The study of the applicability of polymer composite materials for the manufacture of the impeller of a centrifugal compressor

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Abstract. The use of composite materials in modern designs is one of the promising areas. Despite a number of advantages, the use of composite materials imposes a number of restrictions on their use. One of them is a binder’s degradation temperature. The revision of the existing methodology for determining the thermal state of the compressor wheel through the use of modern calculation tools and their experimental justification will allow further reliable thermal calculation taking into account the anisotropy of material properties. For carrying out computational research and testing manufacturing technology, a three-dimensional model of the impeller of a centrifugal compressor and the motor shaft was developed.

1. Introduction
The use of composite materials in modern designs is one of the promising areas [1–4]. Small specific gravity, high strength characteristics determining a composite material are an advantage when choosing small compressors (figure 1). Despite a number of advantages, the use of composite materials imposes a number of restrictions on their use, including binder degradation temperature. Based on this, a reliable calculation of the thermal state of the structure is the basis for the further use of composite material in the manufacture of the compressor impeller.

![Figure 1. Centrifugal compressor impeller made of polymer composite materials.](image)

The objectives of this work were: improving the methodology for determining the thermal state of the impeller of a centrifugal compressor through the use of modern calculation tools and their...
experimental justification; and studying the possibility of using polymer composite materials in highly loaded units of modern aircraft propulsion systems. The problems addressed:

- Three-dimensional models of the impeller of a centrifugal compressor and shaft, taking into account the upcoming technological processes, were created.
- The boundary conditions, temperature distribution $T$ and convective heat transfer coefficients $\alpha$ along the profile of the blades and the back surface of the compressor depending on the gas flow rate for cooling $G_y$, were calculated.
- The thermophysical properties of carbon fibre based on carbon fibres UMT 49S and phthalonitrile binder PN-3M for unidirectional layer and laying used in the manufacture of compressor elements were experimentally determined.
- The thermal state of the impeller of a centrifugal compressor was calculated according to the previously defined boundary conditions.
- The technology of automated calculation of reinforcing material was developed and applied.

As the object of study, the impeller of a centrifugal compressor of a promising small-sized gas turbine engine was selected, having the following parameters: an engine life of 12 hours; a maximum duration of engine operation in high power mode of 3 hours; a maximum operation temperature in the centrifugal compressor of 560 K; and an outlet pressure of 7 bar. As a result of the analysis of the known methods for calculating the thermal state of the impellers of centrifugal compressors, it was determined that the existing methods are applicable only for the calculation of metal compressors and do not take into account the anisotropy of the thermophysical properties of composite materials [5]. A method for calculating the thermal state of the impeller of a centrifugal compressor was developed taking into account the anisotropy of the thermophysical properties of the composite material.

2. Results of three-dimensional modelling and numerical simulation

To conduct design studies and refine the manufacturing technology, a three-dimensional model of the impeller of a centrifugal compressor was developed in the Siemens NX software package, which consists of 20 segments, engine shaft and 5 power rings (figure 2).

![Figure 2](image_url)

Figure 2. Three-dimensional model of centrifugal compressor impeller part.

It is known that the efficiency of the Brighton cycle directly depends on the degree of increase in gas pressure in the compressor [6]; accordingly, makes sense to minimize gas leakage on cooling of engine elements; however, it is assumed that a reduction in gas consumption for cooling can cause heating of the rear surface of the impeller to temperatures significantly exceeding the glass transition temperature of the binder, which in turn can lead to melting of the binder and the destruction of the part. The task is to achieve the minimum required flow rate of gas leakage for cooling the rear surface of the impeller of a centrifugal compressor, nozzle unit and rear bearing.
When calculating the air parameters on the back of the rotor, a program was used for iterative calculation of gas-dynamic parameters. The graphical dependencies (figure 3) confirm the assumption that the reduction in leakage rate $G_y$ can cause significant heating of the rear surface of the compressor rotor. In view of the restrictions on the glass transition temperature $GTT = 450$ degrees Celsius of the binder PN-3M, the choice of leakage rate $G_y = 0.0102 \text{ kg/s}$ is preferable; accordingly, gas-dynamic parameters of air will be used to calculate the thermal state of the impeller of a centrifugal compressor at a leakage rate of $G = 0.0102 \text{ kg/s}$.

![Figure 3. Dependence of the temperature $T^*$ in the sections on the rear surface on the gas flow rate for cooling $G_y$.](image3)

2.1. Setting boundary conditions

In the ANSYS Mechanical module, the three-dimensional model was divided into annular regions according to the cross-sections for calculating boundary conditions (figure 4).

![Figure 4. Setting boundary conditions - Convection.](image4)

To determine the thermal state of the impeller of a centrifugal compressor from composite material using ANSYS Meshing, a finite element mesh was generated containing 263787 nodes and 140344 elements (figure 5).
2.2. Thermal state of the structure
As a result of the calculation, the thermal state of the power rings, the compressor segment, and the entire structure (figure 6) is determined. It is obvious that the back surface is heated to temperatures close to the binder destruction temperature, but not exceeding it.

3. Results and discussion of centrifugal compressor manufacturing
Special attention is paid to the technological solutions used in this design. To manufacture the impeller segments of a centrifugal compressor, the technology of automated reinforcing filler patch was applied, which can be implemented using specialized sewing (or embroidery) machines equipped with CNC, which allow stitching of various types of roving (straight) fibres onto a flat fabric substrate, including carbon [7].

Such two-coordinate machines allow you to lay the fibre on the table plane along a complex path, while simultaneously (or locally) sewing it to the base with an auxiliary thread (figure 7). It is possible to sew the fibres end-to-end to each other with high accuracy and reproducibility, forming a monolayer of the future preform. In each layer, the fibres can be located in any given direction and, therefore, this method allows you to fully realize the strength properties of the fibres by manufacturing a preform with an optimal reinforcement scheme.

Figure 5. Mesh model of a centrifugal compressor.

Figure 6. Thermal state of the structure (Temperature in K).
3.1. Separation of centrifugal compressor impeller segments into separable package

Due to the limitation on the thickness of the sewn preform, which is determined by the strength of the auxiliary (sewing) threads and the need for further processing of the received sewn packages, the sewed object is divided into separate packages.

For strips of a centrifugal compressor rotor impeller segment, the most rational option for splitting was division into blades (figure 8). In this case, the feather of the blade is divided into two symmetrical packages and the disk part into 10 packages. The control programs for the embroidery machine were created in the GIS BasePac 10 software package taking into account the direction of fibre laying for each individual monolayer, the laying step (which affects the final density and, accordingly, the thickness of the bag). In this paper carbon fibre based on UMT49 fibres and binder PN-3M was used as the material for centrifugal compressor impeller segments.

3.2. Centrifugal compressor impeller segment pressing technology

Figure 9 shows the preparation of a segment of the impeller of a centrifugal compressor, made by the method of directional laying of reinforcing material, which will be further impregnated by the RPM method and pressed in technological equipment. After manufacturing 20 segments of the impeller of the centrifugal compressor and five power rings, the set of segments is fixed in the assembly tool, filled with molten paraffin and after curing the paraffin grooves are grooved under the power rings. Then, in the same snap-in, the power rings are pasted.

Studies have shown that the use of composite materials for the manufacture of the impeller of a centrifugal compressor is a promising direction for today, especially with the use of the described manufacturing technology, but the further development of this subject is impossible without the
development of new types of Binders, which would increase the operating temperature and pressure ratio, thereby enabling to make high-performance centrifugal compressors.

Figure 9. “Dry” workpiece of the blade segment of the impeller of a centrifugal compressor, directional styling reinforcing material and centrifugal compressor impeller segments.

4. Conclusion
A method has been developed for calculating the thermal state of the impellers of centrifugal compressors made of composite materials, taking into account the anisotropy of the thermophysical properties of materials and heating of the rear surface of the compressor.

As a result of the calculation, a temperature distribution is obtained for each individual structural element and the assembly as a whole. It was determined that the temperatures on the product do not exceed the permissible glass transition temperature HDT of the binder PN-3M of 450 °C. The calculations showed that carbon fibre based on reinforcing fibres UMT-49S and a binder PN-3M can be used to make the impeller of a centrifugal compressor.

The use of this material will reduce the weight of the impeller by 45% compared with the aluminium prototype. The proven technology of directional laying of the reinforcing material allows to reduce in 3 times the manufacturing time of “dry preforms” in comparison with the manual laying of monolayers, and also reduces the frequency of revealing production defects of products from polymer composite materials.

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