EXPERIMENTAL INVESTIGATION OF A RADIAL MICROTURBINE IN ORGANIC RANKINE CYCLE SYSTEM WITH HFE7100 AS WORKING FLUID

Tomasz Z. Kaczmarczyk*, Grzegorz Żywica, Eugeniusz Ihnatowicz

The Szewalski Institute of Fluid-Flow Machinery, Polish Academy of Sciences
Centre of Mechanics of Machines, Department of Turbine Dynamics and Diagnostics
Gen. J. Fiszera 14 st., 80-231 Gdańsk, Poland
tkaczmarczyk@imp.gda.pl, gzywica@imp.gda.pl, gieihn@imp.gda.pl

* Tomasz Z. Kaczmarczyk, e-mail: tkaczmarczyk@imp.gda.pl

ABSTRACT

The paper presents the results of experimental investigation of the ORC system with prototype microturbine. The prototype of biomass boiler has been used as a heat source. The boiler with a power rating of 25 kW_{th} is powered by biomass (wood pellets) using an auger. The biomass boiler heats thermal oil which is directed to the evaporator where the low boiling refrigerant evaporates. The maximum temperature of the thermal oil in the evaporator is about 210 ^{o}C – 215 ^{o}C. The solvent HFE7100 was used as the working fluid in the ORC system. The prototype of four-stage radial microturbine and biomass boiler has been designed and built at the Institute of Fluid-Flow Machinery of the PAS in Gdańsk. The designed electric capacity of microturbine is 2.7 kW_e at maximum speed of 24000 rpm. The isentropic efficiency for this fluid-flow machine is about 70%. The generated electricity is dissipated by an electric heater with a power of 5 kW_e and eleven light bulbs 100 W_e each. Electrical load can be adjusted according to your needs. At the inlet of the microturbine a condensate separator was applied to protect the blades from erosion and to ensure the proper operation of gas bearings. In the initial phase the steam microturbine is supplied with a high degree of superheat in the range from 30 K to 40 K (the warm phase of the microturbine). During normal operation of the microturbine, superheating degree of the low boiling fluid is in the range of 5 K to 10 K. The working fluid after expansion in microturbine is directed to the regenerator and then to the condenser. The heat supplied to the condenser is dissipated by a fan cooler with maximum power of 50 kW_{th}. Depending on the flow rate of the glycol in the condenser the absolute pressure is in the range of 1.2 bar - 3 bar and a temperature of the working fluid in the range from 20 ^{o}C to 65 ^{o}C can be obtained. The paper presents the characteristics of the ORC system and radial microturbine for different variants of flow rates for different working mediums (thermal oil, HFE7100, glycol). During testing of the ORC system with the prototype of radial microturbine and the biomass boiler (fired with wood pellets) the maximum electrical output power was around 1551 W_e.

1. INTRODUCTION

The Directive 2009/28/WE, approved by the European Union, has committed the majority of its Member States to increase the share of renewable energy sources in total energy consumption to 20% by 2020 (15% in Poland). This is not only an active fight against global climate change, but also a key contribution to boosting the development of modern technologies. That is why the scientists continue to search for new energy-saving technologies. One idea is to use new RES systems or modify existing systems by making use of CHP installations. Combined heat and power (CHP) production, e.g. in ORC systems, can be an alternative for traditional power engineering systems. The cogeneration systems are characterized by energy savings and environmental-friendly technologies. The use of micro-CHP system can easily satisfy single-family home demand for heat and electricity, reducing CO_2 emissions to atmosphere. It is estimated that in order to satisfy these demands for one single-family house, one needs to use a CHP system whose electrical power does not exceed 10 kW_e. For multi-family buildings, power capacity of CHP systems should be in the range of 10 – 30 kW_e (Liu et al., 2011, Onovwiona et al., 2006, Quoilin et al., 2010). In order to meet the EU directives and trends, for systems using RES, a domestic micro power plant (based on the ORC cycle) has been built at the Institute of Fluid-Flow Machinery, in Gdańsk. An expansion device is seen as a key element in any ORC installation which principally decides of the whole system efficiency. That is why many scientists carry out research on ORC cycles with various types of expanders i.e. vane, scroll, piston, screw expanders as well as Stirling engines or turbines. Mayer et al. (2013) 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 cm^3/rev. Purified exhaust gases from the Capstone gas turbine were used as a heat source. The temperature of gas was about 220 ^oC and its mass flow was about 0.3 kg/s. The Carnot efficiency was about 10.1% and the thermal efficiency reached 5.7%. Lemort et al. (2009) 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 7.4%. Quoilin et al. (2010) 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%. Declaye et al. (2013) 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 reverse. 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 0.21kW 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. Qiu et al. (2012) tested the ORC system with 50 kW_{th} biomass-pellet boiler and vane-type air motor as an expander. The experimental results show that the CHP system generated about 860 W_e of electricity, efficiency of electricity generation was 1.41% and CHP efficiency was 78.69%. Bahrami et al. (2013) performed thermodynamic analysis of an ORC cycle, in conjunction with a Stirling engine. The following working mediums were tested: FC72, FC87, HFE7000, HFE7100, Novec649, n-pentane, R245fa and toluene. Operating temperatures of ORC was between 80 ^oC and 140 ^oC. The steam turbine was used as an expansion device. Total power efficiency in the range 34% to 42% was observed for different cases. The ORC cycle efficiency was in the range of 15-19%, depending on the used working medium. They found that the best mediums in this cycle were: toluene, HFE7100 and n-pentane. Smith et al. (2006) carried out research on the ORC cycle with R124 as a working medium. Twin screw compressor was used as an expander. The machine was coupled to a generator, rotating at 1800 rpm, using a vee belt drive. Initial tests showed that the expander generated 22 kW of shaft power with an adiabatic efficiency of 74%. The unit cost is in the range of \$1500-2000/kW_e (water cooled) and \$2500/kW_e (air cooled). Seher et al. (2012) performed experimental studies and computational simulations of the ORC system equipped with two expanders, turbine and piston machine. The heat source was a 12 l heavy duty engine. The thermal power input to the WHR (waste heat recovery) system was from 100 kW_{ht} to 300 kW_{th}. They analyzed several working mediums, including water, toluene, ethanol, R246fa and MM (Hexamethydisiloxane). The piston expander operated as a single-cylinder double acting type and power take-off was at engine speed. Dimensions of the piston machine are: displacement 0.9 l, stroke 81 mm, piston diameter 87 mm. The calculated effective power of the piston machine amounts to 12 kW_e (that is about 5% of the Diesel engine power). The measured mechanical power was around 14 kW (that is about 4.3% of the engine power). The experiment was carried out using water as a working medium. The maximum water pressure reached around 32 bar and the maximum temperature was about 380 ^oC. The double-stage constant-pressure turbine was the second expander. The maximum speed of the turbine was 150000 rpm. The numerical simulation of the ORC cycle with water as a working medium gave the following results: maximum turbine output power 10 kW with an efficiency of 66%. The results of the measurements were as follows: maximum power reached around 9 kW at turbine's rotational speed of about 120000 rpm. The most favourable solutions are either a piston machine using water or ethanol as working fluid and a turbine using ethanol. Kaczmarczyk et al. (2013a), Kaczmarczyk et al. (2013b) investigated the ORC system with an expansion valve (simulating work of a microturbine) and a 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 HFE7100 (working medium): temperature 180 ^oC, pressure 11.76 bar, working medium flow rate 0.16 kg/s. Reaching the shaft rate of 254 Hz, the microturbine generates electric power of 360 W_e. 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%. Liu et al. (2010) 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_e 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_e, 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_e. Li et al. (2011) presented a theoretical and experimental study of heat loss in the radial-axial turbine (with power 3.3 kW_e) in the ORC system. It was a quantitative study on the convection and radiation heat transfer. The results show that the external radiative and convective heat loss coefficient was about 3.2 W/m^2K and 7.0 W/m^2K respectively, when the ORC operated around 100 °C. The total heat loss coefficient in the ORC experimental test was about 16.4 W/m^2K, where its value was estimated at 94.5 W_e. The expander efficiency will be overestimated by about 2.9% if the external heat loss is not taken into consideration. Pei et al. (2011) 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.

2. EXPERIMENTAL STAND – 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 HFE7100 droplet separator is presented in Figure 1.

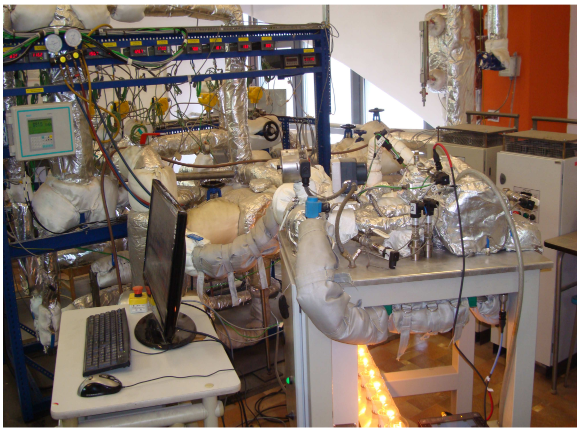

Figure 1: The ORC system with a microturbine and a set of heaters in the test bench

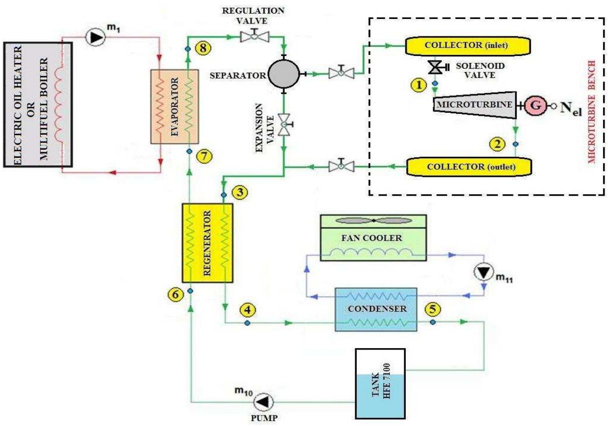

Figure 2: Measurement scheme of the regenerative ORC with a microturbine

The heating cycle consists of oil gear pumps made by Tapflo (model TG L018) and two independent heat sources: a prototypical multifuel boiler and a set of two prototypical electric thermal oil heaters that can operate independently or in series/in parallel. The regulation of rotational speed of the oil gear pumps was carried out through the frequency converter made by Bonfiglioli Synplus (model SPL200 03 F). The ORC installation can operate using an expansion valve (simulating operation of a microturbine), microturbine or a group of expanders. The gear pump used in the experimental system to feed liquid HFE7100 is supplied by Scherzinger (model 4030). The pump can provide a maximum operating pressure of 14 bar, flow rate of 15.75 l/min and rotation speed of 4000 rpm. The maximum power output of the pump is 0.75 kW. The output capacity pump can be adjusted from 0-100%, using a frequency inverter made by LS (model iG5A). The measurement scheme of the regenerative ORC system with a microturbine is presented in Figure 2. The characteristic points 1 – 8 for the regenerative cycle have been marked. These points were used to determine the changes in thermodynamic state of the working medium in the ORC installation.

2.1 Microturbine

The ORC system cooperates with a high-speed four-stage radial microturbine whose parameters are as follows: nominal power 2.7 kW_e, nominal rotational speed 24000 rpm and isentropic efficiency of about 70%. Figure 3 presents a photograph of the microturbine.

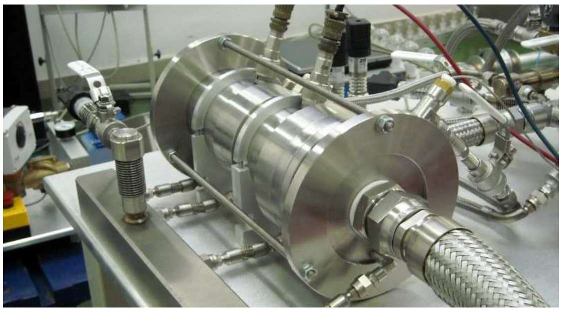

Figure 3: Experimental stand of the microturbine

The turbine shaft is integrated with an electric energy generator and encased in a sealed housing. Given the hermetic construction and the high rotational speed, aerostatic gas bearings powered by a low-boiling medium vapor were used. The microturbine is equipped with a control and measurement system which assures good functioning of the device as well as reception and conditioning of electric energy.

2.2 Heat sources

As it has previously been mentioned, the heating cycle has two heat sources. The first one is a multifuel boiler, alternatively fuelled with biomass, town gas, or gas obtained by gasification of biomass. The other heat source is a prototypical electric flow heater for thermal oil. Both the multifuel boiler (Figure 4) and the electric heater (Figure 5) can operate independently or in series. The prototypical electric flow heater for thermal oil consists of two modules: LKM-25/75-300 and LKM-25/75-301.

Figure 4: Prototype multi-fuel boiler with a solid fuel reservoir (biomass-pellets)

Figure 5: Prototype electric flow heater for thermal oil

Both modules can operate independently or in series and are designed to heat non-conductive fluids (thermal oil) to the temperature of about 250 ^{o}C with low power flow density (below 3 W/cm^2) and the power of 2x24 kW_e. The heater is powered from the network with alternative (50 Hz), three-phase voltage of 3x400 VAC. The boiler is equipped with a coil heat exchanger for double exhaust gas circulation which increases its effectiveness. The maximal boiler power during biomass combustion (pellets of about 5 mm diameter) is about 30 kW_{th}.

2.3 Cooling system

The third cycle in the ORC installation is the cooling system consisting of fan coolers made by GEA (model TDR 01 06 53-C) with a water spraying system, glycol pump made by LFP (model 25 POeC100 Mega) with inverters, JAD-type and plate heat exchangers and piping. The cooling system of the ORC installation performs two tasks. First, it enables cooling of the thermal oil coming to the evaporator, and thus increases the range of adjustment of oil temperature. Moreover, additional cooling of oil protects the system against the excessive temperature rise or enables quick cooling of thermal oil in case of loss of electricity or a breakdown, which assures higher safety while operating the ORC installation. Oil cooling is performed with the use of a JAD-type heat exchanger, cooling glycol pump and a fan cooler. The other important task of the cooling system is quick cooling of the HFE7100 vapor in the condenser (plate exchanger), in a way to obtain liquid of the temperature of 65 ^{o}C at the inlet of the circulation pump.

2.4 The measuring and data acquisition system

The measuring system is based on the National Instruments (NI) devices. The NI PXIe-8130 controller, with appropriate software, controls the operation of the system. Signals from temperature, pressure, power and flow rate sensors, after adjustment in the SCXI-1102b module, are converted into digital form using the data acquisition (DAQ) boards: PXI-6280 and PXI-6251. The NI SCXI-1102B amplifier module with the SCXI-1303 terminal block, the SCXI-1125 and the SCXI-1313 were applied to generate both analogue and digital control signals. The software for the measurement system was made using the NI LabVIEW graphical programming platform. All temperatures were measured with a type K (model TP-211K-b) thermocouple having a diameter of 0.5 mm and a length of 100 mm, with an accuracy of ±0.1°C (made by Czaki). All pressures were measured with pressure transducers made by Trafag (model NAH 8253), with accuracy of 0.15% over the full scale range (16 bar). Differential pressure were measured with a smart differential pressure transmitters by Aplisens (model APR-2000ALW and APR-2200ALW) with permissible measuring error ±0.1%, accuracy of 0.075% over the full scale range (0.5 bar). The Flow rate of the thermal oil was measured with an ultrasonic flowmeter made by Simens (model Sitrans FUS1010,) with 1% at v≥ 0.3 m/s. The flow rate of the HFE7100 was measured using Coriolis mass flowmeter made by Simens (model Sitrans FC Massflo Mass 2100) with an accuracy of ±0.1%. The flow rate of the glycol was measured using turbine flowmeter made by Hoffer (model HO3/4X3/4-30-B-1) with an accuracy of ±0.25%. The electric power output of the generator was measured using a meter of network parameters made by Lumel (model ND20) with phase current and voltage ± 0.2%; power (active, reactive and apparent) ± 0.5%; tangent φ ± 1%; frequency ± 0.2% of the measured value, active/reactive energy ± 0.5%.

2.5 Measurement process

As a result of heating the working medium (thermal oil, HFE7100 and glycol), the changes in the flow rate take place, being caused by the change of physicochemical parameters (i.e. density, viscosity). The definition of steady state was introduced. Steady state denotes the state in which the flow rate change of the working medium does not exceed 1% of the maximum flow rate for 15 minutes. The acceptable maximal (1%) flow rates are: for the thermal oil 0.004 kg/s, for the HFE7100 0.002 kg/s and for the glycol 0.005 kg/s. Additionally, the change of average pressure in the steady state should not exceed 0.12 bar (i.e. 1% of the maximum pressure value) for 15 minutes, and the changes in temperature values should not exceed ± 1 ^{o}C.

3. EXPERIMENTAL RESULTS OF MICROTURBINE IN THE ORC CYCLE

3.1 Thermal-flow characteristics of the ORC installation

Figure 6 presents the graph of the working medium (HFE7100 and thermal oil) temperature changes in the evaporator (system with an electric flow heater for thermal oil).

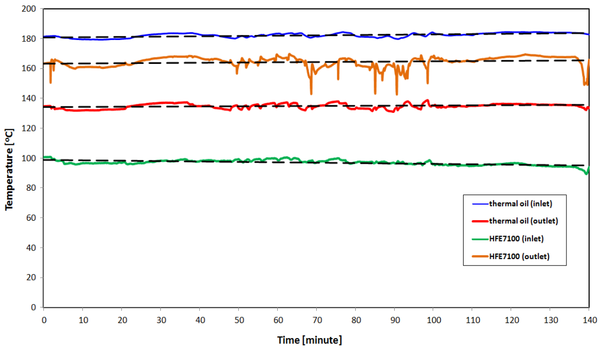

Figure 6: The temperature of HFE7100 and thermal oil in the evaporator vs time

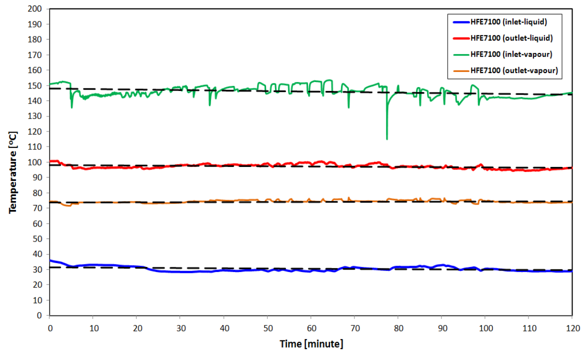

Figure 7: The temperature of HFE7100 in the regenerator vs time

Figure 6 shows that the temperature of thermal oil at the inlet to the evaporator was stable reaching about 182 ^{o}C and was about 138 ^{o}C at the outlet. The temperature of HFE7100 at the inlet to the evaporator was about 100 ^{o}C and reached about 163 ^{o}C at the outlet. The temperaure changes of HFE7100 in the regenerator on the liquid and vapor sides in the steady state are presented in Figure 7. Figure 7 shows that the temperature of HFE7100 at the inlet to the vapour side of the regenerator was about 145 ^{o}C, and about 75 ^{o}C at the outlet, which gives the temperature difference of about 70 ^{o}C. The temperature of HFE7100 at the inlet to the liquid side of the regenerator was about 30 ^{o}C and about 98 ^{o}C at the outlet. Figure 8 presents the temperature changes in the HFE7100 and glycol in the condenser in the steady state.

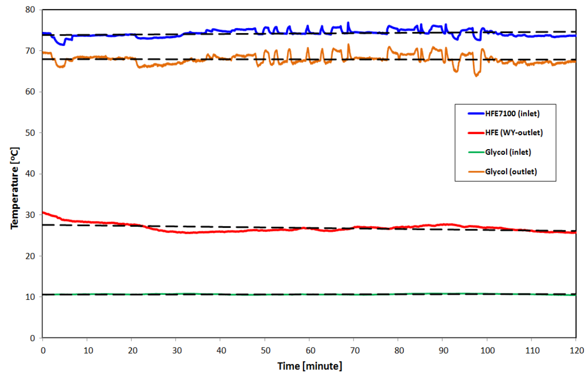

Figure 8: The temperature of HFE7100 and glycol in the condenser vs time

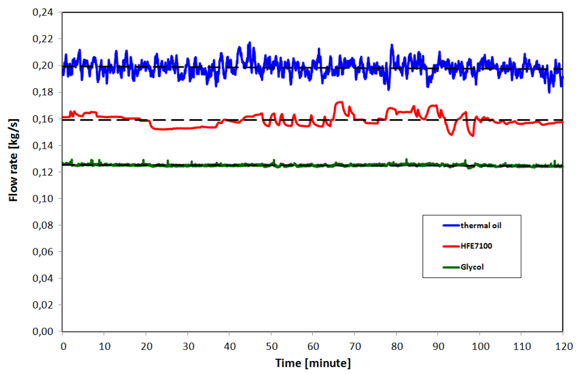

Figure 9: The flow rate of working medium vs time (during microturbine operation)

The temperature of glycol (Figure 8) at the inlet to the condenser was about 10 ^{o}C and 68 ^{o}C at the outlet. The temperature of HFE7100 at the inlet to the condenser reached about 75 ^{o}C and was 28 ^{o}C at the outlet. Figure 9 presents the flow rate waveforms for thermal oil, HFE7100 and glycol measured during microturbine operation. The analysis of the measurement data shows that the average flow rate of the thermal oil was about 0.21 kg/s. Moreover, the average flow rate values for the HFE7100 and glycol were around 0.162 kg/s and 0.125 kg/s, respectively.

3.2 The radial microturbine characteristics

Figure 10 presents the output voltage curve of the radial microturbine recorded during the measurement. Load current diagram of the microturbine generator was shown on Figure 11.

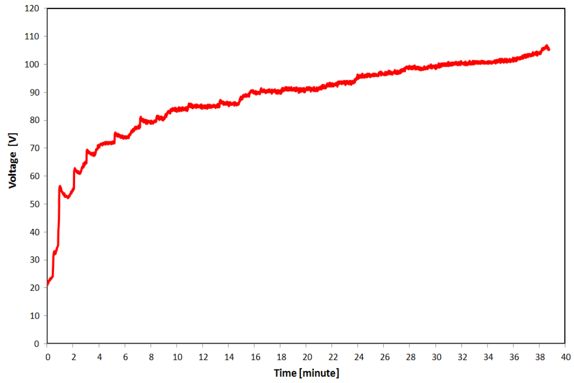

Figure 10: Voltage generated of the radial microturbine vs time

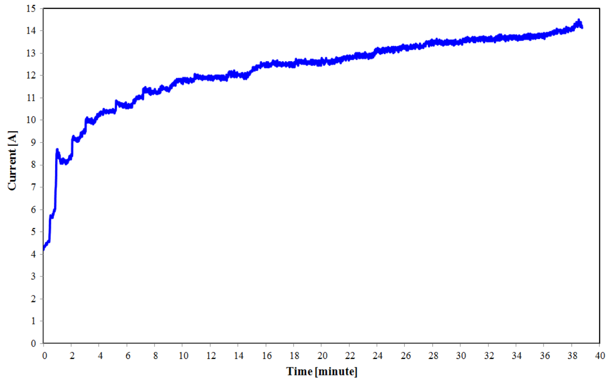

Figure 11: Load current of the radial microturbine vs time

Maximum voltage generated by the microturbine was around 107 V, while the maximum load current was about 14.5 A. Electrical power curve for the radial microturbine operating in the ORC system was shown in Figure 12. The Figure 13 presents the graph containing the course of microturbine rotational speed in relation to the measurement time.

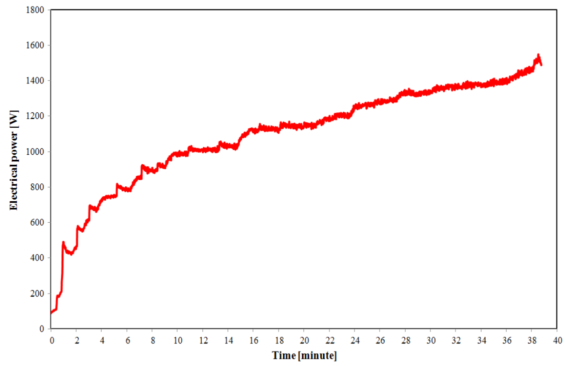

Figure 12: Electric power curve registered during microturbine operation

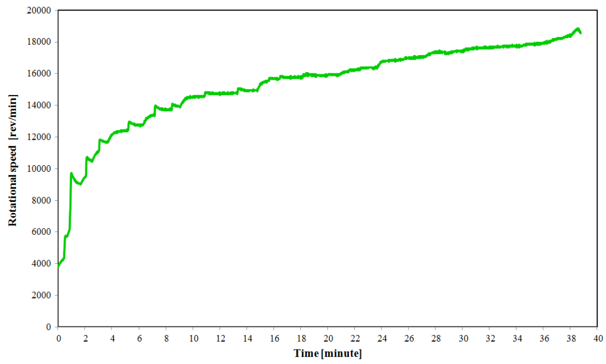

Figure 13: Microturbine rotational speed registered during the measurement

The maximum electric power generated by the microturbine reached the level of 1551 W_e, at the rotational speed of about 18700 rpm. The electric power generated by the microturbine versus rotational speed and pressure drop in the microturbine are shown in Figures 14 and 15 respectively.

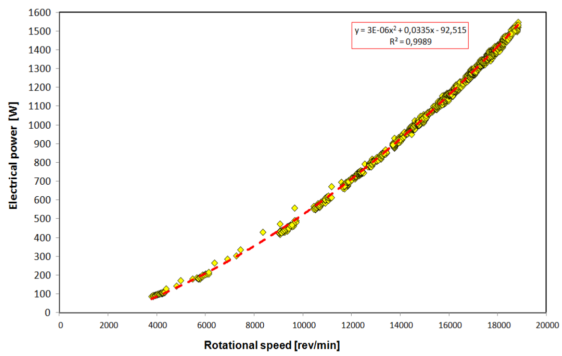

Figure 14: Electric power generated by the microturbine vs rotational speed

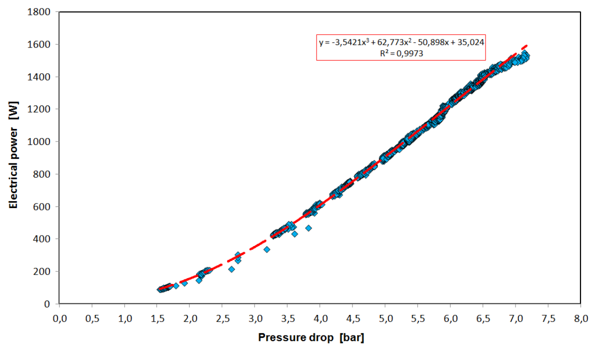

Figure 15: Electric power generated by the microturbine vs pressure drop

On the basis of Figures 14 and 15, knowing the value of rotational speed or pressure drop in the microturbine, electric power of the microturbine can be assessed quickly and easily across the entire power range. These two figures contain red dashed lines representing linear regression, the coefficients of which were calculated by the least squares method. The regression lines are presented with their corresponding equations and coefficients (R^2). The electric power generated by the microturbine versus pressure ratio and inlet pressure is shown in Figures 16 and 17, respectively.

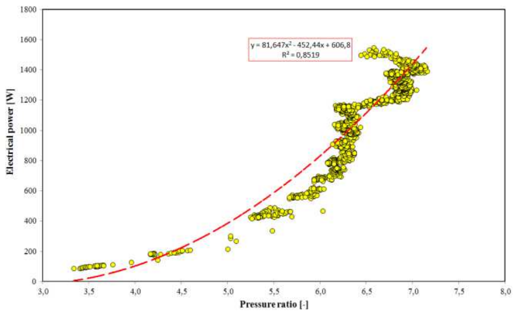

Figure 16: Electric power generated by the microturbine vs pressure ratio

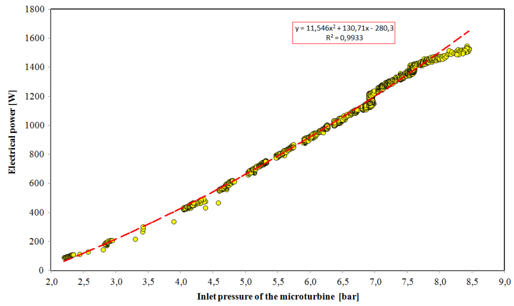

Figure 17: Electric power generated by the microturbine vs inlet pressure

Figure 16 shows that when the pressure ratio is equal to 7, the power generated by the microturbine amounts 1480 W_e. The maximum electric power was generated by the microturbine when the supply pressure was 8.5 bar (Figure 17) and reached about 1550 W_e. The Figures 16 and 17 contain linear regression lines with their corresponding equations and coefficients (R^2). Figures 18 and 19 present the diagram T-s and P-v for the HFE7100 in the ORC system with regeneration, respectively.

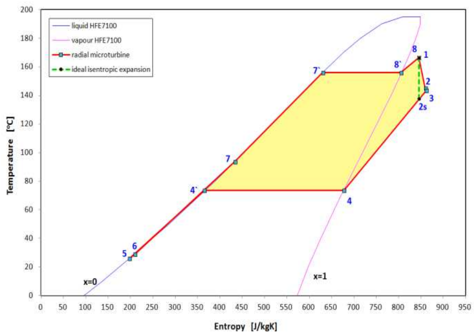

Figure 18: T-s diagram ORC system

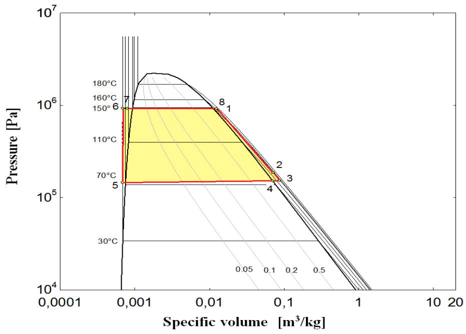

Figure 19: P-v diagram ORC system

Figures 18 and 19 shows the temperatures of HE7100 in inlet and outlet of the microturbine were 166.5 °C and 145 °C respectively. The pressure value at the microturbine inlet was 9.21 bar and outlet 1.86 bar. In this case, efficiency of the radial microturbine amounted to 70.61% and the ORC system efficiency was 5.95%. The calculated Carnot efficiency equalled 31.98% and the exergetic efficiency equalled 18.55%. The equations (1 - 4) on the basis of which the above-mentioned efficiencies were calculated are presented below. The Carnot efficiency was calculated by the relation:

$$\eta_C = 1 - \frac{T_{\min}}{T_{\max}} \tag{1}$$

where T_{min} and T_{max} – temperature for the upper and lower heat source, respectively.
The isentropic radial microturbine efficiency was calculated from the relation

$$\eta_{s,turb} = \frac{h_1 - h_2}{h_1 - h_{2s}} \tag{2}$$

where h is the refrigerant enthalpy, the subscript numbers indicate the state, and the subscript *s* refers to the isentropic process. The thermal efficiency of the ORC system was calculated by

$$\eta_{ORC} = \frac{(h_1 - h_2) - (h_6 - h_5)}{h_8 - h_6} \tag{3}$$

where h_1, h_2, h_5, h_6 and h_8 are the specific enthalpy of the HFE7100. The exergetic efficiency was calculated from the relation

$$\eta_{exerg} = \frac{\eta_{ORC}}{\eta_C} \tag{4}$$

where η_{ORC} – thermal efficiency of the ORC system, η_C – Carnot efficiency.

Figure 20 presents comparison of the power generated by a rolling-piston expander – Zheng et al. (2013), a scroll expander – Yun et al. (2015) and a radial microturbine – present data, versus pressure ratio. Yun et al. (2015) and Zheng et al. (2013) as the working fluid used a R245fa.

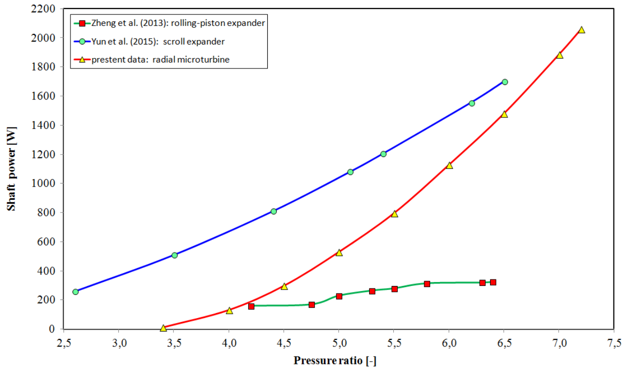

Figure 20: Comparison of the power generated by different expanders and radial microturbine vs pressure ratio

As can be seen in Figure 20, the power curves possess a similar trend. For example, for the pressure ratio 6 the output power of the scroll expander was 1450 W_e, the radial microturbine amounted to 1100 W_e, whereas in the case of the rolling-piston expander it was 300 W_e. The difference between their values manifests itself through the following fact. The values of measured power were obtained using different expansion devices and different working mediums were used.

4. CONCLUSIONS

On the basis of the conducted research on the ORC system with regeneration it was found that the maximum electrical power generated by the radial microturbine reached 1551 W_e. This value was obtained at the rotational speed of 18700 rpm and the HFE7100 supply pressure of 9.21 bar (at the microturbine inlet). The efficiency of the radial microturbine amounted to 70.61%, and the ORC system efficiency was 5.95%. The Carnot efficiency and exergetic efficiency amounted to 31.98% and 18.55%, respectively. The power characteristics contain regression lines along with their corresponding equations in order to facilitate the analyses and comparisons for other researchers.

NOMENCLATURE

h	specific enthalpy	(J/kg)
η	efficiency	(-)
T	temperature	(^{o}C)

Subscript

C	Carnot
e	electrical
exerg	exergy
min	minimum
max	maximum
ORC	organic Rankine cycle

s	isentropic
th	thermal
turb	turbine

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