SIZING MODELS AND PERFORMANCE ANALYSIS OF WASTE HEAT RECOVERY ORGANIC RANKINE CYCLES FOR HEAVY DUTY TRUCKS

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EXTENDED ABSTRACT

INTRODUCTION

The interest in organic Rankine cycles for waste heat recovery on internal combustion engines has grown significantly for the past few years. Indeed, in such engines, only about one third of the energy available is actually converted into effective power, what remains being dissipated into heat. Therefore, since it becomes really challenging to increase the engine efficiency itself, solutions that focus on the recovery of this waste heat are increasingly investigated to improve the energetic efficiency of vehicles. Among these solutions, Organic Rankine Cycle systems are particularly appropriate.

The adoption of such technology in the automotive domain requires a specific R&D activity to select and develop the components and identify the most appropriate system architecture. Particularly, the selection of the working fluid and of the expansion machine technology constitutes an important part of this research.

This paper attempts to address this problematic of selecting the architecture, the expander and the working fluid for a waste heat recovery organic (or non-organic) Rankine cycle on a truck engine. It focuses especially on three expander technologies: the scroll, the piston and the screw expanders, and three working fluids: R245fa, ethanol and water.

STATE OF THE ART

In the first part of this study, a state of the art that aims at highlighting the limitations in terms of rotational speed, pressure and temperature is established. It is based on information available in open access scientific literature and data coming from manufacturers as well as on the experience gained at the Laboratory of Thermodynamics of Liège in the field of expansion machines. A summary is given in table 1.

More detailed information can be found in [1].

Table 1: *Summary of the technical limitations of the studied expanders*

Expander technology	Scroll	Screw	Piston
Rotational speed [RPM]	<10000	<25000	500-6000
Max. Inlet temperature [°C]	215 [2]	490 [3]	>500 [4]
Built-in volume ratio [-]	1.5-4.1	4-5	6-14
Pressure ratio [-]	25 [5]	50 [6]	Same as in ICE

SIMULATION MODELS FOR VOLUMETRIC EXPANDERS

In the second part of this study, semi-empirical simulation models of the 3 different expansion machines are built into the EES software (Engineering Equation Solver).

These proposed simulation models retain the most important physical phenomena inherent to the expansion machine and involve a limited number of parameters (~ 10) which are identified on the basis of performance points. Studies in laboratory showed that these models are able to predict the performance of the expansion machines with good accuracy. Moreover, their semi-empirical nature enables to extrapolate the performance of the machine for different operating conditions and design characteristics (displacement, sections of the inlet and exhaust ports, etc…).

The basic model used is the one proposed by Lemort and Quoilin [6] which has been validated for the scroll expander (Figure 1). This model is well suited for the scroll and screw devices. For the piston expander, in addition, the model has to take the recompression of the dead volume into account. The resulting model is then the one developed in [7].

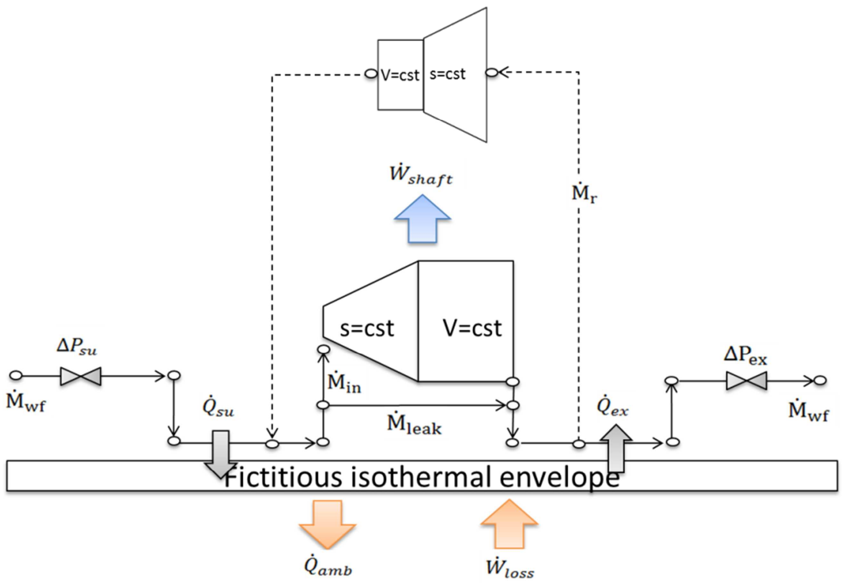

Figure 1: *Volumetric expander model [4]*

Models calibration

As mentioned above, the different parameters involved in the models are identified using measurements performed on real machines. This identification is realized for the three machines by minimizing the error between the predicted and measured values of the shaft power of the expander, of the outlet temperature of the expander and of the fluid mass flow rate.

Scaling of the parameters
The parameters obtained after calibration are the model parameters of the machines tested experimentally. To determine the model parameters of the machines being currently sized and thus adapt the models to these new machines, scaling relations on the basics of the characteristics length of the machines are used.

PERFORMANCE ANALYSIS

The expander models can then be integrated into complete cycle models. Several architectures of Rankine systems, depending on the heat sources available on the vehicle, could be studied. But in the frame of this paper, only three architectures (figure 2) using at most two heat sources (the exhaust gases and the EGR gases) are investigated.

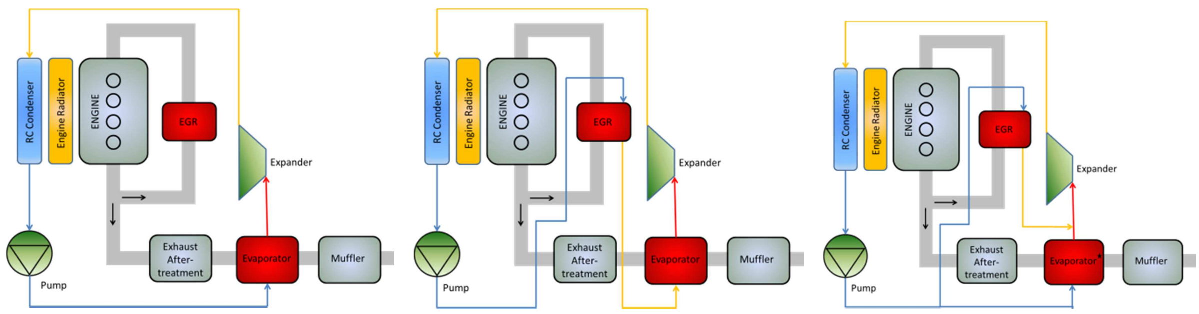

Figure 2: *ORC diagram a) without using EGR, b) using EGR as preheater and c) using EGR in parallel*

Thus, the systems can be sized and their can be predicted and compared for the three architectures, the three expanders and the three working fluids (i.e., 27 systems to compare). This comparison is achieved in the following for nominal conditions of a truck engine.

Sizing and optimization
The sizing is performed by mean of an optimization calculation. The goal of this optimization is to get for each different Rankine system (according to the architecture, expander and working fluid that are selected) the best performance in terms of shaft power. Basically, the evaporating pressure of the cycle and the rotational speed of the expanders remain the two only degrees of freedom of the system model. These values are therefore optimized, taking into account the limitations presented in the state of the art, in order to maximize the shaft power and size the systems that lead to these performance.

Results
For each architecture, the performance obtained for the different couples of expander and working fluid can be compared in terms of shaft power. Figure 3 shows the best performance reached by the three machines for the three investigated architectures.

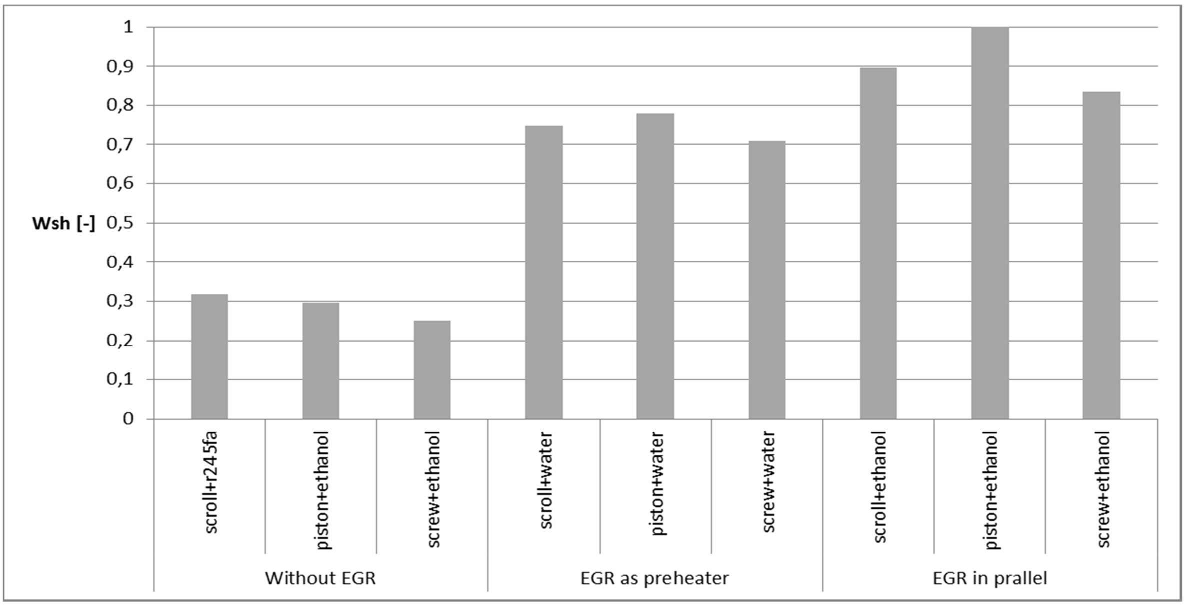

Figure 3: *Predicted shaft power of the expanders in nominal regime*

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