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An experimental and numerical analysis of the performances of a Wankel steam expander

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A B S T R A C T

In the last decades, the energy market increased its interest towards the smart grids and electrically isolated systems. These systems utilize small size power generators in which volumetric expanders may be employed for a wide range of operative conditions, because of their robustness and reliability.

In this work a study on a volumetric expander based on the Wankel mechanism was carried out. The aim of this study was to develop a lumped parameters numerical model able to predict the brake effective torque and working fluid consumption of the expander. This model was validated by comparison with experimental results obtained using steam as working fluid. This model allowed to trace the trends of mechanical and thermal losses versus rotating speed and inlet pressure. The experimental results encouraged the need for a further development of this expander, and showed the capability of the numerical model to predict the effective performances of the device.

1. Introduction

The increment of energy consumptions, the need to reduce pollutant emissions and the limited reserves of fossil fuels increase the necessity of energy production from renewable sources. In order to produce useful power, solar energy, biomass, geothermal heat and waste heat recovery are technologies that may provide low grade heat. In this context, the Organic Rankine Cycle is a suitable technology that allows the exploitation of these sources [1–3]. Considering low size plants, a key components of an ORC cycle is the expander whose performances and costs results in a higher plant efficiency, than using turbines [3].

This was suggested by Quoilin et al. in Ref. [4] that, considering the technical feasibility of an ORC cycle in terms of operating fluids, volumetric expanders and thermal source, found that scroll and vane expanders, are suitable for low output powers (up to 10 kW), while reciprocating expanders mat be employed for power range between 25 and 100 kW. On the other hand, turbines are attractive to produce power higher than 1 MW. Nevertheless, volumetric expanders are suitable also for the systems in which a low vapor quality is obtained at the end of expansion process.

Other Authors, as Pantano and Capata, focused the feasibility of different expanders to convert waste heat provided by a bus engine in mechanical power for the drive of auxiliaries and of the air conditioning system; their conclusion was that a screw device was the best compromise between efficiency, reliability and produced energy [5].

The feasibility of the screw expander to recover waste pressure energy in throttling process was highlighted also by Tian in Ref. [6], providing a numerical model of the twin screw during non-steady state gas conditions. In detail, they described the behavior of pressure losses with the increase of rotating speed, as well as the trend of the filling factor providing a value of the isentropic efficiency between 0.73 and 0.83. Beside the research on the twin screw device, also the single screw expander was developed. In particular, Zhang et al. [7] employed a single screw expander for waste heat recovery applications, providing, at 1538 rpm, maximums of power output and shaft efficiency of 10.38 kW and 57.88% respectively. Moreover, the need to employ large expansion ratio suggested to introduce also a single screw expander based on two stages device as described in Ref. [8], providing an isentropic efficiency of 0.83. However, the improvement of the device is also an important topic in literature; in particular, Wang [9] discussed the influence of the gap on the experimental performances, highlighting the effects of the leaking gas on the specific consumption while Giuffrida proposed an improved semi-empirical model of a single screw expander, whose results were more consistent with the experimental data, as shown by the reduction of the mean

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absolute percentage error [10].

Other studies focused the development of other mechanism as expander devices. Preetham investigated the cycle of a free piston expander suggesting some modification to improve the isentropic efficiency from 0.22 to higher values [11], while an experimental investigation was proposed in Ref. [12] to show the influence of the external load. Tenissara et al. in Ref. [13] presented a piston expander, derived from a Diesel engine, in which compressed air was employed; the operating pressure was between 1 and 10 bar and an optimization provided a maximum isentropic efficiency about 0.85. Furthermore, Giuffrida in Ref. [14] suggested a novel expander based on a rolling piston concept working on a closed-loop Joule-Brayton cycle and Fatigati et al. in Ref. [15] described a strategy for volumetric expanders to maximize the output power by an injection of the suction fluid during the expansion. Finally, an excellent review on the state of art about the performances of volumetric devices [16] highlights that only few prototypes are commercially available in the range 10–50 kW.

The design of a volumetric expander, based on a Wankel engine, was developed at Pisa University to match this power range.

Particularly, a Wankel expander may be suitable for technical applications because of a series of advantages in terms of compactness, economy and reduced mechanical vibrations. Moreover, the main troubles due to wear of seals as well as poor fuel economy and emissions are avoided because of the lowest values of the operating pressure and temperature together with the absence of the combustion process [17]. One of the first studies about the feasibility of a Wankel expander was provided by Badr et al. in Refs. [18,19] simulating a Mazda and Curtiss-Wright commercial engines in a numerical code with steam; their aim was to predict the trend of the power output and fluid consumptions as a function of the operating parameters.

Other analysis focused the timing variation [20] and the influence of the valve discharge coefficient [21], while in Ref. [22] a comparison of the first experimental results based on the use of compressed air and saturated steam was shown; later, Francesconi et al. in Ref. [23] developed a numerical model of the expander to predict the mechanical losses and its performances in terms of power output.

In this study, several experimental tests based on the use of saturated water steam as working fluid, were performed on the Wankel prototype. The main purpose was to investigate the global performances of the expander in terms of rotating speed, indicate cycle and mechanical power. The experimental data were then compared with numerical results predicted by the numerical model of the device proposed in Ref. [23] highlighting a good agreement. Particularly, the differences between the indicated cycle work simulated and measured were less than 15%.

The novelty of these results is to highlight the process in which the mechanical and thermal losses affect the operation of a Wankel device when steam is employed; moreover, it was proved that the developed code may be suitable to predict the real performances of the Wankel expander fueled with organic fluid for ORC micro-generation applications.

2. Characteristics of the Wankel prototype

The prototype (Fig. 1-a) was developed at the University of Pisa on the basis of a commercial Wankel-type internal combustion engine used in karts and ultra-light flight vehicles (Fig. 1-b). Particularly, while the stator was newly built to accommodate the introduction and exhaust valves (Fig. 2-a), the bearings, the main shaft (Fig. 2-b) and the seals of the original engine (Fig. 2-c) were retained. A new rotor without cavities was fitted in order to increase the compression ratio (Fig. 2-d).

A pulleys system was employed to drive the valves (Fig. 3-a) whose timing was adjusted by using a vernier system. The rotation of each valve was based on a shaft supported by two roller bearings (Fig. 3-b). Each introduction valve is situated 17 deg. after the Top Death Center (i.e. TDC) and each exhaust valve is situated 115 deg. after the TDC (Fig. 4-a); the other couple is symmetrically displaced.

The geometry and the kinematic of the device allowed each operating chamber to complete two thermodynamic cycles (Fig. 4-b) during a full rotation of the rotor, requiring two intake and two exhaust valves overall. In addition, the stator shape of a Wankel device depends on the ratio of the value of the eccentricity e to the rotor radius R (Fig. 4-a).

If we consider the general concepts of the theory of volumetric expander and the ideal thermodynamic cycle in Fig. 1b, the following parameters can be calculated according to the literature [21]:

$$Volume\ ratio = \frac{V_{disp} + V_0}{V_0} \tag{1}$$

$$Cut-off\ grade = \frac{V_2 - V_1}{V_{disp}} \tag{2}$$

$$Recompression\ \ grade = \frac{V_5 - V_6}{V_{disp}} \tag{3}$$

In the following Table 1 and Fig. 2, the main design parameters of the prototype are shown. In particular, it was also possible to describe the variation of the displacement of the rotary piston by means of an equivalent value of the crankshaft of a reciprocating engine.

3. Numerical model

The model presented in this papers simulates the operation of the expander by using a lumped parameter approach. A first validation of the model was proposed in Ref. [23] discussing the experimental data provided by tests based on air as working fluid.

In this work, a further development of the investigation is presented by means of the simulation the operation with a generic working fluid, such as organic fluids or steam, whose properties were provided by Refrop®.

The code describes the behavior of the Wankel device investigating the motion of its parts and the fluid thermodynamic transformations.

In detail, the rotor kinematic and the volume chamber trend were found considering the rotor radius, the eccentricity and the axial stator length as explained in Ref. [24]. The velocity as well as acceleration calculations for the rotor parts, were amending for the development of seal's dynamic and mechanical investigation.

The thermodynamic analysis was based on mass and energy balances that required the knowledge of the rotating speed and steam parameters. In detail, these last were the pressure and temperature at the inlet device and at the condenser, in addition to the specification of the cut-off and recompression grades for the evaluation of the inflow and the outflow; these last two quantities affected also the operating pressure in the chamber.

The need to predict the indicated cycle, suggested to model also the leakages between operating chambers and with the external environment.

In particular, this step was faced modeling the leak as a flow through a nozzle [21,23] with a proper value of the discharge coefficient [20,21]. More in detail, the flow calculation in Ref. [23] was based on the ideal gas assumption since the prototype operated