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Experimental investigation of four volumetric expanders

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Abstract

The aim of this paper is to facilitate the selection of the expander for a small-scale organic Rankine cycle based on an experimental comparison of a piston, a screw and two scroll expanders. First, based on a literature review, a comparison between these three technologies of volumetric expansion machines is performed. Afterward, four displacement expanders (~2kW) are tested in a small-scale ORC unit with fluid R245fa: a variable speed swashplate piston prototype, an oil-free twin-screw, a modified lubricated hermetic scroll compressor operating at a constant speed and a variable speed modified scroll compressor. The maximum effective isentropic efficiencies measured are 53% for the piston expander and the screw expander, 76% for the variable-speed scroll and 81 % for the constant-speed scroll machine. However, these performance do not reflect the highest efficiencies achievable by each expander: the test-rig has experimental limitations in terms of mass flow rate and pressure drop (among others) which restrict the achievable operating conditions. The calibration of semi-empirical models based on the measurements allows to overcome this issue and to predict the isentropic efficiency in optimal conditions despite the limitations of the test-rig. When selecting an expander, other considerations than the efficiency have to be taken into account such as the flexibility, the operating conditions, the costs and the components compactness. Based on experimental results and practical considerations, some guidelines are drawn to help the reader to properly select a volumetric expander.

Keywords: Comparison of volumetric expanders, experimental investigation, scroll, screw, piston.

1. Introduction

After a brief comparison of the technologies based on a literature review (section 1), the experimental setup and the four expanders are described in section 2. The experimental performance of the machines is then compared in terms of isentropic efficiency and filling factor (section 3). Based on the experimental data, semi-empirical models are calibrated to identify the main losses of each expander and to identify their optimal operating conditions (section 4). In section 5, an operating map is built based on the models results to help the selection of the optimal expander

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depending on the temperature levels of the ORC. Finally, general recommendations for selecting the optimal expansion machine are proposed while accounting for the flexibility, the compactness, the efficiency, the power range and the ability to handle high pressure/high temperature for a given application.

Nomenclature

FF	Filling factor	(-)	$\dot{V}$	Volumetric flow	(m^3/s)
h	Enthalpy	(kJ/kg.K)	η	Efficiency	(-)

Subscripts

ex	exhaust	s	isentropic
exp	expander	sh	shaft
meas	measured	su	supply
r	refrigerant	th	theroretical

1.1. State of the art

Many theoretical investigations have demonstrated the considerable influence of the expander efficiency over the global performance of ORC systems ([1,2] among others). A single expander technology cannot be identified to be the optimal one for every situation, particularly for micro- and small-scale systems [2-6]. The best technology depends on a large number of parameters, including the cycle operating conditions, the system compactness, its costs and the components availability. It is therefore substantial to evaluate and to compare the performance of different expander technologies in order to help the selection of the best candidate for a given application. Very few references in the scientific literature compare the experimental performance of different expanders. In this paper, such a comparison is proposed. Volumetric machines are often chosen for small-scale applications because of their low rotational speeds, their low flow rate for a relatively high pressure ratio and their acceptance of two-phase flows (which may appear at the end of the expansion in some operating conditions [2]). In this work, four machines, namely a modified hermetic scroll compressor running at constant speed, a variable speed modified scroll compressor, a variable speed twin-screw expander and a swashplate piston expander working at variable speed [7], are tested in a same micro-scale ORC system using R245fa as working fluid [8].

Table 1 summarizes the difference between these three main technologies of volumetric expander used in ORC systems. Piston expanders are suited for low displacement and low power application. They present the advantage to be able to work with high inlet temperatures, inlet pressures and pressure ratio. Scroll expanders benefit from few rotating parts and rather constant filling factor. They present a limited expansion pressure ratio since the volume ratio is limited to 4.2 and wet expansion handling. Screw expanders present several advantages, such as high allowed rotational speeds, compactness, and wet expansion handling. It appears that screw expanders can work at relatively low power but are mainly use in a range of power higher than the scroll or piston expander (due to fabrication costs).

Table 1: State of the art

Parameter	Scroll	Piston	Screw
Displacement [l/s]	0.76-32	[1.25-75]	[25-1100]
Power [W]	[0.005-10,000] [9]	[0.001-10,000] [9]	[2,000-2e5] [9]
Max. rotational speed [RPM]	10,000 [10]	3000 (swashplate :12,000) [9]	21,000 [9]
Built-in volume ratio	[1.5-4.2] [9]	[2-14] [9]	[n.a.-8] [11]
Maximum pressure [bar]	~40	70 [12]	-
Max. temperature [°C]	250 [12]	560 [12]	-
Two-phase flow handling	yes	low	yes
Isentropic efficiency [%]	87 [14]	70 [15]	84 [16]

2. Experimental facility

2.1. Test-rig

The test-rig used to characterize the expanders performance is depicted in Fig. 1. It is constructed using standard mass manufactured components from the HVAC industry. The working fluid is R245fa (with 5% oil mass fraction) and the test bench consists of a brazed plate evaporator, a shell and tube water-cooled condenser, a brazed plate recuperator, a gear pump and a liquid receiver.

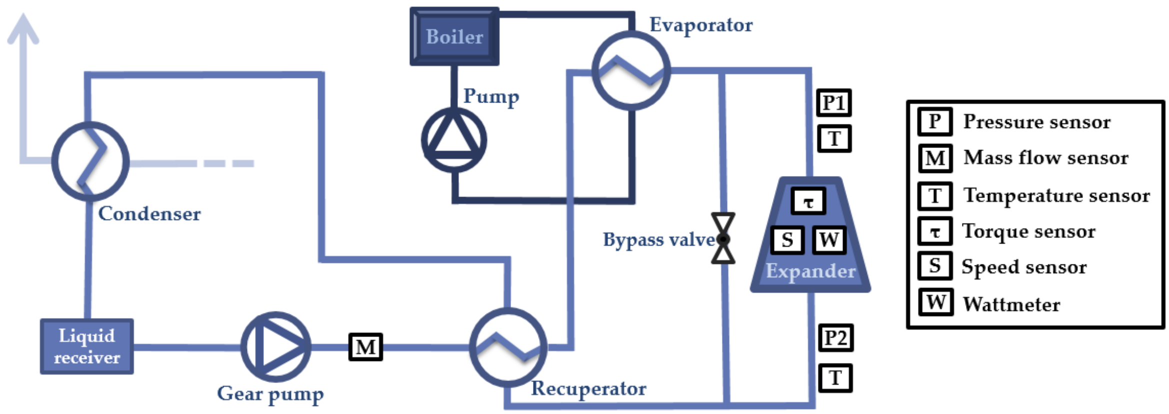

Fig. 1. Hydraulic scheme of the test-rig

Pressures and temperatures at key locations of the system are measured by different sensors. The refrigerant mass flow rate is recorded with a Coriolis flow meter at the pump outlet. A complete description of the sensor can be found in [17].

2.2. Expander characteristics

- Constant speed scroll compressor: The scroll machine investigated is a lubricated hermetic scroll compressor (Emerson ZR34K3E – designed to work with fluid R134a) modified to run in reverse as an expander [17]. It is directly connected to the grid resulting in a constant shaft speed (3,000 RPM) whatever the operating conditions [8]. Its main characteristics are summarized in Table 1. The mechanical power generation is calculated using the electromechanical efficiency of the generator as provided by the manufacturer.
- Piston expander: The piston expander tested is a swashplate piston expander characterized by a total cylinder capacity of 195 cm^3 (Table 1). The lubrication is performed by an external circuit with oil injection at mains friction points. The admission and exhaust processes are achieved by means of a valve-less system that induces symmetric opening and closing of the cylinder volumes. The expander is connected to an asynchronous electrical motor and a four-quadrant variable-frequency drive is used to control the shaft speed [7]. It has been sized for water/ethanol mixture applications and converted to run with R245fa. More recent (efficient) piston expanders exist and should be tested in future works.
- Screw expander: A twin-screw expander is tested. The sizing methodology for this screw expander is presented in [19]. The design of the screw expander is oriented towards an unsynchronized, liquid injection machine with the rotors and bearings being lubricated by the working fluid and the injected liquid. It presents a swept volume of 19.96 cm^3 and a built-in volume ratio of 2.5 (Table 1). The nominal supply pressure (12 bars) is relatively low compared to the two other expanders.
- Variable speed scroll compressor: It is designed for vehicle air-conditioning system with fluid R134a. Its volume ratio is close to the constant speed scroll but the swept volume is lower (12.74 cm^3) as presented in Table 1.

Table 1. Expander characteristics. The compactness factor is defined as the ratio of the nominal shaft power divided by the total volume of the expansion and mechanical parts (without the shaft, the generator and the casing).

Parameter	Scroll expanders (constant speed/ variable speed)		Screw expander	Piston expander
Swept volume [cm^3]	20.2	12.74	19.96	195
Volume ratio [-]	2.2	2.19	2.5	4.74
Maximum inlet temperature [°C]	140	130	140	250
Maximum inlet pressure [bar]	28	25	16	40
Rotational speed range [RPM]	3,000	[800-8,000]	20,000	[1,000-4,000]
Nominal shaft power [W]	2,277	2,000	2,000	4,000
Compactness factor [W/cm^3]	1.099	3.39	21	1.2

3. Experimental results

3.1. Important note about the comparison of performance

Generally, a perfectly objective comparison between different types of expander is not possible for different reasons:

- It is not possible to test expanders with exactly the same level of maturity. In this case, the scroll compressors are produced in large series for many years and have reached a commercial maturity. On the other hand, the piston and screw expander are still at a prototype stage and they might see their performance and commercial maturity increased in the future.
- Not a single expander in this experimental investigation has been sized for the test-rig. This means that limitations in the test-rig in terms of mass flow, pressure and temperature affect the performance of the expanders (not necessarily in the same way for each one).
- The design fluid for those expanders is not the one used in this ORC system (i.e. R245fa).
- Nominal working conditions in terms of pressure and temperature are different for each technology (higher pressure and temperature for the piston, for example).

Nevertheless, the proper choice of an expander technology is not yet straightforward and such an experimental comparison between different expander technologies does not exist in the literature. Some precautions are used to tackle the aforementioned arguments. In this study, the same test-rig with the same organic fluid is used, only the expander is replaced which means that temperature, pressure and flow limitations are the same for each machine. Based on the experimental data, semi-empirical models are calibrated to evaluate the performance in optimal conditions not reachable on the test-rig (section 4). Such methodology allows to properly compare the expander's optimal performance despite of the limitations of the test-rig.

3.2. Efficiencies definition

The experimental comparison is performed in terms of filling factor (FF) and isentropic efficiency (η_{is}) evaluated over a wide range of working conditions (1) and (2).

$$FF = \frac{\dot{V}_{meas}}{\dot{V}_{th}} \tag{1}$$

$$\eta_s = \frac{\dot{W}_{sh}}{\dot{m}_r(h_{exp,su}-h_{exp,ex,s})} \tag{2}$$

$\dot{V}_{meas}$ is the volumetric flow rate$\dot{V}_{th}$, is the theoretical volumetric flow rate, $\dot{W}_{sh}$ is the mechanical power generated at the shaft, $\dot{m}_r$ is the refrigerant mass flow rate, $h_{exp,su}$ is the expander supply enthalpy and $h_{exp,ex,s}$ is the expander exhaust isentropic enthalpy. $\dot{V}_{meas}$ and $\dot{V}_{th}$ are defined at the supply of the expander (without taking recompressed mass from the clearance volume in the case of the piston machine.

3.3. Isentropic efficiency analysis

The experimental isentropic efficiency calculated for the four machines in function of the pressure ratio is depicted in Fig. 2. Only a small range of pressure ratio is covered with the scroll expander because of its constant spindle speed and other experimental limitations on the test rig. The piston expander is able to work on a much larger range and with pressure ratios up to 10.6. The trend is the same for each machine: at low pressure ratio, the efficiency is rather low mainly because of over-expansion losses and at high pressure, a decrease is observed because of under-expansion phenomenon, pressure drop and mechanical losses. Because of experimental limitations of the test rig limitations (low maximum refrigerant flow rate and high pressure drops in the pipelines) the optimum working conditions are not reached for each expander. Section 4 **Error! Reference source not found.**presents calibrated semi-empirical models to evaluate this optimum efficiency versus the pressure ratio to get a comparison unbiased by the test-rig experimental constraints.

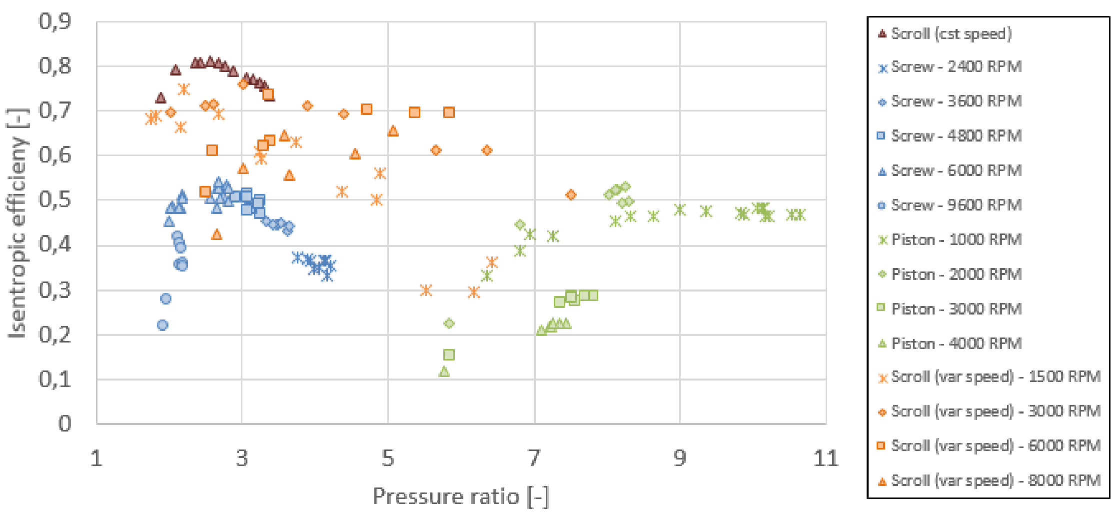

Fig. 2. Isentropic efficiency versus pressure ratio.

3.4. Filling factor analysis

The filling factors measured for each expander are plotted versus the shaft speed in Fig.3. The constant speed scroll filling factor is rather constant with values between 1.033 and 1.12. For the piston expander, the filling factor decreases when increasing the rotational speed and when decreasing the pressure ratio mainly because of the leakages decrease. The screw filling factor is very dependent of the rotational speed and becomes lower than one for values higher than 10,000 RPM. This is explained by a decrease in the fluid density due to pressure drops occurring before the expansion process (in the supply line of the expander).

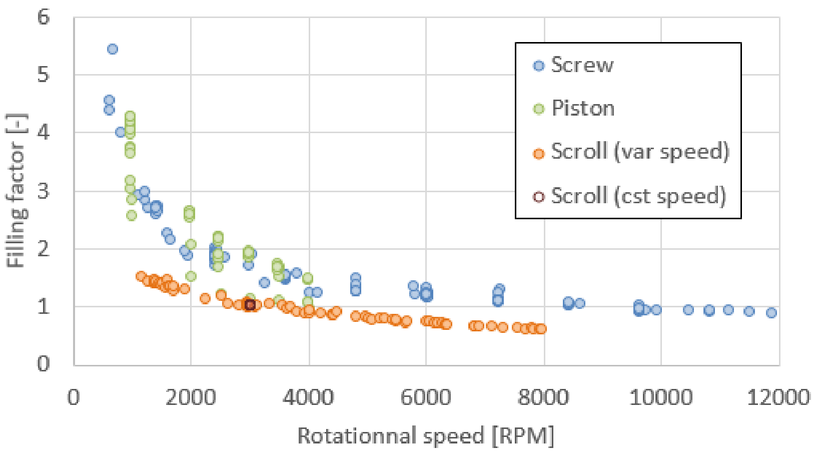

Fig. 3. Filling factor versus rotational speed

4. Optimal efficiency prediction and operating maps

As mentioned previously, the experimental results presented hereabove do not illustrate the optimal performance of the expanders. To overcome this issue, the four volumetric expansion, machines are simulated using the grey-box model proposed by Lemort et al. [20]. By accounting for the most influent physical phenomena in the expansion process with a limited number of parameters, this model demonstrates a good ability to extrapolate the expander performance out of the calibration dataset [17] while maintaining low computational times. Furthermore the same modelling formulation can be used to characterize different technologies of volumetric expander [20] which makes it pretty handy.

In this work, the calibrated semi-empirical model [22] is used to build optimal performance maps for the different machines. To this end, the experimental measurements are used to calibrate the models parameters for each technology. Then, a mapping of the optimal performance is performed for each expander in function of the condensing pressure and the expander supply temperature. More specifically, the model is used to derive the best performance achievable by the expander (in terms of highest isentropic efficiency) if its rotational speed was optimized in function of the operating conditions. The simulations assume a superheating of 5°C at the expander inlet and an ambient temperature of 25°C. The results are depicted in a four quadrant graph (see Fig. 4) for which the different axes are all positive and symmetric to the origin (each quadrant is referring to an expander). Four curves are displayed to inform the variations of the optimal isentropic efficiency in function of the operating conditions. For a given supply temperature, two condensing pressure leads to an identical efficiency because of under- and over- expansion losses. The top horizontal line (i.e. the highest inlet temperature) in each quadrant is referring to the supply temperature limitation of each expander (see Table 1). The black dotted horizontal line represents the critical temperature of the refrigerant. Only for the piston machine, the maximum pressure is reached before the maximum temperature of the machine. In this case, the supply pressure is imposed at its maximum and the supply temperature is increased to cover wider ranges of power.

Here, the constant-speed scroll expander is disadvantaged because of its constant rotational speed (practically and in the model) but still presents the highest isentropic efficiency. The scroll and screw expander maps are rather close. Whatever the isentropic efficiency considered, the screw expander map is slightly narrower because of its inlet temperature limitation and, more generally, its lower isentropic efficiency. The piston shows less possibility to work at low inlet temperature as expected but shows the widest running area because of the high allowed temperature and its high volume ratio.

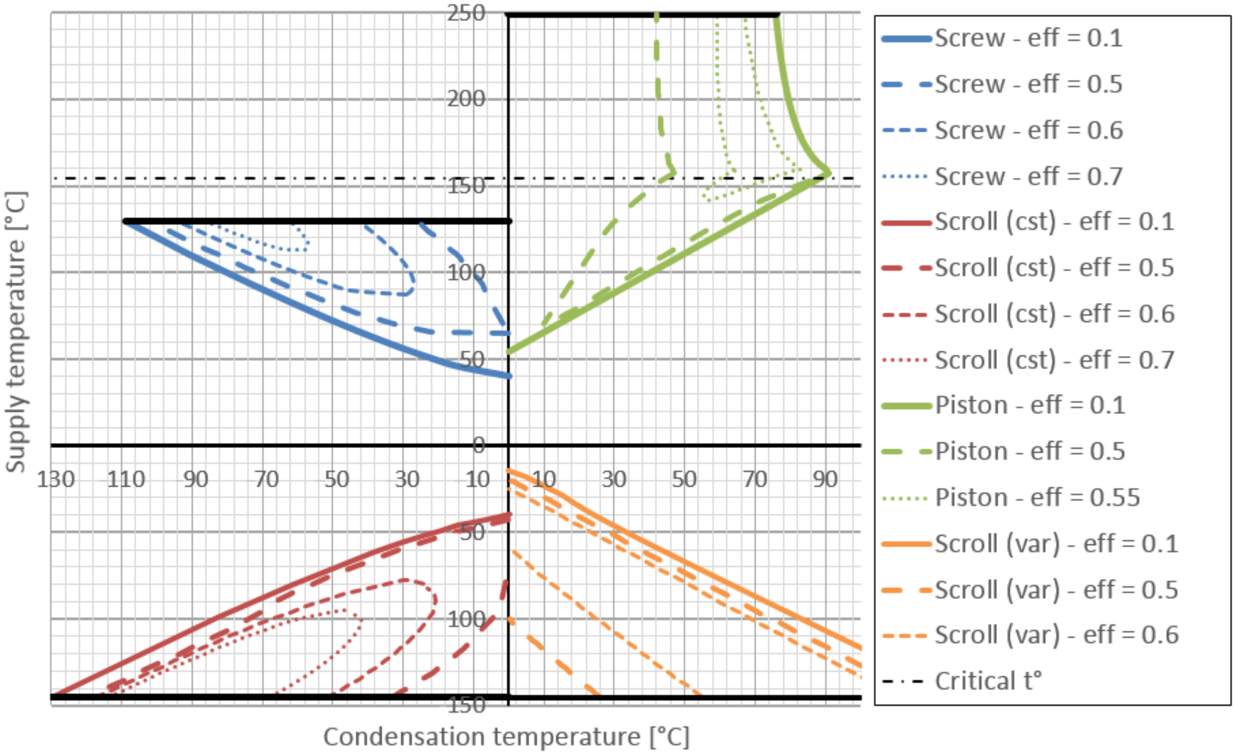

Fig. 4. Optimal performance map for the different prototypes tested with fluid R245fa evaluated for several isentropic efficiencies. In the legend, Scroll (cst) is the constant-speed scroll and Scroll (var) is the variable-speed scroll.

5. Discussion

Based on the scientific literature, one of the main criterion to account for when selecting a volumetric machine is the system power range. For a power larger than tens of kW, screw expanders are recommended. For an expander power lower than ~2500 W, scroll and piston machines should be chosen. Besides the power range, other technical limitations must be taken into consideration such as the highest allowable operating pressure and temperature, the ability to operate without lubrication oil, the highest achievable built-in volume ratio, the machine cost, its compactness. For instance, the piston expander may be used for application with much higher supply pressure and supply temperature. Therefore, it allows to achieve higher shaft power production if those conditions cannot be reached by the other technologies. However, piston expanders only handle limited wet expansions. In terms of compactness, the best choice are screw expanders followed by piston and scroll machines (see Table 1).

In conclusion, the selection of a volumetric expander depends on the requirements of the dedicated application: is the efficiency, the working conditions, the flexibility or the compactness the most important criteria? A comparison in terms of compactness, efficiency, achievable working conditions and flexibility (i.e. the adaptability of the expander speed to varying working conditions) is proposed in Table 2**Error! Reference source not found.**. An economic comparison is not performed since it essentially depends on the maturity of the machine. A large-scale production could decrease the price of a prototype to a level comparable with the cheapest technologies.

Table 2. Comparison of expander advantages and disadvantages

	Power [W]	High Pressure and temperature	Wet expansion	Compactness	flexibility	Efficiency
Piston	Maximum ~10,000	+	-	+	+	+
Screw	Minimum ~2,000	-	+++	++	+++	+
Scroll	Maximum ~10,000	-	+++	+	++	++

6. Conclusion

Four different technologies of volumetric expanders (namely two scroll, one screw and one piston) are tested experimentally in a small-scale ORC test rig using R245fa as working fluid. Experimental measurements over a wide range of operating conditions are used to assess their performance in terms of filling factors and isentropic efficiencies. The experimental measurements are then used to calibrate semi-empirical models in order to extrapolate the machines performance to define optimal performance maps for each technology. The scroll expander shows the highest isentropic efficiency (81%) while the piston and the screw present a 53% efficiency. It is important to note that these results are gathered in the case of small-capacity expanders (<5kW) with different maturity of development. Furthermore, the analysis is performed using only one working fluid (R245fa). A discussion to select the optimal expander for a small-scale ORC is also proposed. Based on the analysis, the choice of the expander technology has to be conducted in parallel with the selection of the ORC architecture, range of power, operating conditions and working fluid for the selected application.

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