the development of reliable models to avoid huge number of tests. The proposed models develop in this article using AMESim® are consistent due to its slight deviation between tests and simulation results. Thus, it could be considered a valuable tool in future ORC installed in ICEs.

NOMENCLATURE

ORC	Organic Rankine Cycle
P-V	Pressure Volume
TDC	Top Dead Center
BDC	Bottom Dead Center
T	Tested
S	Simulated
TPF	Two Phase Flow
Mf	Mass flow
N	Speed
T	Torque
P	Power

Subscript

ET	Ethanol
W	Water
EG	Exhaust Gases
P	Pump
Exp	Expander
C	Condenser
B	Boiler
in	inlet
out	outlet
iso	isentropic
ind	indicated
s	shaft
vol	volumetric
mec	mechanical
cyl	cylinder
sw	swash-plate
glob	global

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