APPLICATION OF A HEAT RESISTANT PLASTIC IN A HIGH-SPEED MICROTURBINE DESIGNED FOR THE DOMESTIC ORC SYSTEM

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ABSTRACT

The paper discusses research works aimed at applying modern plastics to build a high-speed microturbine that is intended for use in a domestic ORC system. Because of the high production cost of the rotor disc, it was decided to make it from plastic. The nominal electric power of the microturbine is 1 kW and the maximum rotational speed of the rotor is 120,000 rpm. It turned out that some plastics can be applied to the microturbine because they can withstand such operating conditions. Machining of these plastics is easier and faster as compared to conventional metallic alloys. Preliminary analyses covered several plastics that met the criteria, which are related to the operating conditions of the ORC system. Selected plastics were subjected to further tests such as chemical compatibility and dimensional stability when exposed to the contact with the ORC system's working medium. Then, for selected materials, strength calculations were carried out, taking into account the full geometry of the rotor disc. Based on the results of the analyses performed, several rotor discs were made of one selected plastic. Already after the first tentative series of plastic blade systems was manufactured, it became clear that it is possible to significantly shorten the machining time and reduce production costs. The conducted research could be of interest for those scientists and engineers who are looking for new material solutions that can enable shortening the production time and lowering the production costs of microturbines employed in ORC systems.

1. INTRODUCTION

ORC (organic Rankine cycle) systems have gained popularity in recent years. They are used in many economic sectors. This is due to numerous advantages of this technology as well as the possibility to adjust operation parameters and output power to an available heat source and the user's demand. One example of a successful attempt to apply ORC systems are single-family houses (Kicinski and Zywica 2016, Klonowicz *et al.*, 2017, Zywica *et al.*, 2017), in which there is a great demand for both heat and electricity. Various renewable and non-renewable fuels can be used in ORC systems for the production of thermal energy. Waste heat can be used as well. Cogeneration systems based on renewable energy sources are considered as the most prospective ones. Attention may be drawn, in particular, to ORC systems that utilise sun energy (Petrollese and Cocco, 2019, Ustaoglu *et al.*, 2019) or geothermal energy (Ebadollahi *et al.*, 2019). The continuing tendency to increase energy efficiency causes that also ORC systems fed by waste heat, from various industrial processes (Pethurajan *et al.*, 2018, Ghoreishi *et al.*, 2019) and combustion engines (Xu *et al.*, 2019), are becoming more widely used. In such systems, no fuel costs are incurred or even its consumption is reduced (Yang *et al.*, 2019), which reduces the operating costs and shortens the recoupment period of capital investments.

Currently, one of the major factors limiting the development of small ORC cogeneration systems (with electric power up to 100 kW) is the high investment costs. The lower the power of an ORC system, the higher its cost per kilowatt hour (Frigo *et al.*, 2014). This is largely due to the fact that small systems have low electric efficiency and the buying cost of such components as heat exchangers and expansion devices is considerable. Therefore, new technologies and new materials, the use of which would reduce the manufacturing costs of ORC systems, are still sought.

One way of decreasing the production costs of cogeneration systems is the more frequent use of new hard-wearing plastics in their constructions. Until now, plastics have been used primarily as ancillary elements to ORC systems (e.g. handles, supports or casings). Carefully selected materials can also be used as parts of the main subassemblies, such as heat exchangers, pumps or expansion devices (Hernandez-Carrillo *et al.*, 2017). A long time ago, advances in materials engineering and the availability of so many plastics made it possible for many industrial branches to quickly develop. One good example is the field of wind power is the wind turbine whose blades are made from glass fibre-reinforced composites developed on the basis of modern plastics. Such composites enable to design wind turbines of larger and larger sizes (Mamanpush *et al.*, 2018). Materials of this type can be recycled and reused (Jensen and Skelton, 2018, Liu *et al.*, 2019). The improvement of mechanical and tribological properties of plastics allowed their application to the more vulnerable machine parts, for example, toothed gears (Mao, 2015). Because of their low density and good vibration-damping capability, plastics are also widely used in the automotive and aeronautics industries (Szeteiova, 2010, Bouzouita *et al.*, 2017). In motor vehicles, besides the parts of bodies, suspension and interior fittings, such materials are already used inside the motor compartment. Attempts are also made to build ultra-light plastic tanks to transport liquids (Collotta and Solazzi, 2017). While discussing new applications of plastics, it is also pertinent to notice additive manufacturing techniques in which 3D printers and different types of polymer materials are used (Wong and Hernandez, 2012). Efforts are also made to manufacture complete fluid-flow machines using the additive manufacturing technology, but, for the moment, machines built in this way are mainly used for research and development purposes (Michaud *et al.*, 2016).

The further part of this article presents an application example of a plastic that was carefully chosen and afterwards used to manufacture some parts of an ORC turbogenerator. The turbogenerator is to be coupled with a boiler, which is usually used in a typical single-family house for heating purposes. The following parts of the article discuss the object of investigation, subsequent stages of the material selection and related research results. The article also presents the microturbine’s rotor disc, which was made of plastic material.

2. OBJECT OF INVESTIGATION

The object of investigation was the ORC turbogenerator with nominal electric power of 1 kW. It was designed and manufactured in the Institute of Fluid Flow Machinery, Polish Academy of Sciences (IMP PAN), under the framework of an R&D project (implemented in cooperation with an industrial partner). The project aimed at developing a turbogenerator that could be coupled with a biomass-fired boiler. The combination of the boiler (whose power is in the range from 15 kW to 20 kW) with the developed turbogenerator makes it possible to build an ORC cogeneration system. Such a system, except heating a single-family house (in particular, heating the living space and water for domestic use), also allows for the generation of electricity that can be used by the occupants. Figure 1 shows a scheme of the ORC system, one of the subassemblies of which is the developed turbogenerator. An analysis of the thermodynamic cycle, the working medium selection process, as well as the characteristics of the blade system, are presented in detail in an earlier publication (Klonowicz *et al.*, 2017). Based on the analyses performed, a single-stage axial-flow microturbine was picked as an expansion device. This is an impulse-type turbine (the degree of reaction is 10%) with partial admission (the arc of partial admission is set at the level of 4/14 as the result of optimisation). Mach number at the outlet of the nozzle is 1.85 and at the outlet of the rotor is 1.17. The speed of sound at the outlet of the nozzle is 225 m/s. Due to very low flow rate, it was decided that the rotational speed of the microturbine would be very high, namely, 100,000 rpm at the nominal power of 1 kW. Several different variants of the microturbine’s blade system were considered (including a radial inflow design), but in the end, a decision was taken to select the one whose impulse stage operating with partial admission is highly loaded. The turbine rotor is unshrouded, but due to the use of gas bearings with low radial clearance, the blade tip clearance is also relatively small. That is why the leakage flows were small in this microturbine. Although in ORC systems with such power level, various types of expanders can be used (Zywica *et al.*, 2016, Pethurajan *et al.*, 2018), including scroll expanders (Kaczmarczyk *et al.*, 2015, Jang and Lee, 2019), it was decided to use a high-speed microturbine as an expansion device since both small size and high reliability were absolutely necessary. Compared to volumetric expanders, microturbines are characterised by lower vibration and noise levels (Kaczmarczyk *et al.*, 2016), which is especially important for devices supposed to be used in a domestic environment.

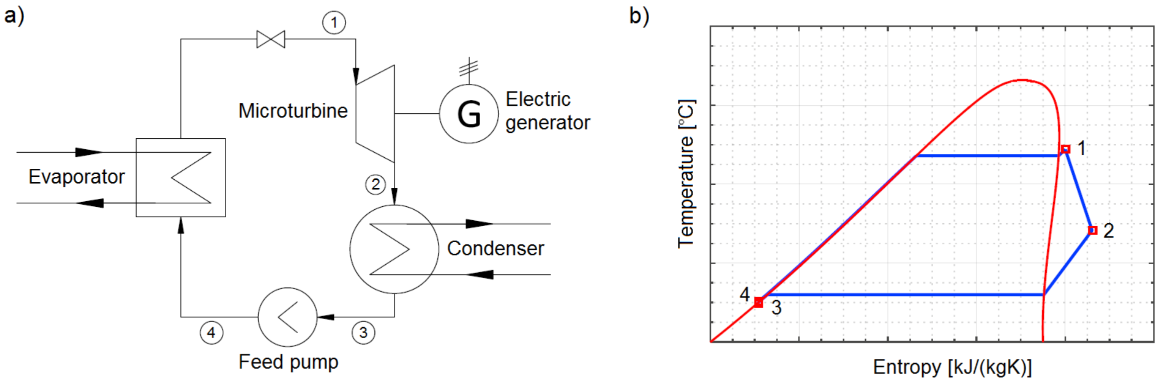

Figure 1: Scheme of the ORC system (a) and the temperature–entropy diagram (b) developed on the basis of the article by Klonowicz *et al.* (2017)

The nominal operating parameters of the developed 1-kilowatt ORC turbogenerator are shown in Table 1. Propanone (also known as acetone) was used as a primary working medium. Differential pressure between the inlet and the outlet at the designed working point is 9.3 bar; the temperature difference is 84°C (at an inlet temperature of 150°C). It should also be noted that the turbogenerator has very small size. Its total length (including the connecting flange at the outlet) is 270 mm, while its height is 140 mm. The outer diameter of the microturbine's blade disc amounts to only 36.2 mm. The deadweight of the complete turbogenerator is 8.3 kg.

Table 1: Basic technical parameters of the ORC turbogenerator

Parameter	**Value**	
	Inlet	**Outlet**
Pressure	10.3 bar (abs)	1 bar (abs)
Temperature	150°C	66°C
Working fluid	Propanone	
Mass flow	0.025 kg/s	
Nominal rotational speed	100,000 rpm	
Maximum rotational speed	120,000 rpm	
Weight	8.3 kg	

Such small overall dimensions of the turbogenerator were achieved using the carefully formulated design concept. This concept was based on the assumption that the electric generator and the microturbine's blade disc would be mounted on the same shaft. Such a solution eliminated the need for using a reduction gear. However, a high-speed generator had to be used. The rotor is supported on gas bearings, which are fed by the working medium's vapour; it is the same working medium that feeds the microturbine's blade system. This approach made it possible to not use oil, which would have been necessary if rolling bearings were applied instead. The worked out design solutions allowed to use a hermetically sealed turbogenerator's casing, the interior of which is filled only by the working medium of the ORC system. Moreover, two angular gas bearings (with specially selected feed ports) enable stable operation of the rotor, even at the maximal speed of 120,000 rpm. It is possible due to the high stiffness of the shaft; its first critical speed is greater than 150,000 rpm. A sectional view of the turbogenerator, with its main components marked, is presented in Figure 2.

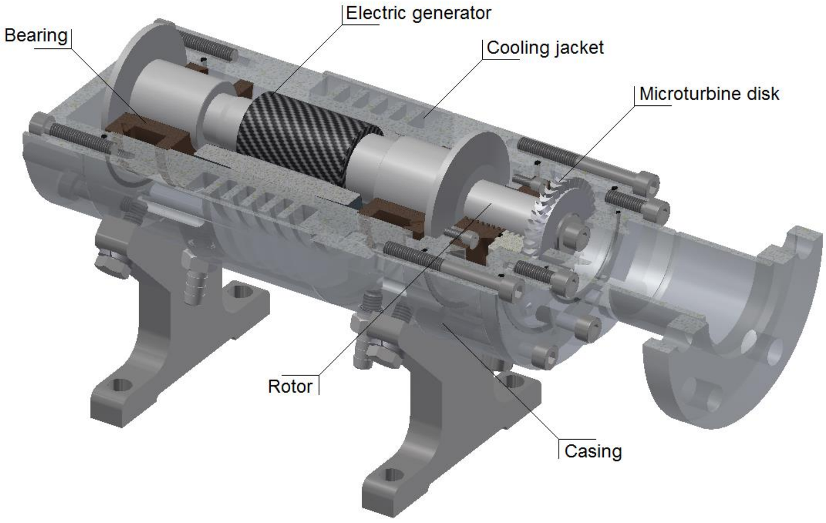

Figure 2: Sectional view of the 1 kW ORC turbogenerator with its main components marked

Due to the high manufacturing costs of the turbogenerator, resulting primarily from the long machining time, actions were taken to lower these costs. Out of all components of the turbogenerator, manufacturing the rotor disc is the most labour-intensive process. That is why efforts were made to develop a technology that would have enabled fast manufacturing of the rotor disc while keeping the required precision. As the production technology is closely related to the used material, it was examined whether there was a possibility to manufacture the disc using non-metallic materials.

3. MATERIAL SELECTION

The aluminium alloy 7075 was used as the primary material of the microturbine's rotor disk. This alloy is characterised by very good mechanical properties and good chemical resistance. However, manufacturing the rotor disk using the aluminium alloy 7075 requires long-lasting machining and consume many tools. Therefore, an attempt was made to use a carefully selected plastic. As far as the series production is concerned, making the rotor disc from plastic using an injection mould would be the most beneficial. Unfortunately, plastics that could be used in elevated temperatures usually cannot be thermoformed. That is why during the work on the turbogenerator prototype an assumption was made that first items of the plastic rotor disk would be manufactured using the classical machining. The fact that plastics can be easily subjected to machining (while using up only a small number of cutting tools) is a considerable advantage. This should, therefore, enable to significantly shorten the time needed for the machining, thus reducing its costs. Some components of the casing and the supports can also be made of plastic. Since these parts have rather simple shapes, their machining is not so time-consuming compared to components of the blade system.

Because plastics have many advantages, they are increasingly used in the constructions of machinery. Compared to metallic alloys their advantages are the following: low weight (low density), great chemical resistance, the ease of shaping and dyeing and low purchase price. Modern plastics, which also include composites that contain various metallic and non-metallic additives, can have very good utility features, even in elevated temperature. These features allow for their use in turbomachines of different types, such as expanders, compressors and pumps. The further part of this section discusses subsequent stages of the work aimed at picking a plastic to manufacture the rotor disc of the ORC microturbine.

When choosing a plastic, the requirements related to a given machine (or its part) should be precisely defined. Basic criteria that are taken into account during the selection of the constructional material in case of fluid-flow machinery are as follows:

- heat resistance,
- chemical resistance,

- mechanical properties,
- thermal expansion,
- technological characteristics (e.g. is heat treatment or machining possible),
- resistance to erosion caused by the flow,
- specific density,
- availability of the material and its purchase price.

As far as the turbogenerator in question is concerned, the constructional material of the rotor disc should have the following features: good thermal resistance (up to 150°C); resistance to the working medium of the ORC system, must be capable of withstanding the stresses occurring on the disc at a rotational speed of 120,000 rpm, its coefficient of thermal expansion should be low due to the small blade clearance, readily available in the market. Since the rotor disc is small in size, the price of the material is of secondary importance. The further part of this section discusses subsequent stages of the work related to the selection of plastic to manufacture the rotor disc of the microturbine.

3.1 Thermal resistance

Due to the operating conditions of the rotor disc, only materials that are capable of resisting temperatures of at least 150°C were considered. Most of high-temperature plastics that are available in the market are capable of long-lasting usage in temperatures of about 120°C; at higher temperatures, only short duration operation is possible. Table 2 contains the list of high-temperature plastics, for which long-lasting operation is possible in temperatures of at least 150°C. During the preliminary selection of materials, their availability in the market was also taken into account.

Table 2: Selected heat-resistant plastics

Symbol	**Material name**	**Density [g/cm^3]**	**Working temperature [°C]**	**Temporary temperature [°C]**
PEEK	Polyetherketone	1.32	250	310
PEI	Polyetherimide	1.27	170	210
PFA	Perfluoroalkoxy polymer	2.20	150	240
PPS	Polyphenylene sulfide	1.35	240	270
PTFE	Teflon	2.18	260	290
PSU	Polysulfone	1.24	150	180
PVDF	Polyvinylidene fluoride	1.78	150	150

According to data given by the manufacturers, some of the selected materials enable long-lasting usage in temperatures above 200°C. These materials are marked with the following symbols: PEEK, PPS, PTFE. Based on the base materials listed above, their varieties (having certain selected properties improved) are created using various additives. In this way, the number of commercially available high-temperature plastics could be increased. Since, in the case in question, the materials marked with the symbols PEEK and PPS have the best thermal resistance, only these materials were considered in further analyses. The material of the PTFE-type was not taken into account as it has a high thermal expansion coefficient and low hardness.

3.2 Chemical compatibility

Propanone (acetone) will be used as a working medium in the ORC system and the turbogenerator. For this working medium, the thermodynamic cycle has high efficiency and the geometry of the blade system is acceptable. The rotational speed of the rotor is acceptable as well. As there is a possibility that the developed turbogenerator could be used also in other ORC systems, the material from which the rotor disc is made should be resistant to other substances (such as, for example, methanol, ethanol, pentane, hexane, SES36, HFE-7100, MDM), which are often used in the systems of this type. On the basis of catalogue data and in-house tests, it was concluded that the materials denoted by the symbols PPS and PEEK had good chemical resistance. Therefore, in further analyses, only these two base materials and their modifications (containing various additives that can improve utility properties) were considered.

3.3 Mechanical properties

Under the framework of the next stage in the plastic selection, material samples were subjected to tensile tests and next strength analysis was carried out using the Finite Element Method (FEM). In the first stage, the in-house strength tests were done. These tests aimed at examining the tensile strength of the material and checking if it was the same as the one declared by the producer. In the research discussed, the material remained in contact with the ORC system’s working medium for a long period of time. For ten days, the material samples were totally immersed in the working medium, and then tensile tests were done (in accordance with ISO 527-2 standard). For the sake of comparison, the same tests were done for the material samples that had no contact with the working medium. The research demonstrated that the working medium had no impact on the tensile strength in the case of plastics of the PPS-type and of the PEEK-type. All the breaking stresses obtained are greater than the values declared by the producer. Figure 3a shows exemplary results relating to the tensile test of the material of the PEEK-type. In this case, the tensile strength (obtained in several tests) is 118 MPa.

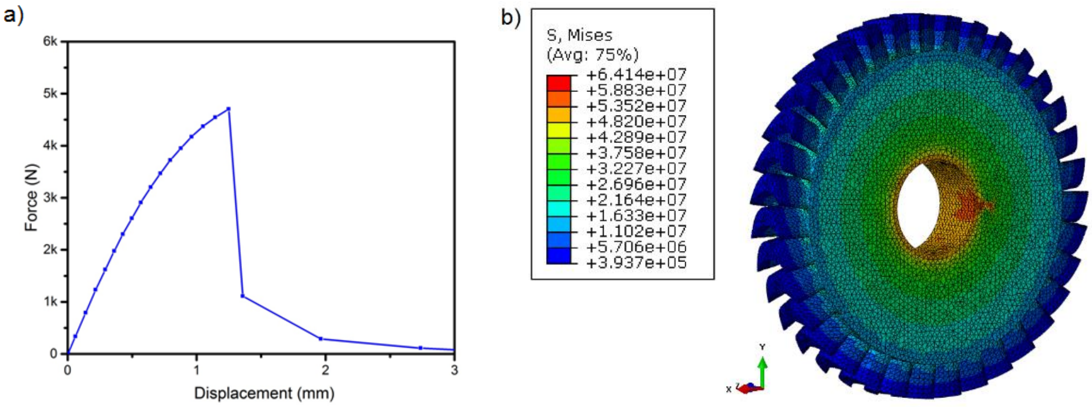

Figure 3: Results of the tensile test for the sample made of the PEEK-based material (a) and the results of the numerical strength analysis of the rotor disc (b)

During the second stage of the strength analysis, the verifying calculations were made using the FEA software, taking into account the full geometry of the rotor disc (including the blades). Since the number of pages in this paper is limited, only the selected results obtained for the plastic of the PEEK-type are presented (Figure 3b). The results were obtained for a maximum speed of 120,000 rpm. Despite the fact that Young’s modulus of the chosen material is more than ten times lower than Young’s modulus of the aluminium alloy, both reduced stresses and deformations have acceptable values due to the lower density of the plastic. The maximum reduced stress values were around 64 MPa (at the pinhole), and the displacement of the blade tips in the radial direction was 0.045 mm, whereas their displacement, caused by thermal expansion of the material (from 20°C to 150°C), was 0.07 mm. Since all these values were at an acceptable level, a decision was made to manufacture several rotor discs made from the selected plastic.

3.4 Machining test

In order to assess the possibility of using the selected plastic in the ORC turbogenerator, several rotor disks were manufactured as a test series. Due to the piece production, it was decided to apply the same manufacturing technology as in the case of the disc made of the aluminium alloy. A roller of material from which the disc was made, at first had been machined using a lathe and then the blades were made using a numerically controlled five-axis milling machine. It turned out that the selected plastic can be easily milled using an end mill. The blade ring consists of 35 blades (each with a height of 3 mm) and the minimal distance between two consecutive blades is 0.9 mm. Despite such small blades, it was possible to manufacture the whole blade ring using only one small-diameter milling cutter. For comparison purposes, it is worth adding that in the case of the disc made from the aluminium alloy a dozen or so milling cutters had to be used. Already the test series of rotor disks demonstrated that it is possible to significantly reduce the time required for the production process.

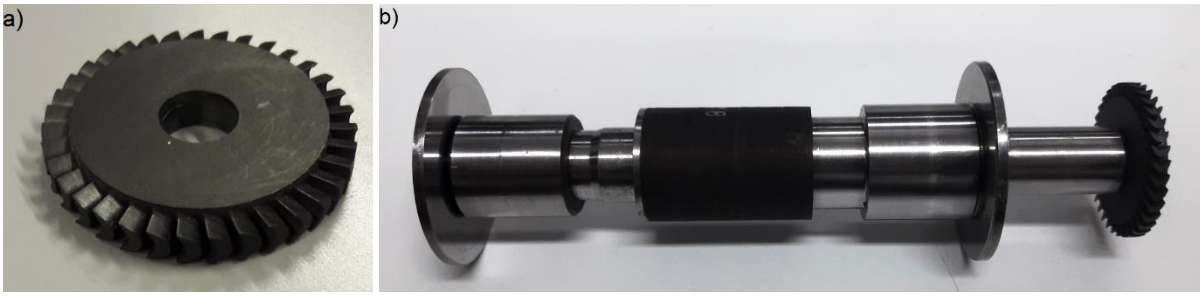

Figure 4: Rotor disc made of the PEEK-type plastic (a) and the complete turbogenerator rotor on which the rotor disk is mounted (b)

4. CONCLUSIONS

The article discusses work related to the selection of plastic and then its application to manufacturing the rotor disc of the single-stage axial microturbine with partial admission, which was designed for the use in the domestic ORC system. The main objective of the work was to bring down the production costs of the turbogenerator. The results of research and analyses already carried out make it possible to draw the following conclusions:

- When selecting a material to manufacture particular parts of a fluid-flow machine, it is necessary to take into account its target operating conditions. As far as the rotor disc is concerned, the most important selection criteria are as follows: heat resistance, chemical resistance, strength properties and thermal expansions.
- Based on the analyses of heat resistance and chemical resistance plastics of the PPS-type and of the PEEK-type were picked. On the basis of strength analysis, the plastic of the PEEK-type was chosen in the end.
- The selected plastic enabled to considerably shorten the period of time needed for machining and reduce wear on cutting tools. An application of the selected plastic in series production of rotor discs should contribute to reducing the manufacturing costs.

In the following stage of work, the ORC turbogenerator with the rotor disc made of plastic will be tested under operating conditions. This will be the topic of further publications.

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