AUTOMOTIVE HEAT RECOVERY WITH PISTON EXPANDERS AND WET FLUIDS

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EXTENDED ABSTRACT

INTRODUCTION

To date, legislation of exhaust emission levels has focused on carbon monoxide, hydrocarbons, nitrogen oxides, and particulate matter. Those still more stringent emissions regulations have caused engine manufacturers to limit combustion temperatures and pressures, thus lowering potential efficiency gains. However, future regulations will focus on CO2 emissions. It requires an increased efficiency of the Internal Combustion Engine and a move to more costly Hybrid Vehicles (HEV) [1].

As HEV technology has achieved considerable market share in recent years, Exhaust Heat Recovery (EHR) which has the potential to decrease fuel consumption without increasing emissions seems a promising technology. Coupled to fuel saving technologies for urban driving (stop-start – regenerative breaking), EHR which can spare fuel on extra urban driving, is a key technology to go further in fuel cuts.

Rankine technology seems favored for EHR by literature for its efficiency. A basic Rankine cycle (RC) is composed of a pump, an evaporator, an expander and a condenser as illustrated in figure 1.

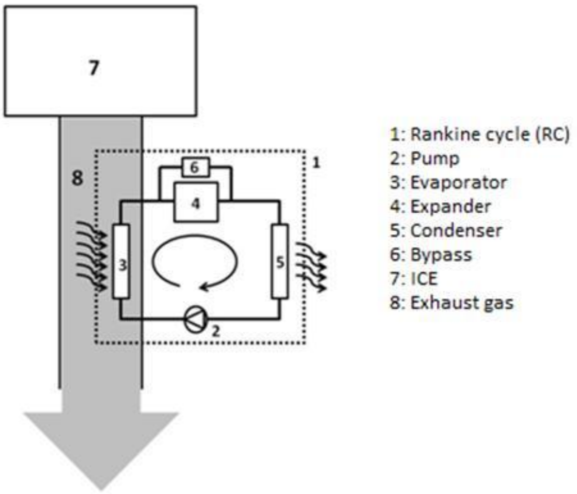


***Figure 1**: Combined cycle for vehicles*

SINGLE CYLINDER TEST EXPANDER DEVELOPMENT

A simple enthalpy model was made in order to compare fluids in the particular operating conditions of transportation. The high cooling temperature set to >60°C makes it difficult to find a good efficiency with refrigerant fluids such as R245fa. Investigations made on alcohols revealed their potential as working fluids for automotive RC. However, the most interesting fluids appeared to be “wet fluids” that would condensate during expansion and they mostly required high expansion ratios to be fully exploited. It was chosen to consider water and ethanol for further experiment. The expander technology preferred for expanding with these working fluids and with the transient behavior of the exhaust gas was the piston expander.

Demler [2] and, recently, Badami [3] suggested the use of a piston expander for EHR. Endo [4] studied HEV using HER and a piston expander. Glavatskaya [5] tested an axial piston expander and calibrated a semi-empirical model of it with a very good error below 5%.

Since 2009, Exoès has worked on piston expanders for wet fluids at high temperature. Particular attention has been paid to lubrication. High steam temperature and hydrolytic environment are major difficulties that basic lubricants cannot easily deal with. Early designs were oriented toward an oil-free single cylinder for model calibration and wear assessment. A piston rod on ball bearings links a cantilevered crankshaft to a ceramic piston. No lubrication is provided to the piston skirt. Two poppet valves for intake and exhaust are actuated by two removable cams on the crankshaft. No oil is provided on the valve guide. Separate lubrication is used for the cams contact.

This expander was manufactured in two exemplars: one for performance tests, the other for endurance tests. The test benches worked with pure water while ethanol is being considered for a second test phase.

***Figure 2**: Single cylinder test expander*

Bore B (mm)	85
Stroke S (mm)	78
Displacement volume Vc (cc)	443
Connecting rod length (mm)	170
Tot Dead Center Volume (% of displacement volume)	3,3
IVO (°CRS)	-3
IVC (°CRS)	33
EVO (°CRS)	115
EVC (°CRS)	343
max. Engine speed (rpm)	1800
Nominal supply pressure (bar)	30
Nominal exhaust pressure (bar)	0,6
Nominal steam overheating (°C)	100
Maximal electric power (kW)	3

***Figure 3**: Expander parameters*

MODEL CALIBRATION

A 0D model (figure 4 and 5) of the expander was carried out. Two parameters have to be tuned for calibration [6]. The filling factor qualifies the impact of pressure drops and leaks. The isentropic efficiency tells us how we exploit the enthalpy gradient. Tests data enabled us to calibrate a 1D model to get a map of these parameters. They are then used to run an accurate simple 0D model of the expander.

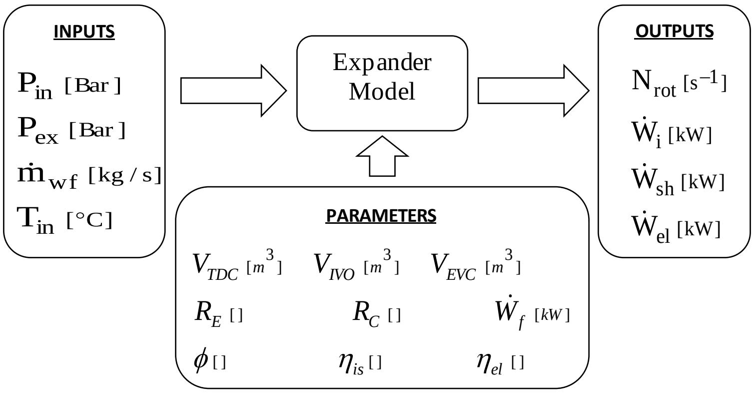
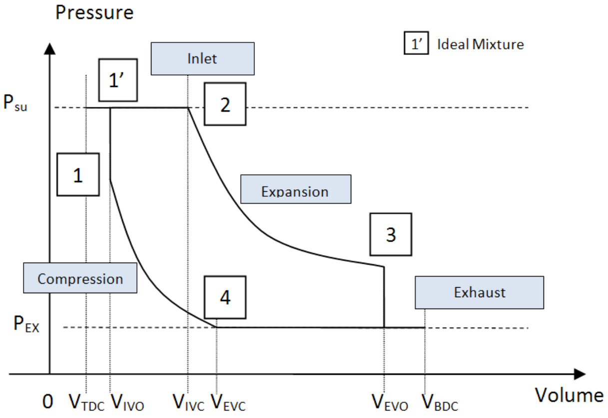


***Figure 4**: 0D model*

According to these definitions (i to iv), a perfect expander would have a filling factor equal to 1 and its isentropic effectiveness would be calculated with its expansion ratio and the inlet and exhaust conditions. Several phenomena will change these indicators: the inlet and exhaust pressure drops, the internal leakage and the heat exchange. In a piston expander, the internal leakage is composed of the leaks from the inlet to the piston chamber, from the piston chamber to the exhaust and from the piston chamber to the crankcase past the rings. To accurately estimate these effects, one would adjust the parameters on the shaft power, steam flow and exhaust enthalpy. In our experiment we lack an energy balance on the expander to define the exhaust steam quality. We did not put in a temperature controlled insulated casing. Thus we only tried to adjust on the first two variables.

To model the leaks and the heat exchange we used a 1D model to make it possible to distinguish between the different types of leaks. We developed a model on GTPower implementing Woshni equations for heat exchange on a cylinder wall at a fixed temperature equal to the one measured on the test bench. We also implemented an inlet valve model where the discharge coefficient has been calculated thanks to a CFD static simulation on Star

CCM+. GTPower basic valve model is based on the ideal gas law with constant heat capacity: we assumed it was good enough for the overheated inlet steam. We then added a leak by having a non zero discharge coefficient when the valve should normally be closed. Last, we added a constant value of annular radial clearance on the piston rings to allow a leak. We did not model leaks at the exhaust being the weakest leak of the three.



$$.\emptyset = \frac{\dot{M}_{wf}}{N_{rot}\ M_{wf,tr}}\ with: \qquad [i]$$

$$M_{wf,tr} = \rho_{wf,su}(V_{IVC} + V_{TDC}) - \rho_{wf,ex}(V_{EVC} + V_{TDC}) \qquad [ii]$$

$$.\eta_{is} = \frac{\dot{W}_{sh}}{N_{rot}} \frac{1}{\Delta H_{is}\ M_{wf,tr}}\ with: \qquad [iii]$$

$$\Delta H_{is} = H_{(wf,su)} - H_{is_{(wf\ ,P_{ex},S_{su})}} \qquad [iv]$$

***Figure 5**: 0D expander model, its parameters and equations*

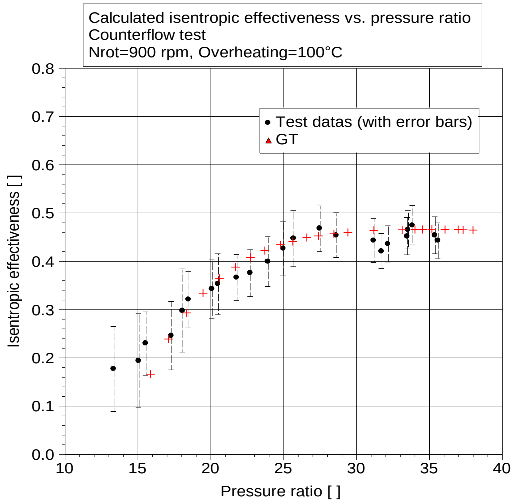


***Figure 6:** isentropic efficiency vs. pressure ratio*

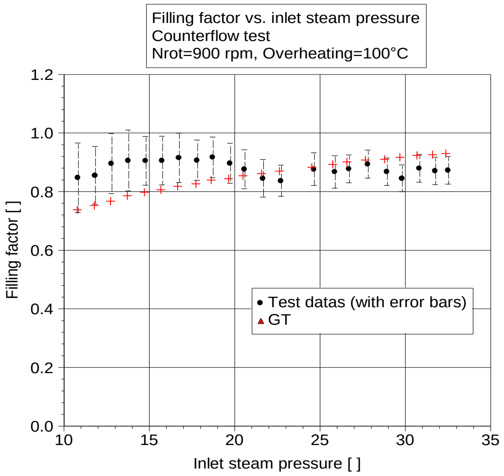


***Figure 7:** filling factor vs. inlet steam pressure*

To tune these two parameters, we first adjust the steam flow while setting a constant discharge coefficient at zero lift and then we adjust the maximal in-cylinder pressure with the ring leak. We plot together the test results and the GTPower data (figure 6 and 7). One can remark that at low inlet pressure the model does not match. The calculated filling factor and isentropic effectiveness are too low. Then we entered the two parameters obtained thanks to GTPower in our 0D model. We took a constant 85% for electrical efficiency which was measured on a dedicated bench. We achieved a ±12% error on the theoretical electrical power at high electrical output (figure 8).

TRIBOLOGY

The endurance test bench has run the piston for more than 5000km demonstrating a low oil free wear rate of 5.10^{-8} mm^3/Nm (figure 9). New design and material are presently tested to lower ten times this rate to enable maintenance free running of the expander during its whole life.

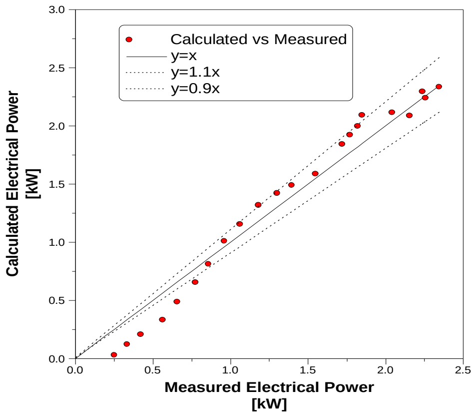


Figure 8: predicted vs measured power

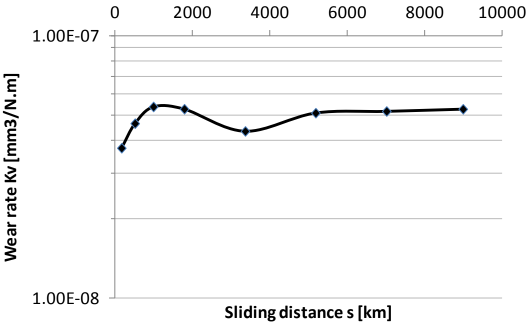


Figure 9: *Wear rate vs. sliding distance*

CONCLUSION

A better model without the ideal gas approximation and taking into account a wider range of phenomena is being built and properly calibrated.

Thanks to the valuable data collected on its test prototype and 0D model, Exoes has currently finished the design phase of a first expander prototype fully designed for vehicle integration. The first tests will occur before this summer on a new test bench including the hydraulic loop especially designed to be embedded in a vehicle.

Figure 10: 200cm^3 expander prototype

LITERATURE

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NOMENCLATURE

P: Pressure, bar
T: Temperature, °C
N: Speed, Round/s
$\dot{M}$: Flow, kg/h
$\dot{W}$: Power, kW
V: Volume, m^3
R: Ratio
H: Enthalpy, kJ/kg
S: Enthropy, kJ/kgK

Greek symbols

η	Efficiency, %
ϕ	Filling factor, -
ρ	Density, kg/m^3

Subscripts

su	supply
ex	exhaust
el	electric
rot	rotation
wf	working fluid
sh	shaft
i	indicated
f	friction
is	isentropic
E	expansion
C	compression
tr	trapped

Acronyms

IVO: inlet valve opening
IVC: inlet valve closing
EVO: exhaust valve opening
EVC: exhaust valve closing