Open Access Journal

Journal of Power Technologies 97 (3) (2017) 259–264

journal homepage:papers.itc.pw.edu.pl

Identification of the characteristics of a carbon dioxide breathing rotary sliding–vane expander

Jarosław Milewski[a,*], Piotr Lis[a], Artur Olszewski[b], Arkadiusz Sieńko[b], Tomasz Sęk[b]

[a] *Faculty of Power and Aeronautical Engineering, Warsaw University of Technology, Institute of Heat Engineering, 21/25 Nowowiejska Street, 00-665 Warsaw, Poland*
[b] *Energia 3000 sp. z o.o. 78 Modrzewskiego Street, 97-320 Wolborz, Poland*

Abstract

This paper presents a study providing the experimental analyses on the rotary vane expander operating conditions with carbon dioxide as working fluid in comparison against air (chosen as reference). Such working fluid is promising for application as energy converters in a waste heat recovery for electric power. Experiments were performed on a prototype of rotary sliding vane expander.

The experiment demonstrated that commercially available multi–vane pneumatic engines can be adopted to waste heat recovery systems. During the experiments, the operation of the multi–vane expander was kept under observation for various inlet temperature, various pressure ratios, and various rotational speeds. Adequate maps of performances for air and carbon dioxide were created, compared against each other, and commented. In general, by using the same machine, power and efficiency can be raised by only change of working fluid.

Keywords: rotary sliding vane expander, carbon dioxide, experiments, maps of performances

1. Introduction

More than half of the energy produced from a fuel consumed by a piston engine is wasted in the form of exhaust gas heat and engine coolant heat. The utilization of a part of wasted heat can be done by implementation of binary system (e.g. Rankine cycle based [1]). It should be noted that a positive displacement expander has many advantages over the turbo-expander typically employed in small scale Rankine cycle systems in terms of the low speed operation characteristics, good part load characteristics, and cost.

Carbon dioxide as a working fluid has several advantages against steam turbine, gas turbine and ORC based systems. Based on a short review of supercritical carbon dioxide based gas turbine cycles [2], the several configurations covered in the available literature can be applied here. The parameters of the cycles are in quite wide ranges: operating temperature (80–800° C), pressure (74–290 bar). The systems operating on carbon dioxide can achieve an ultra high efficiency (60% with TIT = 1,220°C). The reported rotary equipment efficiency is quite high for the small size of the turbomachinery, reaching 87% for the expander and 70% for the compressor. The small size of the turbomachiery requires elevated rotationary speeds of up to 69,000 rpm. On the other hand the volumetric rotary machines, in particular rotary vane types have also many advantages, of which most important are [3]

- arbitrary pressure drops easily achieved in one or many stages
- machine shaft directly coupled with the motor or power receiver
- operation insured also for small agent flows through the machines
- moderate rotational speeds
- simple connection into multi–segment systems

The latter feature is especially important for systems designed for waste heat recovery which can based on carbon dioxide as working fluid.

In [4], the measured efficiency of the rotary-vane-type expander was found at 43, 44, and 48% for a heat source temperature difference of 60, 70, and 80°C, respectively by using a compact Organic Rankine Cycle (ORC) based on HFC-245fa as the working fluid. The maximum expander power

*Corresponding author
Email addresses: milewski@itc.pw.edu.pl (Jarosław Milewski), piotr.lis@aol.com (Piotr Lis), artur.energia3000@gmail.com (Artur Olszewski), arek_sienko@poczta.onet.pl (Arkadiusz Sieńko), tom.sek@wp.pl (Tomasz Sęk)

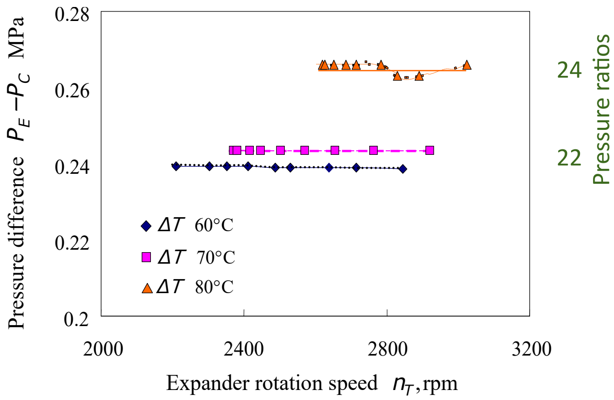

Figure 1: The influence of temperature difference on pressure difference as a function of expander rotational speed [4]

was 32 W in the case of ΔT = 80°C. The measured thermal efficiencies taking into account pump power losses were found at 3.07, 3.14, and 3.82% respectively for mentioned above temperatures. The low obtained efficiencies are resulted by a high pump power consumption, and lack of insulation. Fig. 1 presents the result obtained by the authors, but the it should be noted that they used pressure differences as the rotary equipment parameters. Usually, the pressure ratio is used here, thus the graph was updated by the associated values of pressure ratio (right axis).

In [5], a sliding vane expander was designed to replace the throttle valve in HFC410A refrigerant system for energy recovery and its performance parameters was tested on the built bench. The improvement of performance on energy recovery system was also investigated. Based on the analysis of the experimental results, the variation of isentropic efficiency with the rotational speed of the prototype was presented. The isentropic efficiency increased firstly at the rotational speed of 800 .. 1,200 rpm, then decreased when the rotational speed was larger than 1,200 rpm. The maximum value of isentropic efficiency was 32.7%, when the rotational speed of prototype was 1,200 rpm. Those value correspond to the peak value of recovery power at 178 W.

The work [6] describes a CFD simulation of a vane expander machine adopted as power source inside an organic Rankine cycle. Simulations have been carried out considering three different operating conditions, and results have been compared to measured data, showing an encouraging agreement. The used machine was consisting of a stator, a rotor and a certain number of vanes which are moveable in radial direction. A simple sketch of the expander is shown in Fig. 3.

Experimental measurements and modeling of the vane expander prototype (see Fig. 4) used in an experimental ORC which uses hexamethyldisiloxane as a working fluid is described in [7]. The ORC is cooled by air and uses flue gas as a source of heat. The vane expander reached the maximum shaft power of 1.05 kW with the adiabatic efficiency at 45% and maximum 58% at only 0.8 kW.

The experimental campaign aimed at characterizing the

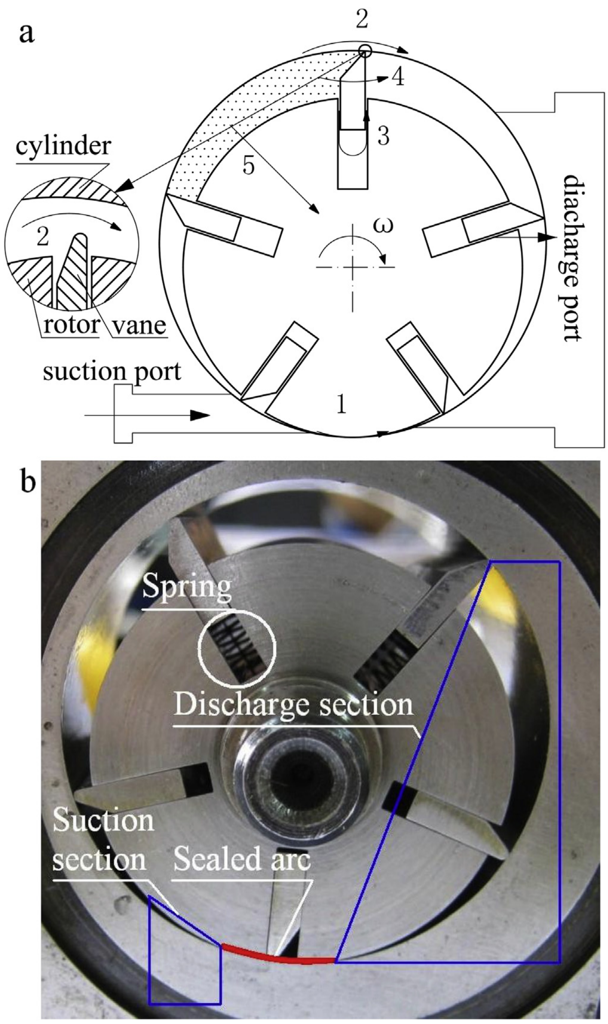

Figure 2:

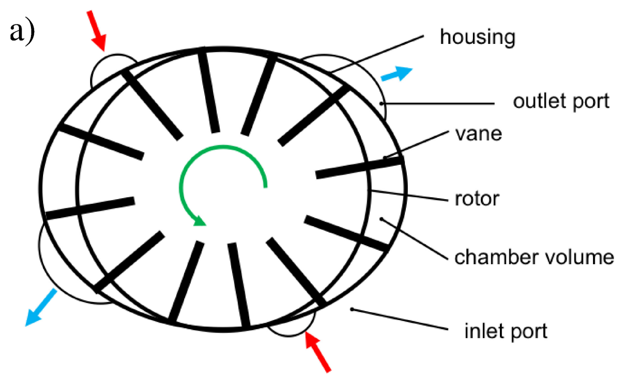

Figure 3: Schematic of the dual chamber radial expander [6]

behavior of a 5.9 cm^3 sliding vane expander based recovery system was done by Bianchi [8]. The expander efficiency, computed as ratio of the mechanical power over the isentropic power was at the level of 53.3%. The result was obtained for off-design conditions with higher heat gain, mechanical power recovered increased due to a higher working fluid mass flow rate and cycle pressure ratio, mechanical

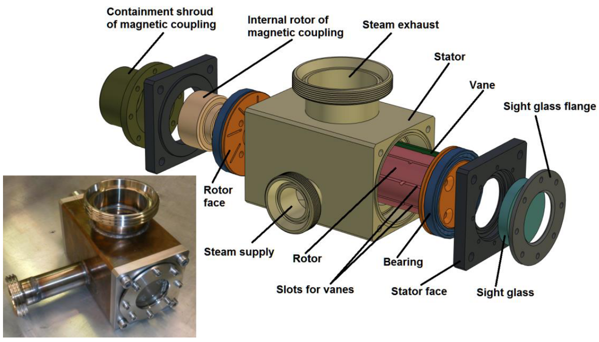

Figure 4: Design of the vane expander [7]

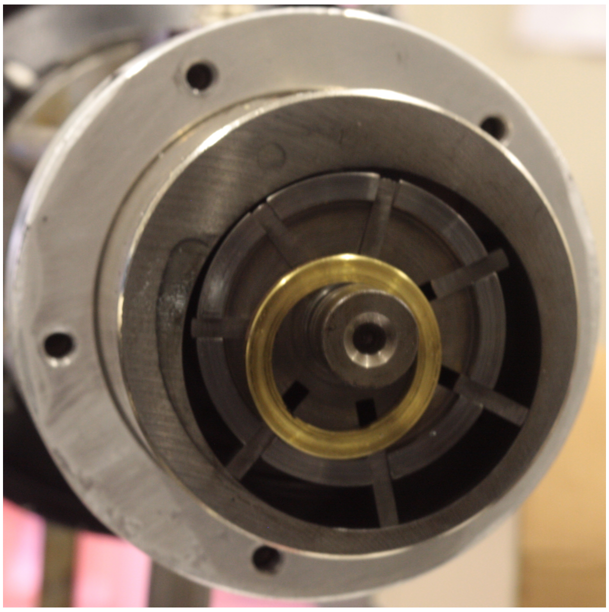

Figure 5: Expander prototype [8]

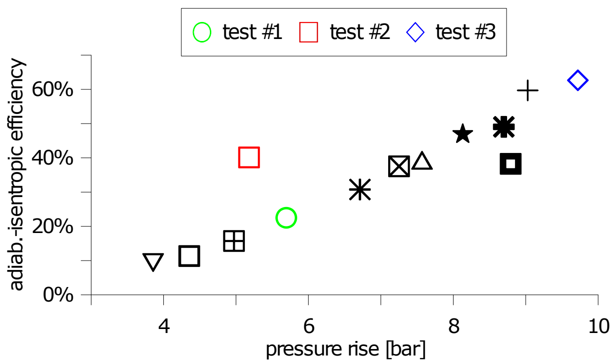

Figure 6: Adiabatic efficiency of the expander [8]

power recovery reached up to 1.9 kW. The results confirm the reliability and efficiency of sliding vane machines as devices for waste heat recovery systems in automotive applications. Compactness and easiness to implement control strategies through linear changes in the mass flow rate acting on the revolution speed are additional advantages.

The paper [9] contains experimental analysis on the rotary

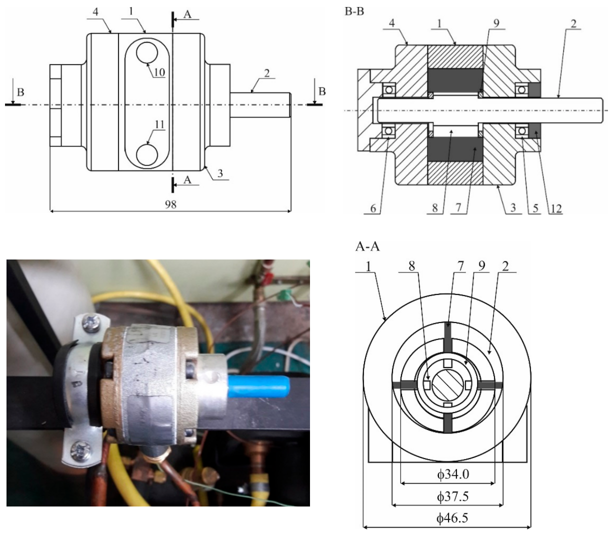

Figure 7: A general view and simplified construction scheme of the expander [9]

vane expander (see Fig. 7) operating conditions in a micro ORC. The expander indicated work and efficiency change depending on the heat source temperature and the pressure ratio. The expander internal efficiency varies in the range of 17.2 .. 58.3%. Progressive lowering the expander internal efficiency and indicated work is observed for higher values of the expansion ratio, giving the optimum expansion ratio at around 2. Thus, increasing the working fluid pressure at the inlet of the expander results in decreasing the efficiency and power of the expander.

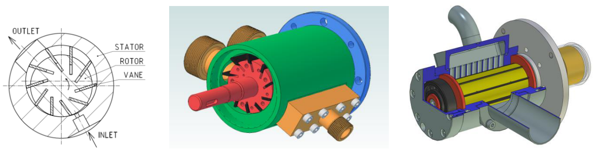

Figure 8: A cross-section of the expander used for μCHP plant [10]

Four units with nominal output 1 .. 5 kW based on rotary vane expander and the applications were built as micro units for waste heat recovery and combined heat and power production are presented in [10]. Rotary vane expanders of in-house design (see Fig. 8) achieve isentropic efficiency of 40 .. 58% in range of mechanical power output of 1 .. 8 kW.

Rotary sliding–vane expanders are used as a part of heat recovery systems. They operated on air or refrigerant based working fluid. The rotary sliding-vane expanders have similar construction as rotary sliding–vane pumps and compressor. On the other hand, carbon dioxide has very favorable compression parameters close to its critical point, giving relative specific power required for the compression (as its behavior is close to liquid). By composing those two aspects (rotary sliding–vane machine for expanding the carbon dioxide as working) may be real breakthrough in the waste heat recovery processes. The paper presents the identification of the commercially available rotary sliding–vane expander operated on CO_2 against the performance obtained for air as working fluid (for the reference).

2. Experimental set-up

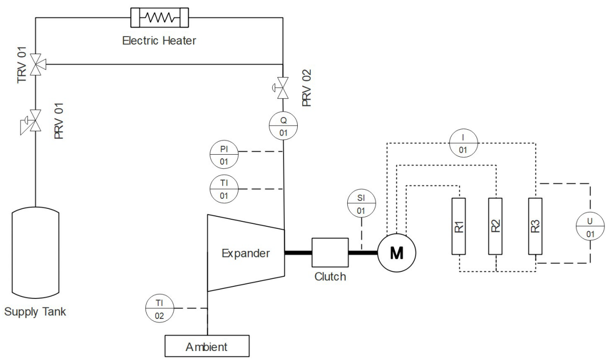

Figure 9: Simplified schematic of the laboratory stand for characterization of rotary sliding vane expander

The experimental test–stand was built at Institute of Heat Engineering at Warsaw University of Technology from materials supplied by Energia 3000 Ltd. It was based on a micro four–vane sliding type expander derived from commercial pneumatic motor. Fig. 9 shows simplified schematic of the test-stand.

The test-stand was created to better understand characteristics of sliding vane type expander and study its potential application in different power systems. The authors focused on comparison of expander performance under different working conditions and using different working fluid.

The test-stand consists of working fluid pressurized tank, pressure reducing valve, temperature regulating valve, electric heater unit, main pressure regulating valve, micro rotary sliding vane expander, and load (electric generator). Test-stand maximum operating temperature is 100°C and maximum operating pressure is 15 bar.

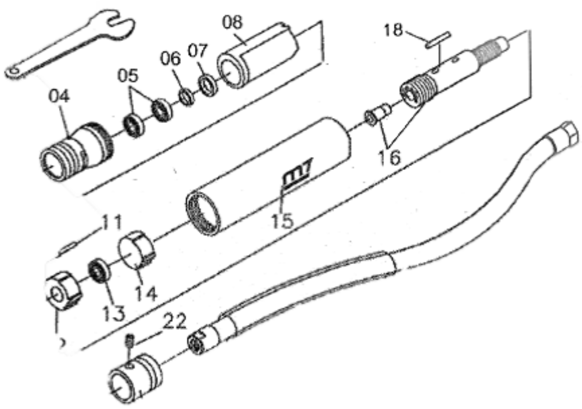

Figure 10: The expander cross section

The expander cross section is presented in Fig. 10. Main components are cylinder (08), rotor (09) and vanes (10).

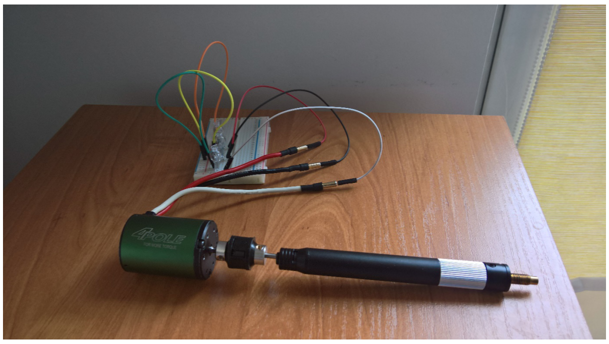

Figure 11: The expander–generator set used for the experiments

Cylinder is eccentric to the rotor thus during rotation the variable volume chambers are occurred and working fluid is expanded. A load for the expander is high speed brushless generator equipped with symmetric resistive load cell which can be changeable. The expander–generator assembly is shown in Fig. 11.

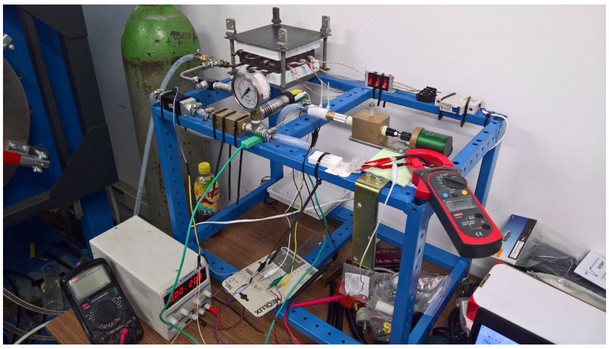

Figure 12: The test stand for characterization of micro rotary sliding vane expander opaerated on CO_2

The test–stand operation is as follows (refer to Fig. 12): a working fluid is supplied to the system from pressurized tank through pressure reducing valve. Depending on required expander inlet temperature regulating valve is used for obtaining a desired hot and cold fluid mixing ratio. A working fluid is heated by three heaters with maximum power rated at 1.5 kW. Desired expander inlet pressure is obtained by pressure regulating valve.

The measurement campaign was carried out for different inlet pressures, temperatures and generator loads. The test was performed for working fluid pressure range of 2 .. 4 bars with step size at 0.5 bar, two working fluid temperatures: 20°C, 70°C and two different generator load values. Experiments were done for two various working fluids air (for the reference) and carbon dioxide.

3. Operation of rotary sliding–vane expander fed by CO_2

Fig. 13 presents the expander pressure ratio characteristic with air as working fluid. The rotary sliding vane expander has relatively constant pressure ratios for given rotational

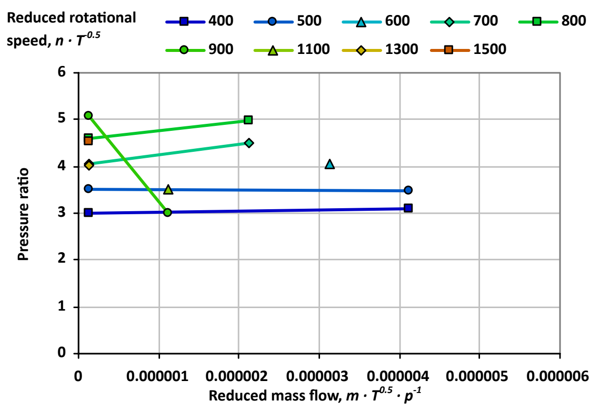

Figure 13: The expander operated on air pressure ratio as a function of reduced mass flow, $\frac{\dot{m}\cdot\sqrt{T}}{p}$ for various reduced rotational speeds, $\frac{n}{\sqrt{T}}$

speeds, this is typical for positive displacement engines with rotating volumes.

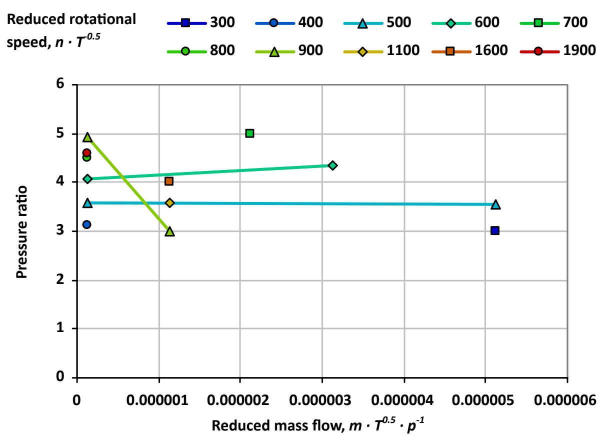

Figure 14: The expander operated on carbon dioxide pressure ratio as a function of reduced mass flow, $\frac{\dot{m}\cdot\sqrt{T}}{p}$ for various reduced rotational speeds, $\frac{n}{\sqrt{T}}$

By changing the working fluid from air to carbon dioxide, the highest mass flows can be reached. Reduced mass flow rises itself by 25% with almost the same pressure ratios as for air.

The expander adiabatic (isentropic) efficiencies are changed themselves from about 5% to 26% for very small mass flows (see Fig. 15). On average the expander reaches about 10% of adiabatic efficiency for various reduced mass flows by changing reduced rotational speed.

For carbon dioxide as working fluid, adiabatic (isentropic) efficiencies are changed themselves from about 7% to 35% for very small mass flows (see Fig. 16). On average the expander reaches about 15% of adiabatic efficiency for various reduced mass flows by changing reduced rotational speed, what means that CO_2 is responsible for rising the expander efficiency by 50%.

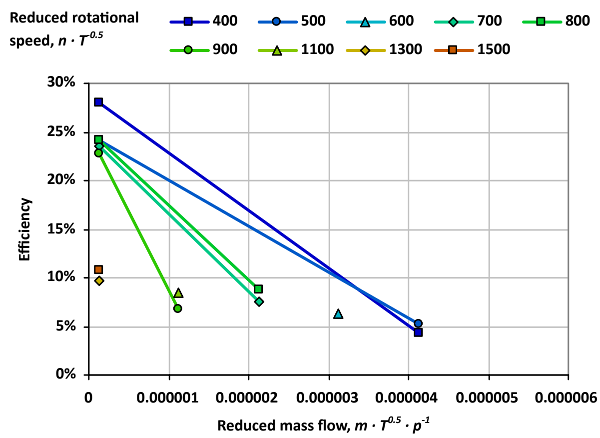

Figure 15: Efficiency curves for expander operated on air as functions of reduced mass flow , $\frac{\dot{m}\cdot\sqrt{T}}{p}$ for various reduced rotational speeds, $\frac{n}{\sqrt{T}}$

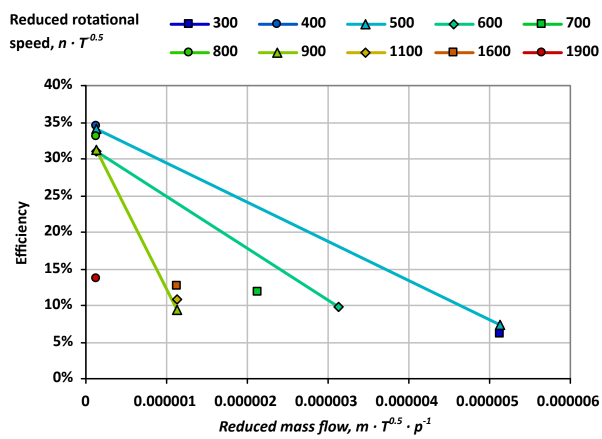

Figure 16: Efficiency curves for expander operated on carbon dioxide as functions of reduced mass flow , $\frac{\dot{m}\cdot\sqrt{T}}{p}$ for various reduced rotational speeds, $\frac{n}{\sqrt{T}}$

4. Conclusion

This paper presents a study providing the experimental analyses on the rotary vane expander operating conditions with carbon dioxide as working fluid in comparison against air (chosen as reference). Such working fluid is promising for application as energy converters in a waste heat recovery for electric power. Experiments were performed on a prototype of rotary sliding vane expander.

The experiment demonstrated that commercially available multi–vane pneumatic engines can be adopted to waste heat recovery systems. During the experiments, the operation of the multi–vane expander was kept under observation for various inlet temperature, various pressure ratios, and various rotational speeds. Adequate maps of performances for air and carbon dioxide were created, compared against each other, and commented. In general, by using the same machine, power and efficiency can be raised by only change of working fluid.

Acknowledgments

The experimental part was financially supported by Energia 3000 Ltd company.

References

[1] Y. M. Kim, D. G. Shin, C. G. Kim, Optimization of design pressure ratio of positive displacement expander for vehicle engine waste heat recovery, Energies 7 (9) (2014) 6105–6117.

[2] J. Milewski, M. Wołowicz, Variant analysis of the structures and parameters of the systems with supercritical co2, in: Hydrogen Power Theoretical and Engineering Solutions International Symposium June 28-30, 2017 - Syracuse, Italy, 2017, p. 232.

[3] Z. Gnutek, E. Kalinowski, Application of rotary vane expanders in systems utilizing the waste heat, in: International Compressor Engineering Conference, 1994.

[4] M. B. M. Tahir, N. Yamada, T. Hoshino, Efficiency of compact organic rankine cycle system with rotary-vane-type expander for low-temperature waste heat recovery, International Journal of Mechanical and Mechatronics Engineering 4 (1) (2010) 105–110.

[5] C. Xia, W. Zhang, G. Bu, Z. Wang, P. Shu, Experimental study on a sliding vane expander in the hfc410a refrigeration system for energy recovery, Applied Thermal Engineering 59 (1) (2013) 559–567.

[6] G. Montenegro, A. Della Torre, M. Fiocco, A. Onorati, C. Benatzky, G. Schlager, Evaluating the performance of a rotary vane expander for small scale organic rankine cycles using cfd tools, Energy Procedia 45 (2014) 1136–1145.

[7] V. Vodicka, L. Guillaume, J. Mascuch, V. Lemort, Testing and modeling a vane expander used in an orc working with hexamethyldisiloxane (mm), ASME ORC 2015 (2015) 136.

[8] G. Bianchi, Exhaust waste heat recovery in internal combustion engines, Ph.D. thesis, Ph. D. Thesis, University of L'Aquila, L'Aquila, Italy (2015).

[9] P. Kolasiński, P. Błasiak, J. Rak, Experimental and numerical analyses on the rotary vane expander operating conditions in a micro organic rankine cycle system, Energies 9 (8) (2016) 606.

[10] J. Mascuch, V. Novotny, V. Vodicka, Z. Zeleny, Towards development of 1-10 kw pilot orc units operating with hexamethyldisiloxane and using rotary vane expander, Energy Procedia In Press.