Experimental investigation of the ORC system in a cogenerative domestic power plant with a scroll expanders

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Abstract: The paper presents the results of experimental investigations of the ORC system with two scroll expanders which have been used as a source of electricity. The working fluid was HFE7100 – a newly engineered fluid with a unique heat transfer and favourable environmental properties. In the ORC system three heat exchangers were used (evaporator, regenerator, condenser) and before expanders the droplet separator was installed. As a source of heat an innovative biomass boiler was used. Studies have been carried out for the expanders worked in series and in parallel. The paper presents the thermal and fluid-flow properties of the ORC installation for the selected flow rates and different temperatures of the working medium. The characteristics of output electrical power, operating speed and vibrations for scroll expanders were also presented.

Keywords: Organic Rankine Cycle; micro CHP; scroll expander; biomass boiler; waste heat; HFE7100

1 Introduction

In the recent years, cogenerative systems allowing for the use of waste heat for electricity production have gained a lot of attention. Especially popular among them are ORC (Organic Ranking Cycle) systems. They use low-temperature heat sources (up to 300°C), either of natural origin (biomass, geothermal, solar power) or in the form of waste heat, for example from post-production processes [1]. The main elements of an ORC are: an evaporator, condenser, heat source (e.g. a boiler), working fluid pump and an expansion element. In order to increase efficiency of an ORC system, a regenerator is often incorporated in the system. The key element of an ORC system is the expansion element as it has impact on the system in its entirety. In low-power ORC systems (1–10 kWel) scroll, piston and screw expanders, as well as turbines are used [2, 3].

Mayer et al. [4] investigated into the ORC system with a scroll expander and HFC-M1 as the working fluid. The scroll Air Squared expander had the following rated parameters: expansion coefficient 3.5, nominal rotational speed 3600 rpm, pressure 13.8 bar, displacement 12 cm³/rev. Purified exhaust gases from the Capstone gas turbine were used as the heat source. The temperature of gas was about 220°C and its mass flow was about 0.3 kg/s. The Carnot efficiency was about 10.1% and the thermal efficiency reached 5.7%.

Kane et al. [5] constructed and launched the ORC using waste heat from two biogas engines (each of 200 kWel) used in the cogenerative system in the biogas power plant - Nant de Chatillon, Switzerland. A scroll expander with a 7 kWel generator was used in the ORC. The working fluid used was HCFC134a. The ORC used heat waste of 80 – 90°C. The net efficiency of the system was 3 – 7% and rose with thermal power of the biogas engine (i.e. within the range of 45 – 80 kWth). The maximum Carnot efficiency reached 18%.

Kaczmarczyk et al. [6–8] investigated into the ORC with an expansion valve (simulating work of a microturbine) and radial microturbine. The experimental investigation conducted in the regenerative ORC test bench with a gear pump and a radial microturbine gave the following physicochemical parameters of HFE 7100 (working medium): temperature 180°C, pressure 11.76 bar, work-
ing medium flow rate 0.16 kg/s. Reaching the shaft rate of 254 Hz, the microturbine generates electric power of 360 W. The Carnot efficiency of the regenerative ORC system with a microturbine was about 32% and the thermal efficiency of the regenerative ORC system with a microturbine was about 5.2%.

Quoilin et al. [9, 10] investigated the ORC system with a prototype of scroll expander and working medium HCFC-123. As an expansion device a modified oil-free scroll compressor was applied. Two hot air flows were used as a heat source. The isentropic expander effectiveness was in the range from 42% to 68% for the pressure ratio of the expander in the range from 2.7 to 5.4. The maximum cycle efficiency was about 74%. Quoilin et al. have proposed different analytical models of components and parameters of the ORC system. Difference between the measured electric power generated by the expander and power value calculated by a numerical model was less than 10%.

Liu et al. [11] used a modified air turbine motor as a turbine in the ORC system. The turbine was connected to a car alternator, which was loaded with resistors and light bulbs. The researchers used two heat sources: electric heater 9 kW and a biomass-fired boiler with power 25 kW \(_{th}\). As the working fluid the HFE700 and HFE7100 were used. In the ORC system with electric heater maximum electrical power was 96 W, electrical efficiency was 1.06% and the efficiency of the CHP system was over 83%. In the ORC system with biomass boiler electrical efficiency was 1.34%, the efficiency of the CHP system was 88%, and the maximum electric power was about 284 W.

Qiu et al. [12] presented the literature review and checked current availability of expanders (with a capacity < 10 kW\(_e\)) on the market. The study showed the average purchase cost of an expander operating in the ORC system. The micro-scale turbine expander (< 10 kW\(_e\)) is not commercially available, and many researchers have attempted to design and build their own construction of microturbine. In the case of screw expanders, the units available in the market have power capacities exceeding 50 kW\(_e\). The net cost of the installation of screw expanders ORC amounts to £2000/kW\(_e\). The scroll expanders are commercially available in the power range from 0.1 to 10 kW\(_e\). The unit with power 10 kW\(_e\) costs about €55000.

Liu et al. [13] presented the results of the modeling of ORC system with a biomass boiler. The three refrigerants: HFE7000, HFE7100 and n-pentane where analyzed. The commercial software EES (Engineering Equation Solver) was used in the calculations of the ORC system. For HFE7000 the ORC efficiency is in the range of 9.2% – 16.0%, the electrical efficiency of CHP system is from 75% – 13.1% with the electricity output between 1.5 kW\(_e\) to 2.61 kW\(_e\). For HFE7100 the ORC efficiency is within the range of 9.2% – 15.4%, whereas the electrical efficiency of CHP system ranges from 75% to 12.6% with the electricity output between 1.5 kW\(_e\) to 2.51 kW\(_e\). When n-pentane is used as the ORC fluid, the maximum electrical efficiency is 16.6% and maximum electrical efficiency of the CHP system is 13.5% with the electricity output of 2.71 kW\(_e\).

Declaye et al. [14] investigated the oil-free scroll expander in an ORC system with R245fa. The scroll expander was obtained by modifying an open-drive scroll compressor to run in inverse. The maximum isentropic efficiency depends on the rotational speed. For an inlet pressure 12 bar, it ranges from 71.3% at 3500 rpm to 75.7% at 2500 rpm. The maximum shaft power is 2.00 kW at 3500 rpm for a pressure ratio of 7.18 and an inlet pressure of 12 bar. The minimum shaft power is 0.21 kW at 3000 rpm for a pressure ratio of 2.36 and an inlet pressure of 9 bar. The maximum cycle efficiency is 8.54% at 3000 rpm for a pressure ratio of 7.1 and an inlet pressure of 12 bar. The minimum cycle efficiency is 0.1% at 3000 rpm for a pressure ratio of 2.36 and an inlet pressure of 9 bar. The exergetic efficiency is 48% at 3000 rpm for pressure ratio 4.32 and an inlet pressure of 12 bar.

Li et al. [15] presented a theoretical and experimental study of heat loss in the radial-axial turbine (with power 3.3 kW) in the ORC system. It was a quantitative study on the convection, radiation, and convective heat transfer. The results show that the external radiative or convective heat loss coefficient was about 3.2 W/m\(^2\)K or 7.0 W/m\(^2\)K when the ORC operated around 100°C. The total heat loss coefficient in the ORC experimental test was about 16.4 W/m\(^2\)K, where its value was estimated at 94.5 W. The expander efficiency will be overestimated by about 2.9% if the external heat loss is not taken into consideration.

![Figure 1: ORC installation working with the use of HFE7100.](image-url)
Pei et al. [16] presented the results of a prototype of radial-axial turbine operating in ORC cycle with R123 as a working fluid. The turbine isentropic efficiency is about 62.5% and ORC efficiency is around 6.8%. The turbine shaft power was about 1 kW.

G. Qiu et al. [17] tested the ORC system with 50 kW\textsubscript{th} biomass-pellet boiler and vane-type air motor as an expander. The experimental results show that the CHP system generated about 860 W\textsubscript{e} of electricity, efficiency of electricity generation was 1.41% and CHP efficiency was 78.69%.

2 Test bench

2.1 ORC installation

The ORC installation in the Laboratory of Cogenerative Micro Power Plants is composed of three basic cycles: a heating cycle, cooling cycle and a working fluid cycle. The ORC test bench with a HFE 7100 droplet separator is presented in Fig. 1.

The heating cycle consists of a group of oil pumps and two independent heat sources: a multifuel boiler and a set of two electric thermal oil heaters that can work independently or in series/parallel. The prototypical electric flow heater for thermal oil consists of two modules: LKM-25/75-300 and LKM-25/75-301. Both modules can work independently or in series and are designed to heat non-conductive fluids (thermal oil) to the temperature of about 250°C with low electrical power density (below 3 W/cm\textsuperscript{2}) and the power of $2 \times 24$ kW\textsubscript{e}. The prototypical boiler enables combustion of gas fuel (GZ-50 or gas from biomass gasification) or solid fuel in the form of biomass (pellets). The maximal boiler power during biomass combustion (pallets of about 5 mm diameter) is about 30 kW\textsubscript{th}. The prototype plate heat exchanger (RB60-60H model) with a heat transfer surface area of 4.1 m\textsuperscript{2} acted as an evaporator in the heating circuit. In the case of the heat regenerator the shell & coil heat exchanger (JADX-K5.38.08.71 model) with a heat transfer surface area of 2.3 m\textsuperscript{2} was used. The prototype plate condenser (LB47-70 model) with a heat transfer surface area of 3.2 m\textsuperscript{2} was operated in the cooling circuit. The arrangement of the heat exchangers on the ORC installation is presented in Fig. 4 and 5. The ORC installation can work using an expansion valve (simulating work of a microturbine), microturbine or a group of expanders.

2.2 Test bench for scroll expanders

The test bench allows for testing two expanders working in different configurations: in parallel, in series or in a single expander system. It also allows for testing expanders using HFE7100 as the working fluid when the pressure of the low-boiling working fluid steam is about 14 bar. The Air Squared scroll expanders [18] are equipped with mag-
netic couplings and electric generators whose nominal rotational speed is 3600 rpm.

The test bench with scroll expanders is presented in Fig. 2.

The test bench with expanders allows for work in different configurations:

- configuration 1: work without expanders (by-pass);
- configuration 2: work of expander 1 (expander 2 turned off);
- configuration 3: work of expander 2 (expander 1 turned off);
- configuration 4: work of expander 1 and expander 2 (work in series);
- configuration 5: work of expander 1 and expander 2 (work in parallel).

The test bench consists of an electric load system and a data-saving system for measurement data: thermodynamic parameters (temperature and pressure of the working fluid) and electrical parameters (electrical generator rotational frequency, current, voltage and power consumed by the load). Furthermore, the installation has two collectors (inlet and outlet) and a group of regulating valves allowing for testing the expanders in different configurations.

The scroll expanders working in parallel in the ORC with an electric thermal oil heater or multifuel boiler is presented in Fig. 3.

A set of 5 light bulbs of 1 kW<sub>el</sub> in total were used as a load for each scroll expander.

### 3 Test results of the ORC system working with scroll expanders

The experimental studies on the expanders, operating in the ORC cycle, were performed for selected flow rate values of the working mediums, that is: thermal oil in the range of 0.18 – 0.21 kg/s, working medium HFE7100 in the interval from 0.10 kg/s to 0.12 kg/s, glycol with distilled water solution in the range of 0.11 – 0.12 kg/s.

In the ORC test bench two measurement tests were carried out. In the first place, the ORC system with two scroll expanders working in parallel was tested – Fig. 4. The other test was performed on the system working with expanders in series – Fig. 5.

Fig. 6 presents a T-s diagram for expander 1 working in parallel in the regenerative ORC system.

In the regenerative ORC system with HFE7100, expanders working in parallel and a gear pump, the temperature of the working fluid at the inlet to expander 1 reached about 155°C (point 1 – Fig. 6). The efficiency of the ORC cycle with scroll expanders running in parallel amounted to 10.8%.
Fig. 5: Measurement scheme of the regenerative ORC system with scroll expanders working in series (system with the electric oil heater or multifuel boiler).

Fig. 6: T-s diagram for scroll expander 1 working in the ORC with regeneration – expanders in parallel.

Fig. 7 presents a T-s diagram for expander 2 working in series in the regenerative ORC.

In the regenerative ORC system with HFE7100, expanders working in series and a gear pump, the temperature of the working fluid at the inlet to expander 2 reached about 164°C (Fig. 7). The efficiency of the ORC cycle with scroll expanders connected in series amounted to 11.6%.

The P-v diagram for scroll expander 1 working in parallel in the regenerative ORC system is presented in Fig. 8.

In the regenerative ORC system with HFE7100 and expanders working in parallel, the pressure of the working fluid at the inlet to expander 1 was 9.14 bar.

The P-v diagram for scroll expander 2 working in series in the regenerative ORC system is presented in Fig. 9.
In the regenerative ORC system with HFE7100 and expanders working in series, the pressure of the working fluid at the inlet to expander 2 was about 9.34 bar.

Fig. 10 presents changes in rotational speed of scroll expanders working in parallel in the regenerative ORC system.

It can be seen from the measurement data that in the parallel system the maximum rotational speed of scroll expander 1 was about 2400 rpm, whereas in expander 2 it reached 2420 rpm.

Fig. 11 presents the changes in rotational speed of scroll expanders working in series in the regenerative ORC system.

It can be seen from the measurements that in the series system the maximum rotational speed of scroll expander 1 was about 2620 rpm, whereas in expander 2 it reached 2820 rpm.

Fig. 12 presents changes in electric power in expanders 1 and 2 as well as in total power measured in the ORC test bench in the parallel system versus time.
Figure 10: Changes in rotational speed of scroll expanders working in parallel in the ORC system.

Figure 11: Changes in rotational speed of scroll expanders working in series in the ORC system.

Figure 12: Changes in electric power generated by expanders working in parallel in the ORC system.
It can be seen in Fig. 12 that the total electric power in the ORC system with the expanders working in parallel was about 1100 W; electric power parameters of expanders 1 and 2 were similar and of about 550 W.

Fig. 13 presents electric power of expanders 1 and 2 working in series in the regenerative ORC system.

The total electric power in the regenerative ORC with the expanders working in series was about 1135 W. The maximum electric power of expander 1 was about 650 W, and 770 W in expander 2.

4 Measurement of scroll expanders vibration

While carrying out the above mentioned tests on the expanders, vibrations were also measured with the use of equipment for the assessment of dynamic states of machines. The main goal of the test was to assess the general vibration level, find characteristic frequency parameters, as well as establish standard conditions of the machines. The measurements were performed with the use of single axis accelerometers with magnetic base. Due to the difficulties in attaching the vibration sensors to the aluminium body of expanders, the sensors were attached to the steel elements directly under the tested machines.

Measurement of vibration was carried out perpendicularly to the rotation axes of the rotors, within the frequency range up to 1600 Hz and the resolution of 1 Hz. The portable machinery health analyser Emerson CSI2140 was used for measurements.

Fig. 14 presents the measurement results for the vibration spectra of expanders working in parallel in the ORC system; Fig. 15 presents similar results for the series work.

With the expanders working in parallel, the synchronous component was at the frequency of about 42 Hz. In the serial system, the synchronous component was at the frequency of 41 Hz for both expanders. The maximum vibration amplitude in both cases did not exceed 15 mm/s. Apart from the synchronous components, it was possible to observe harmonic components, corresponding to the times of the basic frequency, but their amplitudes were much smaller.

On the basis of the results, it can be stated that despite of many harmonic components registered in the vibration spectrum, both machines worked correctly. No defects were detected in the vibration spectrum.

5 Summary and conclusion

Basing on the presented investigations into scroll expanders in the regenerative ORC system, it has been stated that scroll expanders working in parallel generate total electric power of 1.1 kW. The electric power generated by each of the expanders working in parallel reached 550 W. In the parallel system, the maximum rotational speed of scroll expander 1 was about 2400 rpm and reached about 2420 rpm in expander 2. The efficiency of the ORC cycle with scroll expanders connected in parallel amounted to 10.8%.

The total electric power generated with the use of expanders working in series in the regenerative ORC sys-
The maximum electric power of expander 1 was about 650 W, and reached 770 W in expander 2. In the serial system, the maximum rotational speed of scroll expander 1 was about 2620 rpm and reached about 2820 rpm in expander 2. The efficiency of the ORC cycle with scroll expanders connected in series amounted to 11.6%.

It has to be stressed that the test bench was not thermally isolated while carrying out the above mentioned tests. The thermal isolation that is to be installed should drastically reduce heat losses and allow for achieving higher electric power parameters.
Nomenclature

I  current, A
N  electric power, W
n  expander rotation, Hz
P  pressure, Pa
T  temperature, °C
U  voltage, V
v  specific volume, m³/kg
Z  regulation valve

Subscripts

th  thermal
1–8  state points
e  electrical

Acronyms

CHP  combined heat and power
ORC  Organic Rankine Cycle

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