Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 105 (2017) 2929 – 2934

Energy Procedia

The 8th International Conference on Applied Energy – ICAE2016

Experimental results of a Wankel-type expander fuelled by compressed air and saturated steam

M. Antonelli[a,*], M. Francesconi[a], A. Baccioli[a], G. Caposciutti[a]

[a]*University of Pisa, Department of Energy, Systems, Territory and Construction Engineering, 56122 Pisa, Italy.*

Abstract

The work presented in this paper deals with the experimental tests which were carried out on a prototype of a rotary volumetric expansion device based on the Wankel mechanism. This expansion device is addressed to small size power plants (in the range 5-50 kW) for distributed micro-generation using various sources of thermal energy, such as sun, biomass and waste heat.
The prototype was built using an internal combustion Wankel engine, employing the shaft, the rotor, the bearings, while the statoric case was newly built on the design of the University of Pisa.
Firstly, the tests were carried out with the compressed air produced by a compressor, then the prototype was fed with the saturated steam produced by a biomass boiler. In the first case, the exhaust back-pressure was the atmospheric one, in the second case vacuum conditions were employed thanks to a condenser. The inlet pressure was between 4 and 8 bar.
The results showed the capability of the prototype to rotate regularly at 3000 rpm, and allowed the validation of numerical models presented in previous papers. Moreover, the expansion device showed the capability of developing the expected power.

Keywords: *Wankel, CHP, micro generation, renewable energies*

1. Introduction

The employment of renewable energies is often limited by the relatively low dense availability of the resources themselves and this is typically the case of biomasses, waste heat recovery, thermal solar energy. The possibility of building low cost, simple and reliable small size plants would therefore encourage the use of those resources whose employment would not be competitive if employed in larger size plants.

Amongst the various solutions proposed, few of them in the field 10-50 kW are commercially available. In most cases, Scroll machines are proposed for size below 10 kW [1-8], while Screw expanders [9-12] are more suited in the range of 20-100 kW. Piston expanders, which were the most

doi:10.1016/j.egypro.2017.03.669

widespread type before the diffusion of turbines, were also proposed even in quite recent research papers [13, 14]. If compared with piston engines, rotary machines provide a smoother and quite behaviour with less vibrations and higher power densities. on the other hand, Piston machines are quite attractive due to their flexibility of use and adaptation capability, because of their possibility of fitting the cut off ratio through the variation of the valve timing. Nevertheless, they can be derived from piston reciprocating engine or reciprocating compressors, which are widely diffused and low cost machines.

Several research papers proposed the employment of the Wankel mechanism for the realization of a volumetric, rotary expander and its application to Organic Rankine Cycles (ORC) for various applications was also discussed in previously published works [15-21]. In the above-mentioned literature, very few experimental data can be found, especially with two-phase working fluids.

To the authors' knowledge, for the first time this paper shows the experimental measure of the indicated cycle of a prototype of a Wankel expander fed with steam. This prototype, whose features were already discussed in previously published works, was built by employing some parts of an internal combustion Wankel engine, while most of its components were newly built to fit to the new cycle. The experiments were carried out by using saturated steam as working fluid, with intake pressures in the range 4-6 bar and rotational speeds in the range of 1000-3000 rpm. Finally, the indicated cycle and the torque curves are presented in the following sections.

2. Methodology

The expander analyzed in this paper is a prototype (fig. 1) derived from a 316 cm^3 internal combustion engine designed for karts and ultra-light flight vehicles; however, it features some modifications aimed at improving expander performances and facilitating assembly and calibration activities. The main features of the prototype (please refer to [19, 20] for a more complete description) are summarized in Table 1.

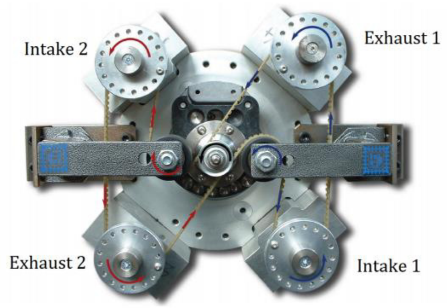

Figure 1: Front appearance of the prototype used during the tests.

Table 1. Specification of expansion device used in the study

Number of rotors	1
Displacement	316 cc
Cut-off ratio	0.45

As widely recognized [13, 14], volumetric expansion devices performance are largely influenced by the cut-off ratio. Here a cut-off ratio of 0.45 was used for this first experience; although, it was a too high value in order to expect a high efficiency during steam operations. However, it proved suitable for organic fluids [19] and it was anyway employed for this first case study.

The measure of the indicated cycle of the Wankel expander required the use of two pressure probes distributed along the stator case. The reader may find further details of the indicated cycle acquisition procedure in [19] and [20].

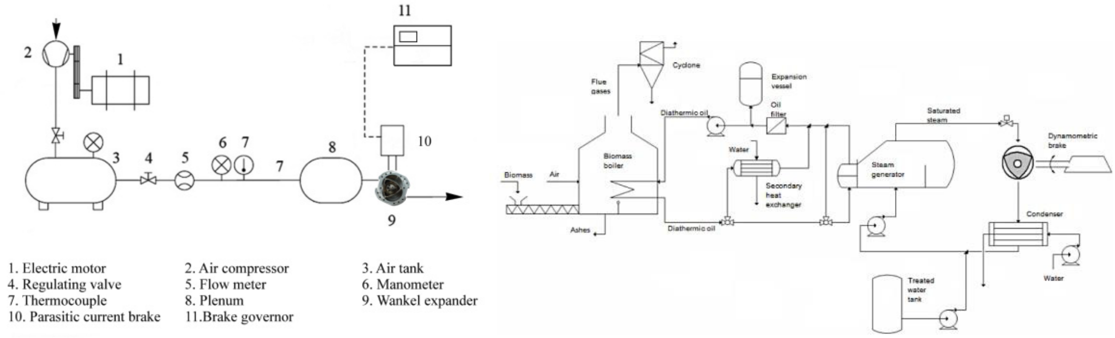

Figure 2: Compressed air (left) and steam (right) test rig schematic.

3. Results and Discussion

3.1. Expander performance

The results of the tests were reported in the form of the torque and power curves as a function of the rotating speed for the various inlet pressure values.

Ideally, the torque delivered by a volumetric expander should not depend upon the rotating speed as currently happens with turbines, since the ideal cycle work depends only upon the pressure ratio and the cut-off and recompression grades. However, when a real machine is treated, the presence of the fluid dynamic resistance across the valves, the heat exchange, the leakages and all the other phenomena, which may occur in reality, let the torque to be variable with speed. Some of these effects are counter-acting. In fact, the fluid dynamic resistances increase with speed, while the leakages and the heat exchanges generally do the opposite.

Based on these considerations, while observing the behaviour of torque as a function of speed (Figure 4), it is easy to conclude that the fluid dynamic resistances effect prevail on the others, especially in the case of air tests, the inlet fluid is nearly at the ambient temperature. When the expander was tested with steam, especially at the lowest inlet pressure, the torque curve slope was less pronounced and a more appreciable decrease was observed only at the highest rotating speeds.

3.2. Indicated cycle

In the ideal cycle the intake and the exhaust phase are at constant pressure, the spontaneous discharge happens at constant volume and the expansion and the recompression are isentropic. The real cycle clearly shows none of these features, in addition (like in the internal combustion engine) there is no distinct separation between a phase and the following one

The effects of leakages mentioned in the previous paragraph are clearly visible in the indicated cycle (figure. 5), as already showed in a previous paper published [19], in which the leakage of fluid between one chamber and the other were discussed and explained.

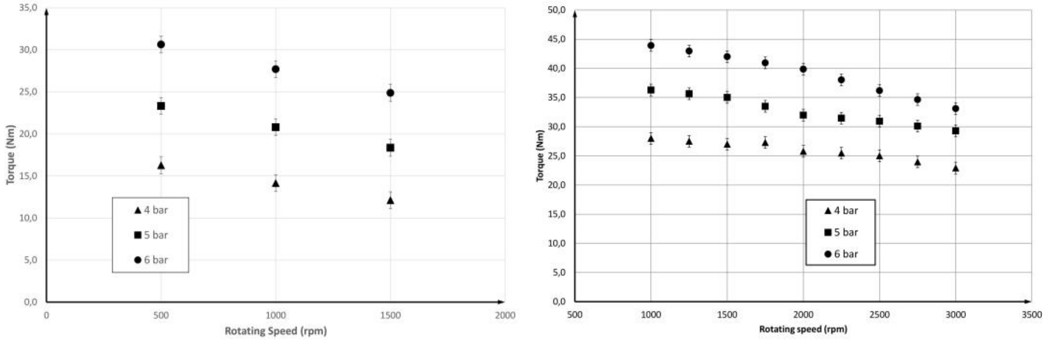

Figure 4: Expander torque with air (left) and steam (right).

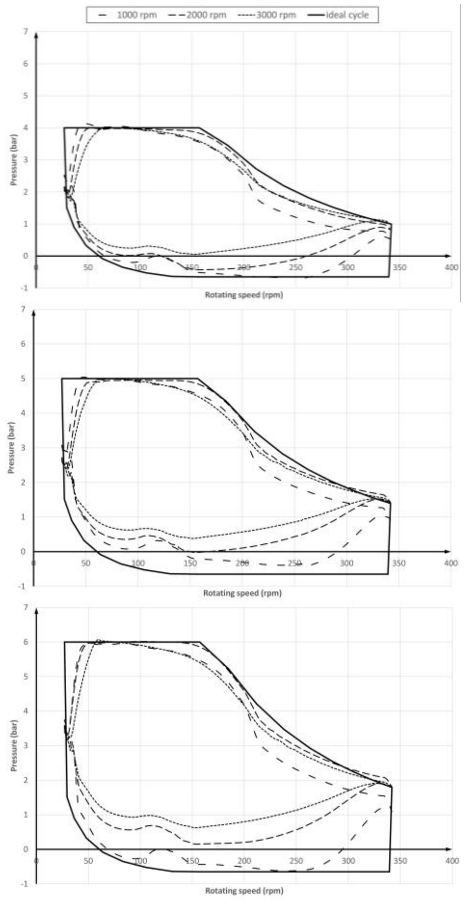

Figure 5: Indicated cycles with steam at 4 (top), 5 (center) and 6 barg (below).

Due to the relatively high rotating speed, in comparison with piston expanders, the pressure losses across the valves were quite evident, especially during the exhaust phase. Starting from 1000 rpm and going towards 3000 rpm, the pressure during the exhaust became higher and higher. At 1000 rpm the value of the condensing pressure was attained nearly at the half of the exhaust phase, but at 2000 and 3000 rpm the in-chamber pressure was always higher, resulting in a growing work loss.

Besides this, the valves opening are not instantaneous, and this effect was easily identified at the beginning of the inlet and exhaust phases, when the in-chamber pressure did not raise and fall at constant volume.

3.3. Remarks on the test results

The result of the tests led to draw the following observations:

- The cut-off ratio which was employed here was in effects too large for the use with steam, even at low pressure. By this way the end of expansion pressure was far higher than condensing pressure, thus leading to incomplete expansion and to the so-called "triangular loss";
- The performance of the valves need to be improved by means of combined numerical and experimental technique, in order to decrease the pressure losses across them;
- There was a noticeable difference (about to about 20%) between the delivered torque and power between air and steam tests. This was an expected fact since during the steam test a condenser, with an internal pressure below the atmosphere, was employed.
- The lower back-pressure employed during the steam test provided an evident difference in the delivered work, even though the pressure loss across the exhaust valves prevented the in-chamber pressure to approach the condenser pressure.

4. Conclusion

This paper shows the first experimental results of a steam expansion device built based on the Wankel mechanism. The prototype proved a very smooth and vibrations-less running, without any trouble of reliability during the whole test duration. The analysis of the indicated cycle showed the expected differences as compared to the ideal cycle, as well as a fair performance in terms of delivered power. Due to the high cut-off ratio, the residual pressure at the end of the expansion was relatively high, and the intake and exhaust valves behaviour showed that further improvements might be attained through the valves timing and shape optimization. On the other hand, a relatively high power was obtained at about 10 kW @ 6 barg and 3000 rpm.

This experience allowed the authors to trace the way for the future development of the research, indicating the main modifications to be done to this prototype.

References

[1] Lemort V., Quoilin S., Cuevas C., Lebrun J. Testing and modeling a scroll expander integrated into an Organic Rankine Cycle (2009) Applied Thermal Engineering, Volume 29, Issues 1415 pp. 3094-3102.

[2] Declaye S., Quoilin S., Guillaume L., Lemort V., Experimental study on an open-drive scroll expander integrated into an ORC (Organic Rankine Cycle) system with R245fa as working fluid (2013) Energy, Volume 55, pp. 173-183.

[3] Quoilin S., Lemort V., Lebrun J., Experimental study and modeling of an Organic Rankine Cycle using scroll expander (2010) Applied Energy, Volume 87, Issue 4, pp. 1260-1268.

[4] Clemente S., Micheli D., Reini M., Taccani R. Energy efficiency analysis of Organic Rankine Cycles with scroll expanders for cogenerative applications (2012) Applied Energy, Volume 97, pp. 792-801.

[5] Clemente S., Micheli D., Reini M., Taccani R. Performance study of a twin-screw expander used in a geothermal organic Rankine cycle power generator (2015) Energy, Volume 90, pp. 631-642.

[6] Kim H.J., Ahn J.M., Park I., Rha P.C. Scroll expander for power generation from a low-grade steam source (2007) Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 221 (5), pp. 705-712.

[7] Giuffrida, A. Modelling the performance of a scroll expander for small organic Rankine cycles when changing the working fluid (2014) Applied Thermal Engineering, 70 (1), pp. 1040-1049.

[8] Guangbin L., Yuanyang Z., Liansheng L., Pengcheng S. Simulation and experiment research on wide ranging working process of scroll expander driven by compressed air (2010) Applied Thermal Engineering, Volume 30, Issues 14 and15, pp. 2073-2079.

[9] He, W., Wu, Y., Peng, Y., Zhang, Y., Ma, C., Ma, G. Influence of intake pressure on the performance of single screw expander working with compressed air (2013) Applied Thermal Engineering, 51 (1-2), pp. 662-669.

[10] Wang, W., Wu, Y.-T., Ma, C.-F., Liu, L.-D., Yu, J. Preliminary experimental study of single screw expander prototype (2011) Applied Thermal Engineering, 31 (17-18), pp. 3684-3688.

[11] Desideri, A., Gusev, S., van den Broek, M., Lemort, V., Quoilin, S. Experimental comparison of organic fluids for low temperature ORC (organic Rankine cycle) systems for waste heat recovery applications (2016) Energy, 97, pp. 460-469.

[12] Papes, I., Degroote, J., Vierendeels, J. New insights in twin screw expander performance for small scale ORC systems from 3D CFD analysis (2015) Applied Thermal Engineering, 91, pp. 535-546.

[12] Tang, H., Wu, H., Wang, X., Xing, Z. Performance study of a twin-screw expander used in a geothermal organic Rankine cycle power generator (2015) Energy, 90, pp. 631-642.

[13] Ferrara G., Manfrida G., Pescioni A. Model of a small steam engine for renewable domestic CHP (combined heat and power) system (2013) Energy, . Article in Press.

[14] Badami M., Mura M. Preliminary design and controlling strategies of a small-scale wood waste Rankine Cycle (RC) with a reciprocating steam engine (SE) (2009) Energy, Volume 34, Issue 9, pp. 1315-1324.

[15] Badr O, Naik S, O'Callaghan PW, Probert S D. Rotary Wankel engines as expansion devices in steam Rankine-cycle engines. Applied Energy Volume 39, Issue 1 (1991) 59-76.

[16] Badr O. Naik S. O'Callaghan P W, Probert S D. Wankel engines as steam expanders: Design considerations. Applied Energy Volume 40, Issue 2 (1991) 157-170.

[17] Antonelli M., Martorano L. A study on the rotary steam engine for distributed generation in small size power plants (2012) Applied Energy, Volume 97, pp. 642-647.

[18] Antonelli, M., Baccioli, A., Francesconi, M., Desideri, U., Martorano, L. Operating maps of a rotary engine used as an expander for micro-generation with various working fluids (2014) Applied Energy, 113, pp. 742-750.

[19] Antonelli, M., Baccioli, A., Francesconi, M., Martorano, L. Experimental and numerical analysis of the valve timing effects on the performances of a small volumetric rotary expansion device (2014) Energy Procedia, 45, pp. 1077-1086.

[20] Antonelli, M., Baccioli, A., Francesconi, M., Martorano, L. Numerical and experimental analysis of the intake and exhaust valves of a rotary expansion device for micro generation (2015) Energy Procedia, 81, pp. 461-471.

[21] Antonelli, M., Baccioli, A., Francesconi, M., Desideri, U., Martorano, L. Electrical production of a small size Concentrated Solar Power plant with compound parabolic collectors (2015) Renewable Energy, 83, pp. 1110-1118.

[22[Antonelli, M., Baccioli, A., Francesconi, M., Desideri, U. Dynamic modelling of a low-concentration solar power plant: A control strategy to improve flexibility (2016) Renewable Energy, 95, pp. 574-585.

Biography

Marco Antonelli was born in 1975, September 11. He got the Master degree in Mechanical Engineering in 2000 and the PhD title in 2004. He works as a researcher at the University of Pisa since 2006 and his main activity focuses are energy systems, renewable energies, internal combustion engines and distributed micro co-generation.