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On the conceptual design of the novel balanced rolling piston expander

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ABSTRACT

This work presents a novel type of positive-displacement expander, named the balanced rolling piston expander. It proposes also a design procedure and assesses the mechanical behavior of a virtual prototype. The expander is conceptually capable of operating at higher fluid temperatures than other positive-displacement expanders, such as scroll- or screw-type machines. Moreover, it employs a radially balanced rotor, differently from common rolling piston technologies and does not require any timing mechanism for filling and emptying the working chambers, differently from Wankel or reciprocating solutions. The investigated virtual prototype is chosen for the study case of a small-scale heat recovery unit currently under investigation. The results indicate that a prototype of about 300 mm in diameter and 100 mm in length is capable of an ideal power of 20 kW. Moreover, vane accelerations can be relatively high but anyhow comparable to those in sliding vane machines, while pressure drops in percent terms are in general lower than 1%. Lastly, load-induced displacements are manageable by a proper radial clearance at room temperature. In brief, the balanced rolling piston expander is a promising option for small-scale power generation units operating with temperatures not achievable by common technologies and, hence, it deserves further investigation.

1. Introduction

The power generation infrastructure is changing from a system in which electricity used to be produced exclusively in large power plants to a system in which diffused generation and smart grids will be integrated closely with those larger technologies. In such a transition, small-scale power generation units are becoming more and more common. Similarly to the large plants, these small units can be based on a Rankine cycle or a Joule-Brayton cycle. However, the great reduction in the output capacity imposes a fundamental switch in the technology of the fluid machines, which are not mere reduced-scale models. In the small units, positive-displacement expanders must replace generally the turboexpanders of the large plants because of their lower process flow rates and rotational speeds as well as of their ability to operate under large pressure ratios and at good performance [1]. Organic Rankine Cycles (ORCs) offer an example of this technology switch: positive-displacement expanders are employed for units scaled up to tens of kilowatts, whereas turbomachines above a hundred of kilowatts [2].

There exist many types of positive-displacement expanders [1], such as reciprocating, rolling piston, scroll, single- as well as twin-screw, sliding vane, and Wankel. Each type is characterized by a maximum temperature of the working fluid at the machine inlet, as explained in the next section. This maximum temperature can hinder the use of an expander type within small-scale power generation

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units operating at mid and high temperatures.

1.1. Overview on positive-displacement expanders

The open literature provides several studies about diverse types of positive-displacement expanders. An overview is reported here focusing mainly on the maximum temperature of the working fluid at the machine inlet. In particular, the expander types are presented in an increasing order of this temperature.

Thanks to their relatively simple technology, rolling piston expanders are proposed primarily as substitutes of the throttling valves in carbon dioxide heat pumps to improve their coefficient of performance, as indicated by Haiquing et al. [3]. In addition to heat pumps, however, rolling piston expanders are also applied to micro-scale ORC units in which the maximum temperature does not exceeds normally 90 °C, according to Zheng et al. [4].

Sliding vane expanders operating with compressed air are adopted usually to substitute electric motors, for example inside pneumatic tools, in spark-prohibited environments. Although originally sliding vane expanders are not designed to operate with organic fluids, Qiu et al. [5] state they are a good option after proper modifications for power outputs lower than a few kilowatts. Small ORC units employing sliding vane expanders are investigated in a number of works spanning over diverse working fluids and over different maximum temperatures up to about 130 °C [6–11].

There are various studies about the performance of scroll expanders [12–14] or that of ORC units employing them, as reported by Quoilin et al. [15]. The manufactured prototypes are developed usually for laboratory tests by modifying commercial scroll compressors. Their operation is limited now to maximum temperatures not higher than 175 °C [12,16]. Such temperatures are possible in case of open-drive machines, but Lemort et al. [17] highlight that lower maximum temperatures are necessary for hermetic machines in presence of lubricating oil.

Screw expanders shall be distinguished into single- and twin-screw technologies. Among the several researches about the single-screw technology, Desideri et al. [18] characterize experimentally an ORC unit by modifying a single-screw compressor to run in reversed mode. The expander is tested with two working fluids but at a maximum temperature limited to 125 °C. On the other hand, about the twin-screw technology, Smith et al. [19] report a maximum pressure of the fluid at the expander inlet of 25 bar that, considering the working fluid is water, corresponds to a maximum temperature not less than 225 °C.

Ultimately, much higher maximum temperatures are achievable by way of Wankel and reciprocating expanders. They are indeed technologies adapt for internal combustion engines, where temperatures can be remarkably higher than those for the above mentioned technologies. Unlikely Wankel engines, Wankel expanders require though a proper timing mechanism for filling and emptying the working chambers that may be realized via dedicated valves actuated by gears or pulleys [20–22]. Alternatively, a port plate can be adopted, as demonstrated by Badr et al. [23], to control at least the emptying process, which is a solution employed widely in positive-displacement machines for oil-hydraulic applications [24,25]. In their turn, the timing mechanism in reciprocating expanders is realized similarly to reciprocating engines. Despite the potential, reciprocating expander are employed in power generation units, waste heat recovery systems from internal combustion engines, and refrigeration cycles with power requirements of only a few kilowatts and with temperatures in the low range 380–560 °C [1].

1.2. Scope of the work

This work proposes a novel type of expander, named the balanced rolling piston expander, which is a rotary machine with two major characteristics:

1. it can operate at both low and high maximum temperatures of the working fluid, where this high temperature falls between that of a twin-screw and that of a Wankel or reciprocating machine;
2. it does not require any timing mechanism for filling and emptying the working chambers, unlikely Wankel and reciprocating expanders.

As a first investigation of the novel type of expander, the goal of this work is, on the general side, providing the conceptual definition of the balanced rolling piston expander and, on the specific side, verifying the mechanical behavior of a virtual prototype under operational loads. To achieve the later point, a three-step design approach is executed as follows:

1. a geometrical procedure is developed to define the shape of the prototype primary components as well as to compute the velocities and, most importantly, the accelerations of the moving parts (spring-loaded vanes as explained in the next section) during the rotation of the shaft of the prototype itself;
2. a set of thermodynamic laws is utilized to compute the outlet condition of the working fluid, which combined with the previous procedure allows tuning the geometrical parameters to reach a targeted outlet condition;
3. a finite element method analysis of primary components of the prototype is performed to assess their displacements induced by pressure, rotation and temperature.

The following sections of the work present in sequence: the conceptual definition of the novel expander, the design approach as well as the assessment of a virtual prototype, and the conclusions on the feasibility of the expander itself.