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Design and investigations of the ethanol microturbine

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Abstract The paper presents the results of the design analysis and experimental investigations of the microturbine set consisting of the microturbine with partial admission and permanent magnet generator. The microturbine was designed for operation with the vapour of ethanol as a working fluid. Microturbine unit was tested for different parameters of the working fluid and varying the electrical load. The examples and the comparison between experiment results and numerical simulations are shown and discussed in the paper.

Keywords: Micropower generation; Microturbine; ORC power plants

1 Introduction

In the distributed power engineering microdevices are used for local production of electric power and heat [1]. The 'micro' scale increases the construction and technological challenges. In many research centers there are carried out intensive works on compact heat exchangers as well as microengines. Work on heat exchangers is conducted in two ways. On the one hand, techniques for intensifying heat transfer in plate heat exchangers are applied [2,3]. On the other hand, compact heat exchangers are built, for example based on microchannels [4], helical coiled tube [5] or microjet

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heat transfer technology [6,7]. In the case of engines, volumetric [8–11] and turbine engines are developed in parallel [12–14]. In the literature we can find the micro powerplants with the original approach to the heat utilization aspects [15,16].

Microturbines have found applications in micropower plants, including the polygeneration power systems and the combined installations [17–20]. Turbines of very small output are even used in power plants built in the MEMS technology (micro-electro mechanical system) [21]. Apart from the traditional fluids, i.e., steam, also low-boiling fluids (as a rule organic ones) are applied. Two types of vapour cycles are considered: organic Rankine cycle (ORC) and organic flash cycle (OFC) [22,23]. For many years the installations of electric output of several hundred kilowatts and higher have been used in power plants based on biomass combustion [24,25]. The cogeneration systems working with organic media are already available within wide a range of electric and heat power, e.g., the power plant of 300–600 kW electric power and 1500–2800 kW heat power, or that of 200–1000 kW electric power and 1000–6000 kW heat power [26]. However, only a few examples can be found of ORC installations of output power smaller than 100 kW [27,28] or less than 30 kW [29] of electric power. On the market, only a few examples can be found of ORC co-generation installations of electric output lower than 5 kW. The published results of experimental examination of microturbine sets operation can be found, for example in [30–33].

The cogenerative micro power plant with the ethanol (C_2H_5OH) as a working medium was designed and built for experimental investigations. The schema of its cycle is presented in Fig. 1. The assumed values of design cycle parameters are as follows:

- pressure at turbine inlet $p_0 = 1.2572$ MPa,
- temperature at turbine inlet $t_0 = 160$ °C,
- pressure behind the turbine $p_2 = 0.072564$ MPa,
- temperature behind the turbine $t_2 = 70$ °C,
- estimated medium mass flow rate $m = 0.025$ kg/s.

Special attention was paid to the advanced design of the main elements of the power plant namely boiler, heat exchangers and circulationpump. The view of the experimental test stand with ethanol ORC cycle is shown in Fig. 2. The liquid working medium (ethanol) is stored in the tank (1). The

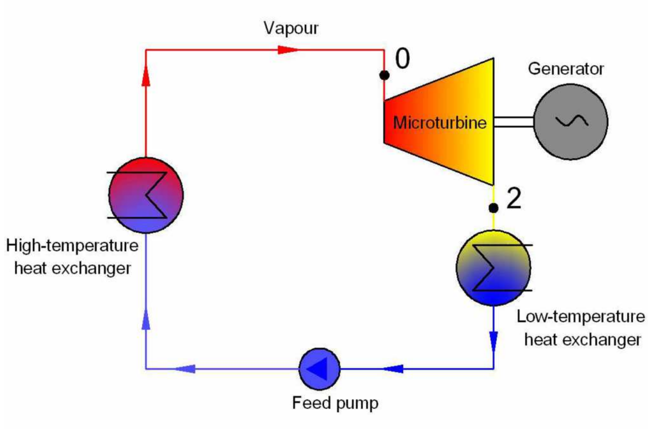

Figure 1: Schema of micro-power plant cycle.

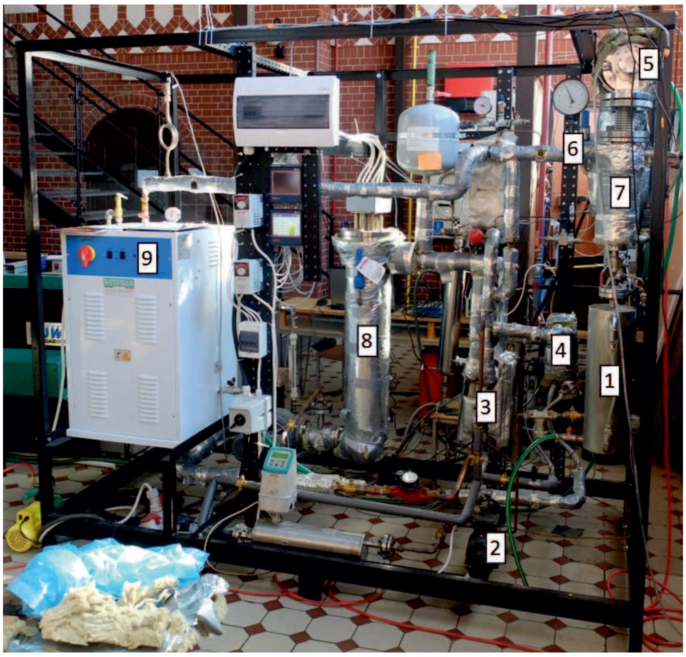

Figure 2: View of the test stand with ethanol ORC cycle: 1 – liquid ethanol tank, 2 – ethanol pump, 3 – heat exchanger heating ethanol, 4 – evaporator and superheater, 5 – microturbine set, 6 – reducing valve, 7 – condenser, 8 – thermal oil heater, 9 – water steam boiler.

flow of the medium provides the pump (2). The stand allows a flow rate regulation by speed pump changing or directing excess of working fluid back to the ethanol tank (by-pass). The pump introduces liquid ethanol into the primary heat exchanger (3) in which it is heated up. The heating medium in the exchanger is the thermal oil supplied from the electric heater (8). Then ethanol goes to the secondary plate heat exchanger (4). In this exchanger the alcohol evaporates and vapour is overheating. The heating medium in the secondary heat exchanger is steam supplied from the electrically heated boiler (9). The ethanol vapor is directed to the microturbine (5) where the energy of the working fluid is converted into mechanical energy and then into electric energy. In order to protect the turbine during a start-up operation, the bypass pipeline with reducing valve (6) was applied. Ethanol vapour from the turbine goes to the condenser, where condensation occurs under vacuum conditions. The condenser is cooled by water in the open circuit. The condensate of the ORC working fluid flows from the condenser back to the tank.

Within the performed numerical analysis the single-stage axial-flow microturbine type was designed. The turbine stage flow calculations were performed using commercial Fluent Anasys software. Finally microturbine was built and tested experimentally. The design and results of experimental investigations are described in detail in the paper.

2 Single stage axial microturbine

Detailed flow calculations of many variants of turbine stage geometry and different values of the main design parameters allowed to select the optimum solution of the flow part of the microturbine for the assumed ORC cogeneration power plant. The particular data of the turbine geometry are as follows:

- stage diameter: 98.2 mm,
- blade height: 10 mm,
- partial admission arc: 7.88%,
- rotor speed: 36 000 rpm.

Due to partial admission in the microturbine stage it was possible to keep the values of the main design parameters within the range typical of steam turbines (velocity ratio, degree of reaction or blade height to chord ratio). This allowed to apply typical nozzle and blade profiles.

The cross-section of the microturbine set and the microturbine view are shown in Figs. 3 and 4. The set comprises a single stage axial microturbine which drives a three-phase generator with permanent magnets. A characteristic feature of the turbine is partial admission system. The turbine rotor and the generator rotor are mounted on one shaft supported on ceramic rolling bearings. The electric current generator is situated on the low-pressure side of the turbine. The generator stator is mounted in the turbine exit body, while the rotor is fastened on the conical surface of the shaft. In this way tightness of the turbine set is ensured. Diaphragm with nozzle and rotor of the microturbine are shown in Fig. 5.

The electric current generator was the three-phase generator mSpW 5.5/ 4.5-4-a1 ENCA, produced by E+A Elektromaschinen und Antriebe AG, with permanent magnets in rotor.

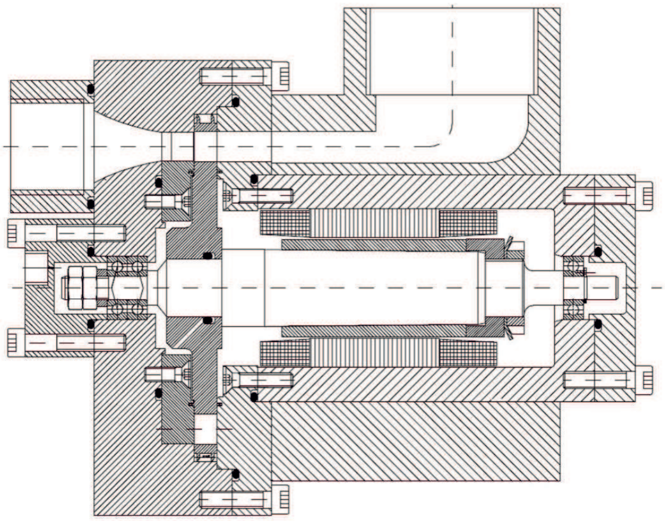

Figure 3: Cross section of the single stage axial microturbine set.

The example of the static pressure distribution field of the flow part of the microturbine, obtained as a result of computational fluid dynamic (CFD) calculations, is presented in Fig. 6. Figure 7 shows the Mach number field in the nozzle channel example. Attention is paid to the relatively large values of the Mach number (up to Ma = 2.3). Turbine power and efficiency as a functions of rotational speed, at the design working fluid conditions, are presented in Figs. 8 and 9, respectively.

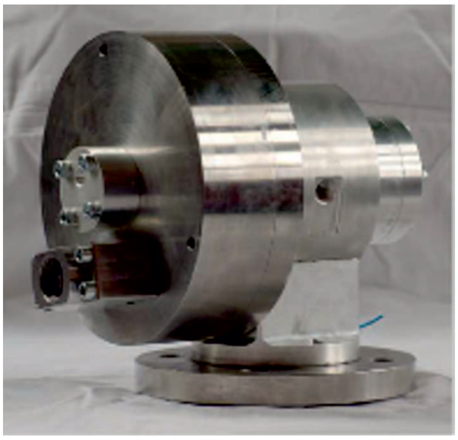

Figure 4: View of the microturbine set.

Figure 5: Diaphragm with nozzle and rotor of the microturbine.

The microturbine experimental stand was designed to enable the measurement of the electric output, rotor speed, pressure and temperature at the inlet and outlet. The stand equipment allowed to record measurement data using the data acquisition device. The application monitoring the operating state of the microturbine set and recording the measurement data has been prepared.

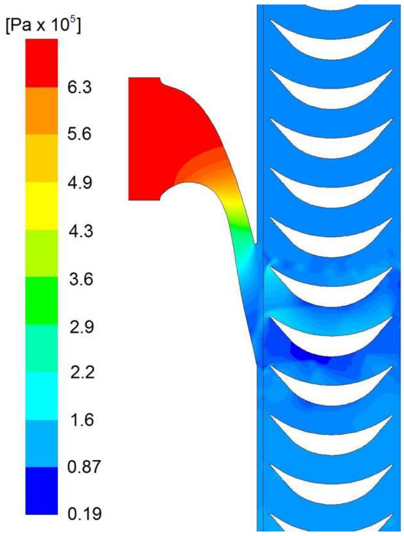

Figure 6: The static pressure distribution, at the mean diameter, for the design turbine parameters.

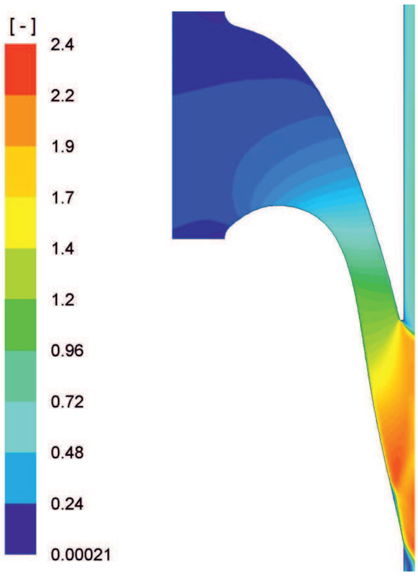

Figure 7: The Mach number distribution, at the mean diameter, in the nozzle channel, for the design turbine parameters.

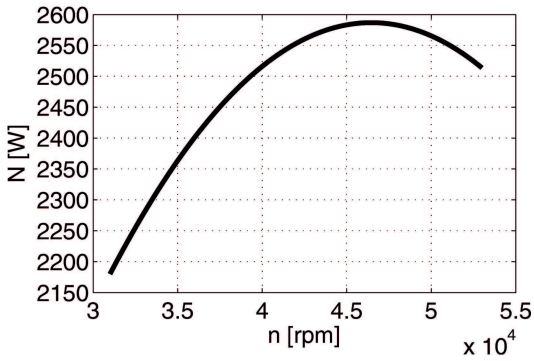

Figure 8: Turbine power as a function of rotational speed at the design working fluid conditions, obtained as a result of CFD calculations.

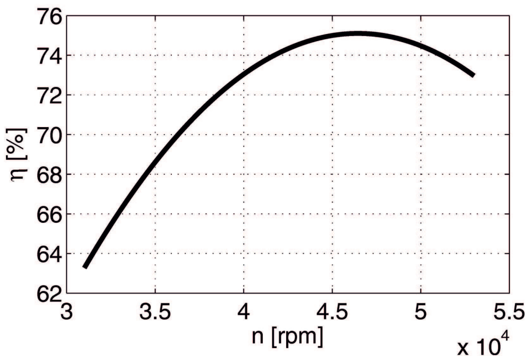

Figure 9: Turbine efficiency as a function of rotational speed at the design working fluid conditions, obtained as a result of CFD calculations.

3 Experimental research

The experiments were performed for different values of inlet and outlet medium pressure, turbine load and rotor speed. The results of the experiments correspond very well with the appropriate CFD calculation data. The example of the comparison between the measured power values and the calculated results is shown in Fig. 10.

The dynamic behavior of the microturbine set was also examined during start-up and shutdown operations. Figure 11 shows the example of time-histories of the turbine inlet and outlet pressure, rotational speed, voltage and electric current, recorded after increasing the opening of the microturbine supply valve. Test were performed for constant electrical load. The

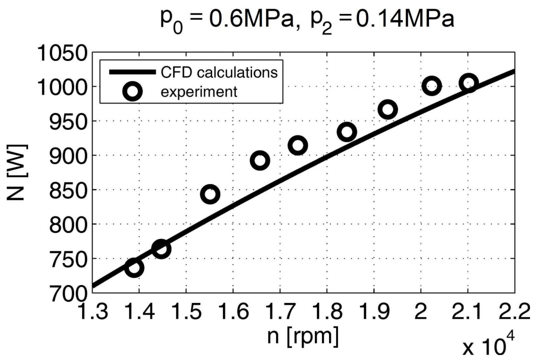

Figure 10: Comparison between the calculated power, N, as a function of rotational speed, n, and the measured results.

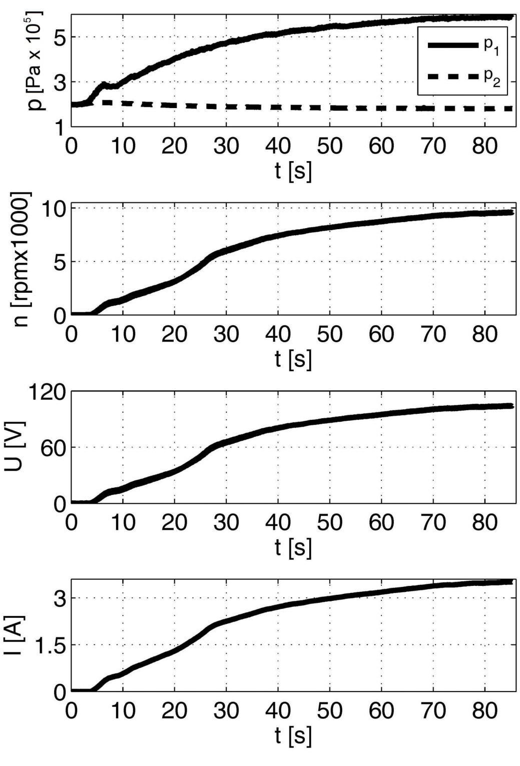

Figure 11: Inlet pressure, p_1, outlet pressure, p_2, rotational speed, n, voltage, U, and electrical current, I, as a function of time, t, during microturbine start-up.

total microturbine start-up time was over 80 s. Such a long time resulted from properties of the ORC installations delivering medium for the microturbine. The installation did not allow to realize large pressure changes in a short time. In addition due to temperature of the working medium (about 140 °C) the start-up velocity was limited for protecting the microturbine elements from an excessive increase of thermal stresses. An example of the microturbine shut down process is shown in Fig. 12. Shut down time lasted 28 s and, like the start-up, it was the result of the limited pressure changes in the installation in a short time.

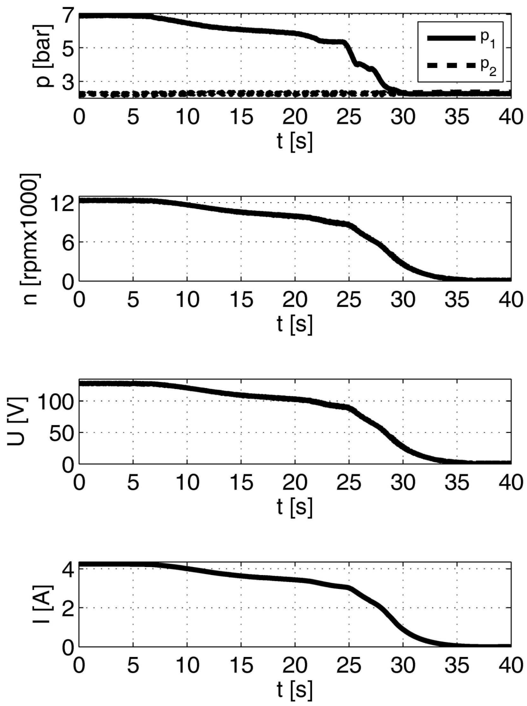

Figure 12: Inlet pressure, p_1, outlet pressure, p_2, rotational speed, n, voltage, U, and electrical curren,t I, as a function of time, t, during microturbine shutdown.

In addition, attention was paid that the relatively low pressure pulsations of the medium before the microturbine which influenced the rotational speed and electric energy parameters. This is clearly visible in Fig. 13. It presents the inlet pressure, rotational speed, voltage and electric current as a function of time. During the test in the turbine inlet pipeline there were cyclically repeating pressure pulsations with average amplitude of 0.08 bar and average frequency 0.4 Hz. Fluctuations of the same frequency, but delayed in the phase relative to pressure pulsation of about 0.5 s, were observed in the rotational speed signal. The average signal amplitude of the rotational speed was 70 rpm. Similar pulsations were also observed in the time histories of voltage and electrical current.

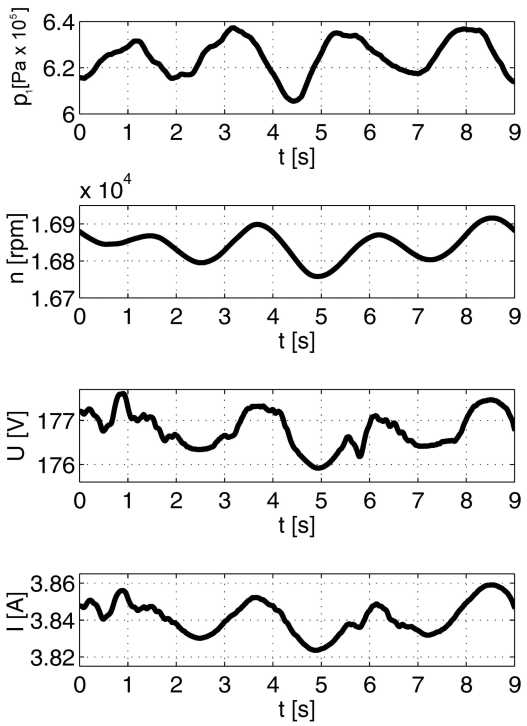

Figure 13: Pressure at the microturbine inlet, p_1, rotational speed, n, voltage, U, and electrical current, I, as a function of time, t.

The results presented in the figures are only some examples of the extensive tests carried out for various values of operating conditions. It can be concluded that the work of the microturbine set is stable in a wide range of electric load, rotor speed and media parameters. However, it should be noted that even small pulsations of the vapour pressure affect the operation of the microturbine set. This indicates the need for detailed research on issues related to the interaction of ORC installation components and microturbine set.

4 Conclusions

The investigations proved that it is possible to build a microturbine set of about 2 kW power level with a higher efficiency than that found in the existing machinery. It is worth emphasising that a relatively high microturbine efficiency may be achieved by very careful and advanced design process. Safe and reliable behavior of the microturbine set was confirmed during the operation tests. The results indicates the need for consider interactions between ORC installation components and microturbine.

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