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Design and Manufacturing of Micro-Turbomachinery Components with Application of Heat Resistant Plastics

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The article discusses issues associated with the use of modern plastics for the construction of high-speed fluid-flow machines. Currently available plastics exhibit high chemical resistance as well as dimensional and shape stability across a wide temperature range. This allows them to be used for manufacturing components of micro turbomachinery, thereby reducing production time and costs. This article discusses the criteria for the selection of plastics suitable for a particular machine, namely micro turbogenerator operating in the organic Rankine cycle (ORC). In addition to the initial selection of materials based on their chemical and physical properties, strength calculations of selected turbogenerator subassemblies were carried out. The obtained results confirmed that some plastics can replace traditional materials used in the manufacture of ORC turbogenerators. This concerns, in particular, the components of the microturbine blade system. After the manufacture of a trial series of such components, it became apparent that, with appropriately chosen plastics, it is possible to shorten the machining time and reduce production costs, all while maintaining the required dimensional tolerances. The results obtained so far prove that it is possible to use plastics to produce components of modern turbomachines, for instance, parts of high-speed microturbines that have to withstand high operating temperatures.

Keywords: microturbines, micro-turbomachinery, plastics, high-speed machines.

1. Introduction

Intensive development in many fields of science and technology in recent decades enabled to develop many new material solutions that surpassed the previously used construction and functional materials. This can be seen noticed in the case of plastics, which are now used more often in parts made up to now only from various metal alloys. Whereas in previous years, selected plastics were used for lightly loaded machine parts [1], recently they have been successfully used also for manufacturing more strategic components [2, 3] and protective coatings operating in difficult conditions [4]. This is evidenced by the wider use of plastics in the automotive and aerospace industries [5, 6]. The use of such materials leads to a decrease in weight of vehicles and aircraft, and facilitates the suppression of undesirable vibrations and noise [6]. In addition to the elements of the bodywork, suspension and interior fittings of vehicles, correctly selected plastics are also used within the engine compartment [7], and attempts are made to make ultralight tanks used in fire trucks [8]. Whilst discussing new applications of plastics, it is also worth mentioning the techniques of rapid prototyping [9] using 3D printers, which are usually based on different types of polymer materials. Attempts are made to make entire rotating machines using additive manufacturing, but for now, machines constructed in this way are mainly used for research and development purposes [10].

The growing demand for plastics results from their many advantages, the most important of which are: low weight (low specific density), chemical resistance, ease of forming and dyeing, and low price. Modern plastics, which are often composites containing various metallic and non-metallic additives [6], can achieve very good durability properties and work longer at higher temperatures. These features enable their use in various types of energy microturbines [11], which are increasingly used in distributed cogeneration [12]. In the further part of this article, an example of plastics selection for chosen parts of the steam microturbine is presented, which, through the ORC system (the organic Rankine cycle) will cooperate with the boiler used in housing for heating purposes [13]. Due to the relatively low temperature level at which ORC micro-turbines usually work, the use of correctly selected plastics for their construction can be a very beneficial solution in many aspects.

2. Selection of plastic materials

2.1. *Determination of operating parameters*

When one selects materials for the machine parts, it is necessary to define the parameters at which they will work very precisely. In the discussed case, plastics will be used for the construction of a turbogenerator operating in the ORC system. Due to the high cost of manufacturing and the long processing time of the parts included in the microturbine blading system (ie rotor disc and guide vanes), the greatest benefits can be achieved by making these elements out of plastics. It may also be a beneficial solution to make the turbogenerator housing or at least some of its components out of plastics too. The use of these materials for the turbogenerator supports and all pipe connections is also taken into account.

In the turbine generator designed by IMP PAN, the most demanding operating conditions occur in the case of the microturbine blading system. According to the parameters of the designed ORC installation, the fresh vapor of the low-boiling medium is supplied to the turbine blades at a pressure of about 10 bar and has a temperature of about 150°C. The working medium of ORC can be various organic substances, such as, for example, methanol, ethanol, pentane, cyclopentane, hexane, SES36, HFE-7100, MDM and many others. Due to the range of operating temperatures and the installation's target site (single-family houses), the operating factors taken into account in this case included only new generation mediums, eg such as HFE-7100. In atmospheric conditions, these are very often odorless, non-toxic and non-flammable liquids. The plastic that will be used in the turbogenerator must be chemically resistant to these types of operating agents.

2.2. *Heat-resistant plastics available on the market*

Due to the targeted working conditions, the range of possible plastics has been limited to materials that can be used continuously at a temperature of at least 150°C. While there is quite a large group of materials presented by their producers and suppliers as high-temperature materials on the market, for most of them the maximum temperature of long-term use is about 120°C. At higher temperatures, they can usually be operated only for a short period of time. Table 1 presents a list of several selected plastics for which the long-term use temperature is at least 150°C. It should be emphasized that this is not a complete list of materials that can be used in such temperatures, but during its creation their availability on the market was taken into account.

Table 1 List of selected heat-resistant plastics

Symbol	Material name	Working temp. [°C]	Temporary temp. [°C]
PTFE	Teflon	260	290
PEEK	Polyetherketone	250	310
PVDF	Polyvinylidene fluoride	150	150
PEI	Polyetherimide	170	210
PPS	Polyphenylene sulfide	240	270
PFA	Perfluoroalkoxy polymer	150	240
PSU	Polysulfone	150	180

According to the collation above, some materials can be used for a long period of time in temperatures exceeding 200°C (PTFE, PEEK, PPS). Above this temperature, the temporary work of elements made from the PFA and PEI material is also allowed. Based on the basic composition of plastics, various modifications are also made, for which specific properties are improved by appropriately selected admixtures. For example, in order to improve the sliding properties, the native material is mixed with Teflon or graphite. This way, plastics manufacturers create groups of materials with the same base composition, but different in terms of admixtures and certain properties. In trade, they are available in the form of plates or rollers.

2.3. *Criteria for material selection*

In addition to the high temperatures, resistance discussed in the previous chapter, materials used for machine parts must meet a number of other requirements, which depend on the performance parameters. In the case of materials used for micro-turbine rotor discs, strength properties and thermal expansion are also of great importance. These elements rotate at very high speed (even above 100,000 rpm), which results in a large centrifugal force that attempts to tear them apart. In this case, thermal expansion is important due to the need for the turbine blades to retain complex shapes and dimensional tolerances as well as the required very small blade clearance. These factors determine the efficiency of the turbine. Chemical resistance to the medium is also an absolute requirement. Because in order to obtain high flow efficiency, the turbine blades have a complicated geometry, the material used to make them should have good technological properties. The most important criteria that have been taken into account when choosing plastic for the rotor blades are shown below. Those were:

- thermal resistance,
- chemical compatibility with the working medium,
- strength properties,
- thermal expansion,
- technological properties (eg good machinability and the possibility of hot forming of complex shaped elements),
- resistance to flow erosion,
- lightness (low specific density),
- price and availability of material.

As it can be seen above, the same material must in this case meet different, sometimes contradictory criteria. Therefore, when choosing a construction material, it is necessary to focus on a few criteria that are crucial in a given case. In the case of the microturbine rotor, these will certainly be: thermal and chemical resistance, high mechanical strength and low thermal expansion. Because it will be a small element, the low price of the material is less important. On the basis of those criteria, three plastics were selected, which were subjected to further analysis. Chemical resistance tests were carried out for the selected plastics and the tensile strength was checked after a long-lasting contact with working agents.

3. Strength and dynamic analysis of the rotor disc

The next stage of material selection for the ORC micro-turbine disc was performing a strength analysis. The purpose of these was first of all to check the maximum stresses and deformations of the disc and the displacement of the blade tips. Strength analysis was performed only for materials that met all the previously discussed criteria and successfully passed self-conducted tests of chemical resistance to low-boiling agents. Due to the commitment to technical secrecy, the exact names of selected plastics have not been stated in this article. From an engineering point of view, it is important that the selected materials, compared to typical aluminum alloys, are characterized by more than ten times smaller Young's modulus and about twice lower yield point. This comparison looks even worse in the case of steel alloys. The advantage of using plastics in the discussed application is, however, almost twice lower density in comparison to one of aluminum alloys. Referring to the density of steel, for selected materials it is more than five times lower. This directly affects the reduction of the rotor disc loads, which in the case of rotating elements are primarily caused by the centrifugal force. The coefficient of linear expansion of selected plastics is 50% higher than in the case of aluminum alloys and about 100% higher than steel. Due to the small dimensions of the rotor disc, the actual increase in diameter caused by the temperature increase is relatively small.

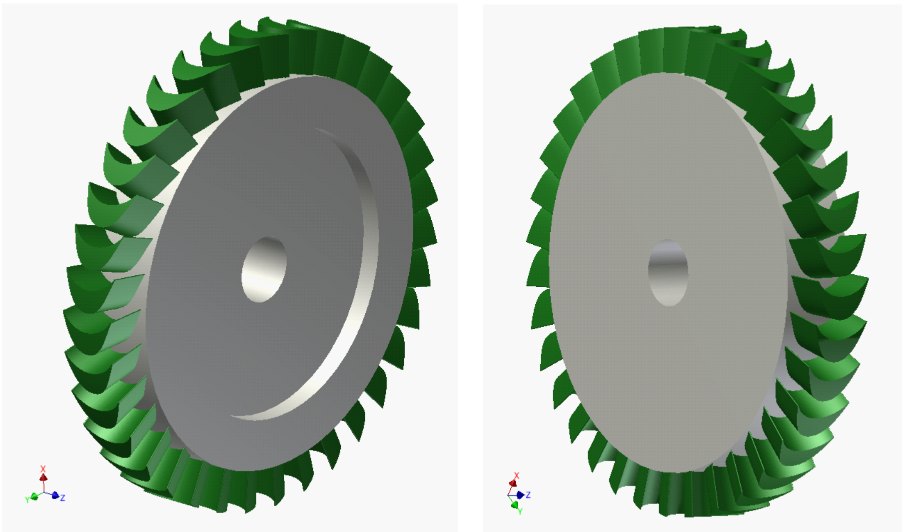

Figure 1 Three-dimensional geometry of the microturbine rotor disc

The geometry of the rotor disc has been designed using a parametric CAD type program. The model takes into account the 3d geometry of the turbine blades, which has been optimized using CFD techniques to achieve maximum flow efficiency. The diameter of the disc was 36 mm, and the height of the blade was equal to 3 mm. The nominal rotational speed of the turbogenerator rotor was 100,000 rpm, and the maximum speed did not exceed 120,000 rpm. A recess was made on one side of the disc, and a through hole in the axis of the disc (Fig. 1). These elements have been provided for mounting reasons.

Based on 3d CAD geometry, the FEM model was developed. Due to the preliminary nature of the calculations, the use of four-wall finite elements and partially automated algorithms supporting the process of discretization were used to construct the FEM mesh. The FEM model of the rotor disc consisted of a total of 686,000 finite elements and over 400,000 degrees of freedom. In order to accurately reproduce the geometry of the disc and increase the accuracy of the analysis, in some areas of the model the density of the FEM mesh was increased, which is visible in Fig. 2. The disc was fixed in the central hole, with the displacement on the cylindrical surface being limited radially, and displacements in the axial direction were blocked on one edge of the hole on the smooth side of the disc. During the calculations, the centrifugal force acting on the rotor disc at nominal and maximum rotational speed was taken into account. The results of strength analysis in the form of reduced stress distributions and displacement distributions are presented in Figures 3 and 4, respectively.

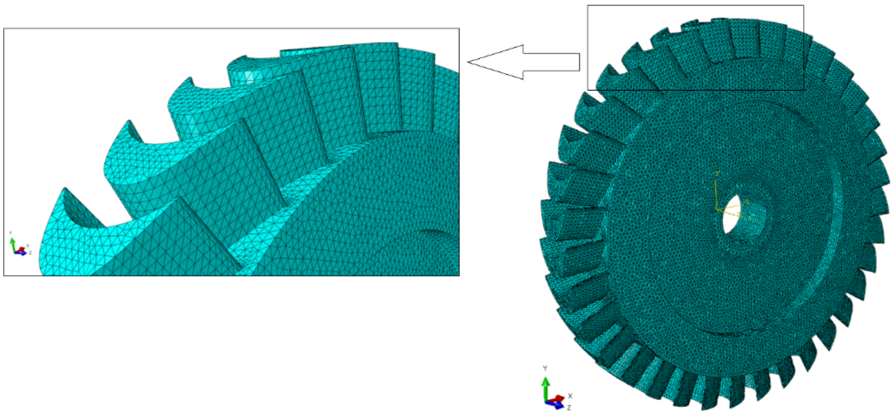

Figure 2 FEM model of the microturbine rotor disc

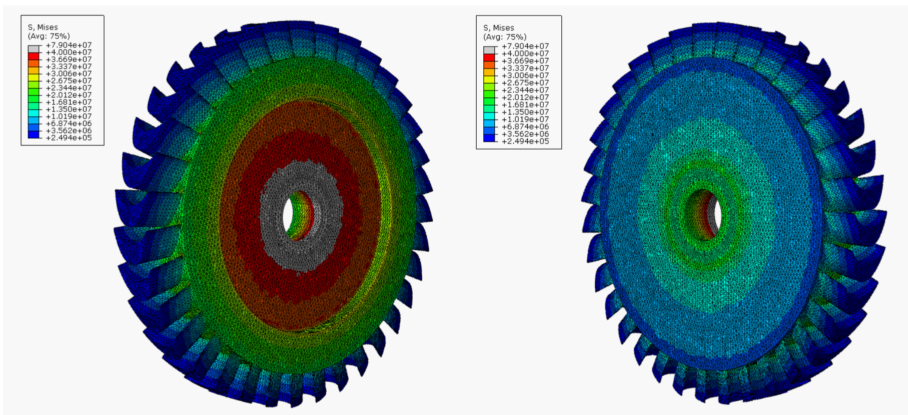

Figure 3 Stresses in the rotor disc at a nominal speed

The results of the simulation showed, that in certain areas of the disc, the acceptable stress levels were exceeded, which for the analyzed material were determined at 40 MPa. This area is marked in gray in Figure 3. The acceptable stress level

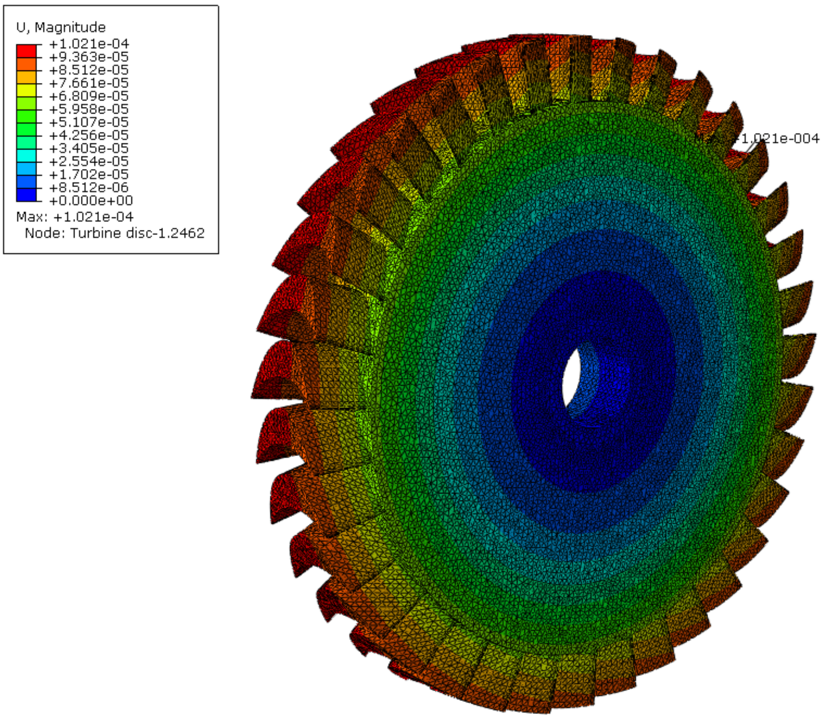

Figure 4 Displacements in the rotor disc at a nominal speed

exceeded only on one side of the disc, on which the recess was made. The method of fixing the model also had some influence on the local stress increase. In other parts of the rotor disc, the obtained reduced stresses did not exceed the acceptable levels. Therefore, it can be assumed that after removing the recess and a more accurate mapping of boundary conditions, the maximum stresses should not exceed the acceptable levels in any part. This was confirmed by later calculations.

Referring to the obtained displacement distributions, it can be concluded that, as expected, the maximum values were obtained on the tips of the blades. They reached up to 102 μm, but in the radial direction they were only 56 μm. Larger displacement of the blade's tip in the axial direction was caused by the asymmetry of the disc, caused by the one-sided recess. This was another argument in favor of removing the recess in the final version of the disc. The estimated displacement value of the tip of the blade, caused by the thermal expansion of the plastic itself, should not in the worst case exceed 60 μm. This means that the total displacement of the blade tip in the radial direction during the operation of the turbogenerator should not exceed 120 μm. Considering the typical clearance gap in the axial microturbines with the impulse stage, it can be stated that those are acceptable values.

The strength calculations performed at a later stage of the design took into account the changed geometry of the rotor disc (including removing the one-side recess) as well as flow and thermal loads of the rotor disc obtained as results of CFD analysis. The results of these calculations showed, that both stresses and displacements in the rotor disc were smaller than the preliminary studies showed. The maximum reduced stress did not exceed 20 MPa and the maximum radial displacement of the blade's tip (taking into account all loads) was at the level of 80 μm. This confirmed the possibility of using the selected plastic.

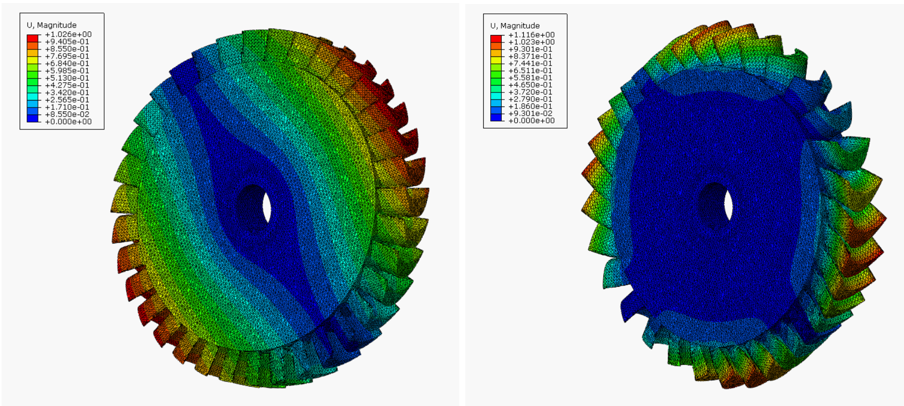

Figure 5 Eigenmodes of the rotor disc made of plastic, which were obtained at frequencies of approximately 5,700 Hz and 34,000 Hz (respectively on the left- and right-hand sides)

In addition to the analysis of strength properties, the dynamic properties of the plastic rotor disc were also checked using the finite element method. This analysis showed that despite the use of a material with inferior mechanical properties, the disc was characterized by very high rigidity (Fig. 5). It resulted mainly from its small size and low density. The first form of natural vibration of the entire disc occurred at a frequency above 4,400 Hz, and the vibration of individual blades only at a frequency close to 22,000 Hz. It can be concluded that in the analyzed system there is a very low probability of excitation of vibrations of both the rotor disc and its blades during the operation of the turbogenerator. At this stage of the analysis no disturbing dynamic phenomena were observed. The modal analysis results also confirmed, that selected plastics could be used to make a micro turbine rotor disc.

4. Strength tests of the plastic

The physical characteristics of plastics given in manufacturers' catalogs are obtained under conditions specified in relevant standards. Basic strength tests are carried out at room temperature and a test sample is surrounded by the air of an appropriate humidity. Catalog data of plastics are often insufficient to assess their utility in the construction of subassemblies of turbines in which they would be exposed to chemical reagents and high temperature. Therefore, under the framework of the research on the application of new constructional materials, the IMP PAN team performed the strength analysis during which test samples made of plastic were exposed to the working mediums for a long time.

This part of the article discusses strength tests of a sample made of the plastic that was chosen as a material from which the microturbine's rotor disc will be made. The choice of this material was made according to the above-described criteria and on the basis of information provided by the manufacturer. According to the available information, the selected plastic is characterized by the chemical resistance against the working medium of the ORC system and has an appropriate strength. The aim of the conducted research was to check whether the long-term contact of the material with the working medium does not affect the deterioration of strength properties and whether the sample does not change its dimensions due to absorption.

The sample was completely immersed in the working liquid of the ORC system for 14 days and then was subjected to a tensile test. The test was carried out using an automated tensile testing machine (HT-9711 model) produced by Hungta Company, which is a piece of the laboratory of the Mechanics of Intelligent Structures Department at the Institute of Fluid Flow Machinery of the Polish Academy of Sciences. The test sample (type B1) was manufactured according to the DIN EN ISO 527-2 standard (Fig. 6).

Figure 6 The test piece made of plastic, which was subjected to a strength analysis

To obtain reliable results, tests were carried out for 3 samples immersed for 14 days in the liquid used as a working medium and additionally for 3 samples that had no contact with it. That way, it was possible to check whether the working medium could affect the strength properties. The results of the tensile test for the chosen pair of samples are presented in Fig. 7. These are curves that show the elongation of the samples under the tensile force. The ultimate tensile strength was calculated for the last point after which the sample was failure. The values of the ultimate elongation are easily visible on both graphs.

The experimentally determined tensile strength of the samples was about 118 MPa, independently whether they were immersed in the liquid used as a working medium. The results of the subsequent tensile tests differ by not more than one percent, which indicates a high repeatability of obtained values. It was also estimated that the yield point (proof stress) of the investigated material is about 88 MPa and the unit elongation at the yield point is approx. 3.2%. These results are consistent with the data provided by the material supplier and the experimentally obtained yield point is even higher than that declared by the material manufacturer (the catalog value is 84 MPa). On the basis of the conducted research, it can be concluded that the low-boiling liquid had virtually no impact on the strength properties of the tested plastic. Carrying out accurate geometric measurements and inspecting the mass of samples showed that the tested material exhibits a low absorption capacity. After the 14-day immersion of a sample, its dimensions and mass increased respectively by approx. 0.5% and 1%. As expected, our own tests confirmed that the selected material is characterized by resistance to the working medium of the ORC system.

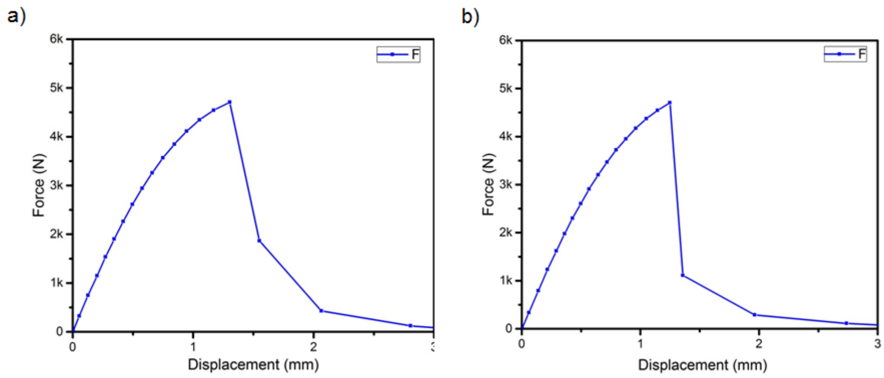

Figure 7 a) results of the tensile test carried out on the dry test sample, b) the test sample that was soaked in the liquid used as a working medium

5. Conclusions

The article discusses the problems associated with the application of modern plastics to elements of fluid-flow machines that have to cope with high loads. The problem was presented with a practical example of a high-speed turbogenerator designed to work in a micro ORC installation. The possibility of using plastics was considered in relation to the rotor disc as it is one of the most labor-intensive and expensive elements of a cogeneration unit.

The first part of the article discusses the operating parameters of the rotor disc, and examples of high-temperature plastics and selected criteria used in the choice of plastic are presented. In the case of the heavily loaded rotor disc of the microturbines, the key criteria were: the possibility of long-term operation with elevated temperature, chemical resistance to the medium used, and good mechanical properties. The low thermal expansion and density of the material were also significant. The second part of the paper presents an exemplary strength and dynamic analysis of a plastic rotor disc. The analysis was carried out using the FEM model built on the basis of 3D disc geometry. The results of the analysis showed, that despite exceeding the acceptable stress level, some modifications of the pre-developed geometry of the rotor disc should allow it to be made of plastics. The use of such a disc should enable proper and safe operation of the ORC turbogenerator in a wide range of working conditions.

Conducting the strength tests proved that some subassemblies of the ORC turbogenerator can be made of the selected plastic. Within the framework of this study, samples of the material before tensile tests were directly exposed to the working medium of the ORC system.

To sum up, it can be concluded that the conducted research and analyses carried out have been positive. It was found that with an adequate adaptation of the rotor disc design, selected plastics could replace traditional metallic construction materials. This issue certainly requires further analysis and experimental research. At a further stage of the research, the ORC turbogenerator with the rotor disc made of plastic will be checked for correct functioning under laboratory conditions.

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