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ПРОДЛЕНИЕ СРОКА СЛУЖБЫ ГАЗОТУРБИННЫХ ЭЛЕКТРОСТАНЦИЙ, ПРИМЕНЯЕМЫХ НА МЕСТОРОЖДЕНИЯХ ПОЛЕЗНЫХ ИСКОПАЕМЫХ

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Аннотация: рассмотрен вопрос повышения надежности газотурбинных двигателей (ГТД) и продления срока их службы. ГТД используются в качестве электрогенераторов на месторождениях полезных ископаемых. Ресурс ГТД зависит от совершенства системы охлаждения турбины. С целью улучшения охлаждения турбинных лопаток представлен уникальный турбулизатор для лопатки турбины, а также результаты аэродинамического эксперимента и CFD-моделирования потока через спиральный турбулизатор. Дано сопоставление результатов. В конструкции охлаждаемой лопатки турбины со спиральным турбулизатором в качестве конструкционного материала используется графен — революционный материал 21 века, способствующий более быстрому охлаждению лопатки. Рассмотрены перспективные пути получения такого турбулизатора для охлаждения турбины. Спирали можно эффективно использовать в случаях, когда необходимо турбулизировать воздух или уменьшить напор потока.

Ключевые слова: турбина, система охлаждения, газотурбинный двигатель, лопатка.

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Extending the service life of gas turbine power plants used at mineral deposits

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Abstract: This article deals with the issue of improving the reliability of gas turbine engines (GTEs) and extending their service life. GTEs are used as power generators at mineral deposits. For this purpose, a unique turbulator for the turbine blade design is presented with the results of an aerodynamic experiment and a CFD simulation of the flow through a spiral turbulator. The results are compared. The design of the cooling turbine blade with a spiral turbulator includes the use of graphene as a construction material, a revolutionary material of the 21st century with a large cooling capacity. Promising ways of obtaining such a turbulator the purpose of turbine cooling are considered. The spirals can be effectively used in situations where it is necessary to turbulize the air or decrease the flow pressure.

Key words: turbine, cooling system, gas turbine engine, blade.

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1. Problems of extending the service life of gas turbine power plants

1.1 Use of gas turbine engines for energy generation at mineral deposits

It is known that a gas turbine power plant is commonly used for the supply of power at mineral deposits. Due to remote conditions of most of the fields, there may be problems with the reliability of gas turbine power plants, when engine failure may deprive the field of power and require replacement of damaged parts. This can become a serious problem. It is also important to note that by 2040 the demand for gas turbine plants will increase to 99.19% [1]. It is clear that this is also related to the reliability of the gas turbine engines used for power generation in the energy sector of the Russian Federation. Gas turbine plants (GTPs) can be flexibly turned on and off, even if it happens for a few hours a year. In 2017, there were 2,152 GTPs in the Russian Federation [1]. After 2020, high growth is projected for gas turbines engines and power plants

1.2 Defects of turbine blades

The reliability of an engine depends on the service life of a number of parts. One of the main parts that can be considered a determinant of the service life of these engines is the first stage turbine blades. These blades work under difficult conditions. High temperatures and high dynamic loads increase the likelihood of defects that can dramatically reduce the service life of both the turbine and the engine as a whole. The causes of burnouts (Fig. 1) can be divided into two main groups: operational and environmental causes [2].

The main cause of blade failure is the burnout of the exterior blade walls. This is caused by excessive heat (one of many operational causes). The most problematic is the leading edge of the nozzle (stator) blades. This is the zone through which high-temperature gases pass (compared to other sections along the length of the profile). Other operational causes are insufficient cooling, blockage of cooling airflow and improper burning process.

1.3 Cooling as a way to increase the service life of turbine blades

In nozzle blades the leading edge has a separate cooling channel, i.e., in the leading edge zone, an independent cavity is created, where a coolant is supplied. Also, the results of tests of full-scale turbines show that the radial plot of the gas temperature in front of the blade has a maximum that is located approximately in the middle part of the upper half of the blade profile (i.e., approximately 2/3 of the height of the blade from the lower section). Taking into account the requirements to the level of cooling efficiency needed for promising turbines and the results of determining the radial gas temperature before the turbine of an actual engine, we can propose the following nozzle blade design. Such a blade contains a profile, the inner part of which is divided

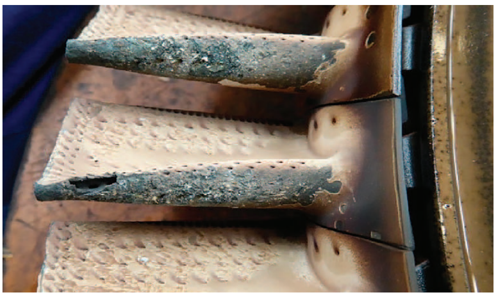

Fig. 1. Burned HPT T1 blade with through-burn [2]

into three cavities: two in the area of the leading edge (located above each other in height) and one more for cooling the middle and the tail part of the blade. The advantage of such a blade is that its design allows to deliver a flow of cooling air (which is separate and does not cool other sections of the blade profile) to the most problematic section of the blade profile (in terms of thermal stress), thereby a higher level of cooling efficiency is achieved, the blade temperature is intensively reduced, therefore, the possibility of cracks and burnout is reduced. As a result, the reliability of the blade increases, thereby increasing its service life.

2. Use of spiral turbulators

2.1 Modern types of turbulators and their purpose

The practice of design of cooling turbine blades in GTPs allows using turbulators of various shapes in inner channels [3, 4]. Today, the following are commonly used: pins, matrices, ribs, etc. It is advisable to consider new forms of turbulators, which will provide the necessary increase of intensive heat exchange without critical decrease of air pressure in a cooler (Fig. 2). This is done to release air that was used for heat removal. The authors propose a new option in the form of a spiral.

2.2 Experimental analysis of airflow through different spiral models

The experiment was conducted using an aerodynamic stand (Fig. 3). To obtain the aerodynamic characteristics of the spirals, they were modeled in Unigraphics NX and 3D printed at the university (Department of Materials Science and Additive Technologies). Because of the nature of 3D printing, they were split in half. Then, they were installed inside a tube, where they were held in place with screws. This setup ensured the stability of the spirals stable during strong airflow.

The pressure receiver was programmed to move along the radius of the spiral (Fig. 4). For a given radius, the receiver moved to the left, and then passed 10 points towards the 180-degree mark. Radius measurements were recorded for different radii. Excess pressure of the airflow at the

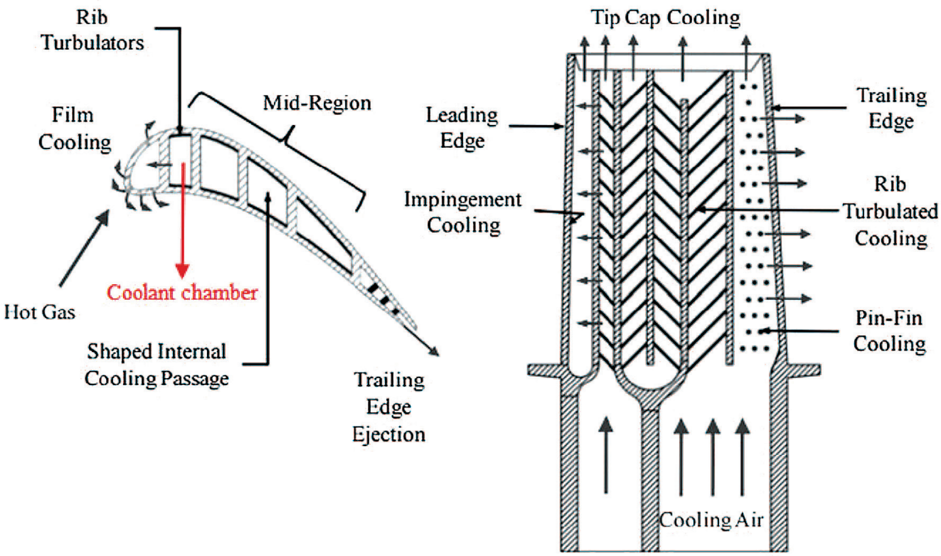

Fig. 2. Methods of internal cooling of gas turbine blades [5]

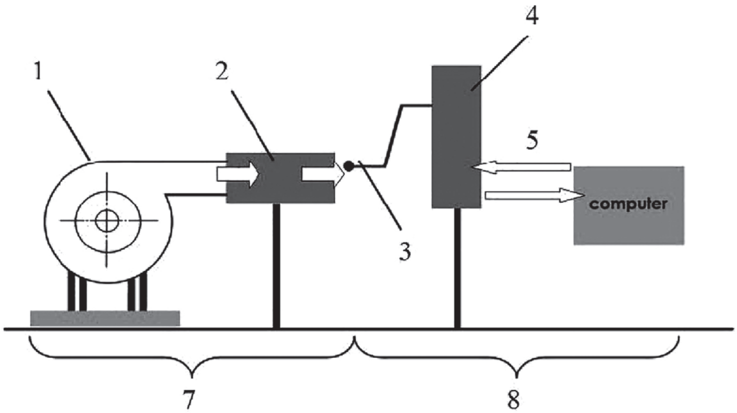

Fig. 3. The scheme of the aerodynamic stand: 1 — engine; *2* — model; *3* — pressure receiver; *4* — coordinate receiver/sender; *5* — controller; *6* — computer; *7* — wind tunnel; *8* — measurement unit

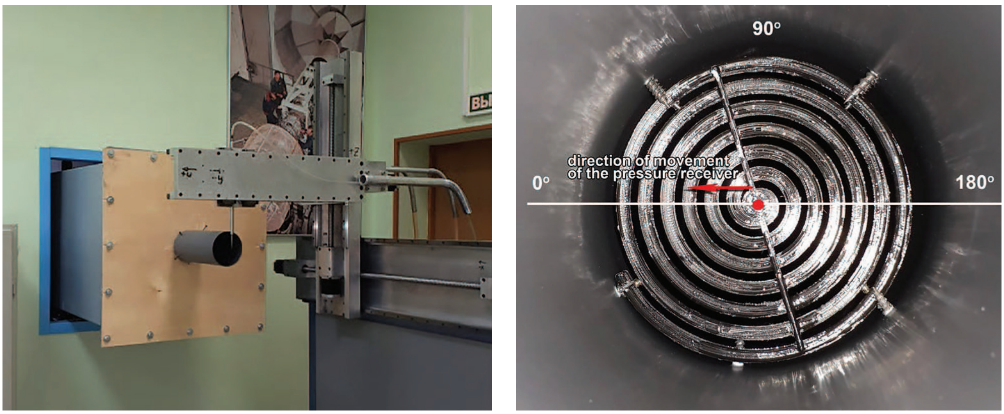

Fig. 4. Left: General view of the model in the tube and measuring stand. Right: Movement and direction of the pressure receiver along the spiral 3

end of the exit from the channel (cylinder) was measured (Fig. 5).

To obtain a smoother surface, the spirals were coated with a polisher (Fig. 6). The spirals had differences in their constructions, the difference being the number of turns — n, where the diameter was constant 96 mm, with a thickness of 4 mm. Table 1 shows the ratio of Δ to b.

Experimental study of spiral flow patterns conducted by the authors showed that this type of turbulator allows it to have a higher level of turbulization, which will lead to more efficient heat removal. The spiral-shaped turbulator is installed exactly where the cool air is supplied, in the inner channel, where the end wall of the blade is located.

It is safe to say that vortices were shedding [6] down in some zones of the spiral very quickly, and then alternating vortices joined each other along the way (Fig. 7).

In another experiment, spiral 2 was 3-D printed twice more so that it could be added to the experimental cylinder. The three spirals were placed in the cylinder and the overpressure was measured along the radius at an angle of 110—112. Three spirals were placed in the cylinder, and

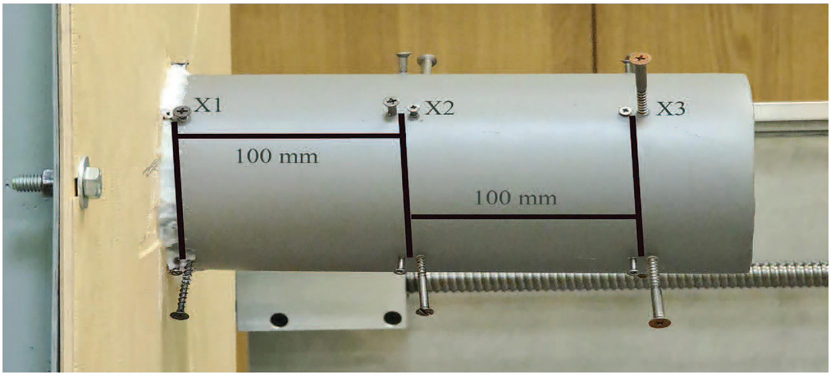

Fig. 5. Experimental cylinder with three spiral positions: X1, X2, and X3.

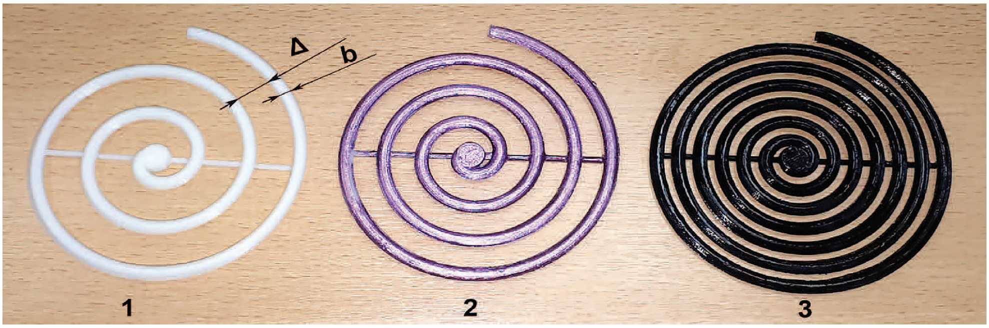

Fig. 6. Left: spiral 1. Center: spiral 2. Right: spiral 3. Δ is the distance between the turns. b is the width of the turn, n is the number of turns

Table 1
Parameters of the spirals

	Distance between the turns Δ, mm	Width of the turn b, mm	Ratio of Δ/ b	Number of turns n	Maximum radius, mm
Spiral 1	12.25	4	3.0625	3	50
Spiral 2	8.2	4	2.05	4	50
Spiral 3	2.91	4	0.7275	7	50

overpressure was measured along the radius at 110 – 112

A comparison of the backpressure distribution in the case of one spiral and a combination of three spirals showed similarities (Fig. 8).

Obviously, the combination of three spirals reduces the flow pressure by almost half. One spiral allows for higher flow turbulence.

Moreover, the points of local maxima and minima indicate the twisting of the airflow in the direction of the spiral twist.

2.3 CFD analysis of airflow through a spiral model

A CFD simulation of the turbulent passage of hot air through a spiral was attempted. To perform numerical simulations, the spiral model was created in Unigraphics NX and imported into

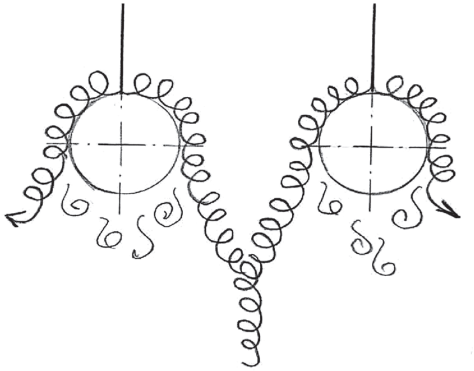

Fig. 7. Representation of the vortices shedding and joining

Autodesk CFD. A fine mesh of the spiral model 3 was created (Fig. 10) and boundary conditions were applied, including an appropriate turbulence model, flow parameters at the ends of the cylinder, and properties of the air-fluid.

As a result of the simulation, the distribution of pressure and flow velocity fields flowing through the spiral were obtained (Fig. 11). The spiral was able to provide minimal pressure losses, which in its turn is good and for the release of cold air out from the turbine blade.

The study of the flow around the three Archimedean spirals allowed led to conclusions about a high degree of turbulization of the flow generated around the spiral. The installation of an Archimedean spiral directly near the leading edge of the turbine blade allows creating a well-swirled flow that spreads upwards along the leading edge, which contributes to its intensive cooling. It is recommended to release this air radially upwards.

The error when comparing the experiment with the simulation is about 12% (Fig 12). This is a low percentage, and it shows that the CFD simulation is reliable.

3 Turbine blades with spiral turbulator made from graphene

3.1 Properties of graphene

The problem in creating spirals is the technical capacity of making turbulators from graphene. Studies of the cooling characteristics of graphene show that graphene performs heat removal at a higher rate [7]. Graphene can be made with a two-dimensional structure, and since it is also elastic, this can allow the construction of nanotubes, in which many layers of graphene are joined radially and eventually bent into a tube. This tube is stretched into a spiral and held

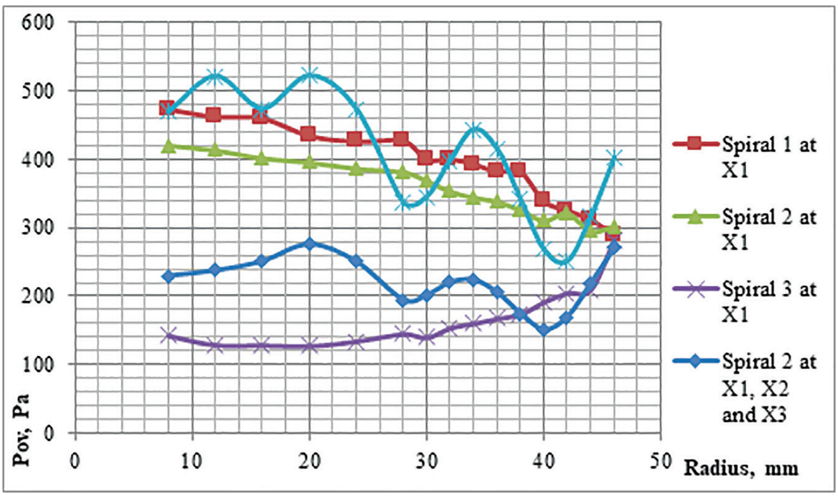

Fig. 8. Comparison of changes in overpressure along the radius of the spirals

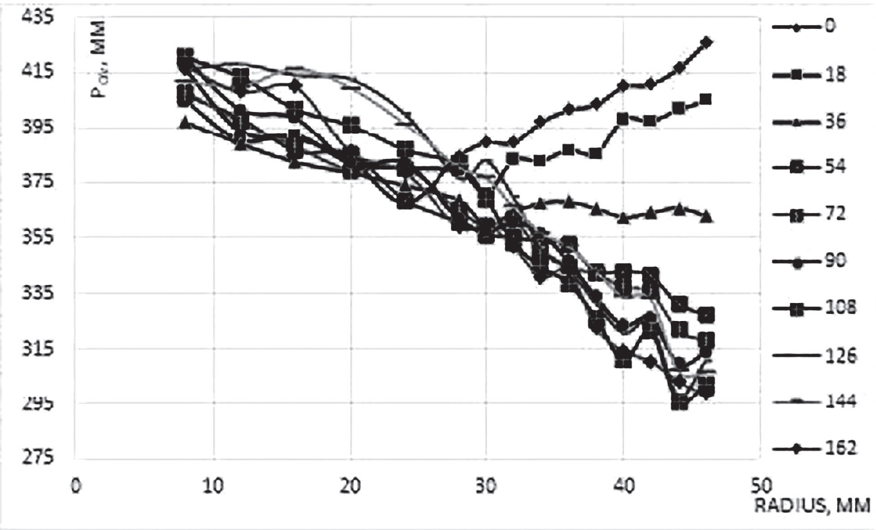

Fig. 9. The change in pressure along 10 radii of the spiral

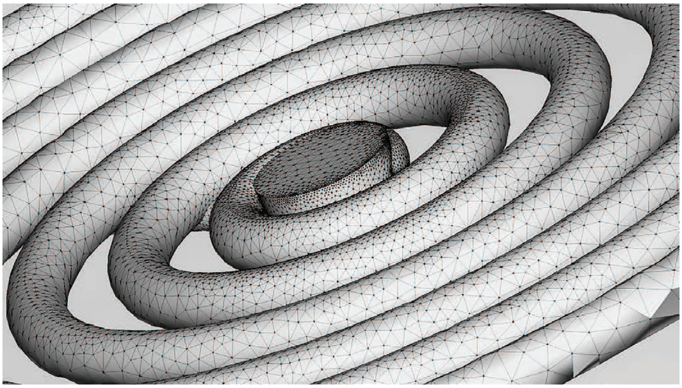
Fig. 10. Spiral mesh in Autodesk CFD

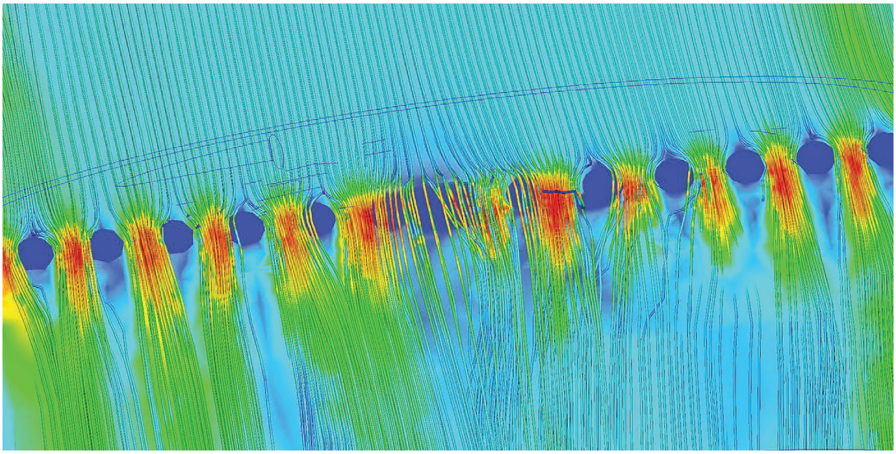
Fig. 11. Representation of traces through spiral 3

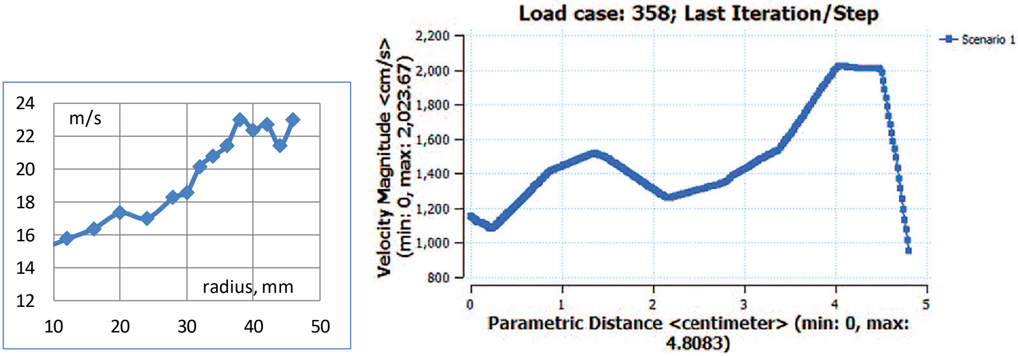

Fig. 12. Comparison of experimental (left) and simulation results (right) for spiral 3

in place. Another way to produce spirals would be by using wire electric discharge machining (WEDM) to produce any small graphene models, as it can conduct electricity very well. WEDM is already used to cut diamond, which has the ability to conduct electricity, similar to graphene and graphite. The properties of a spiral turbulator made from graphene will be very high both in terms of strength and heat transfer.

3.2 Graphene as a material for spiral turbulators

Graphene was obtained by electrolysis. To obtain the electrolyte ammonium sulfate was mixed in deionized water with a molar fraction of 0.5. The use of graphene foils of 0.2 mm thickness on the anode and cathode during the experiment made it possible to obtain graphene and graphite in the solution. The solution was filtered. Filtration was repeated by adding deionized water to obtain pure graphene/graphite powder. Black tea was prepared as a medium with deionized water to allow ultrasonic bathing of the powder. The powder was added to the tea solution before bathing in water. This is done to induce vibration and split many layers of graphene and graphite particles that turn the brown tea solution into a jet black solution. Bathing was performed for about two hours at 20,000 KHz. A centrifuge was used to separate the liquid from the solid particles in the jet black solution, after which the liquid was decanted. Deionized water was added to the solids formed on the bottom to remove the remaining tea. The centrifuge was used again, decanted, and then the tubes were placed in an oven at about 100 °C to remove any moisture in the graphene product. The product was then safely placed in a clean jar.

The heat dissipation of the graphene sample was compared with that of titanium and aluminum alloys. The experiment showed that graphene dissipated heat faster than others (Fig. 13).

A turbine blade with a unique spiral turbulator is shown (Fig. 14). In the inner section, two rods are connected to the part through which the cooling air flows, and spirals are mounted on these rods. The flow of cooling air will contact the spirals and increase the level of turbulence. Thus, the temperature of the turbine blade can be effectively reduced.

4 Promising and modern processes for creating a graphene turbulator

The future development of graphene production technology will make it possible to produce a lightweight and durable turbulator, capable of generating enough powerful turbulent flow to effectively cool the turbine blades, especially when it is already making its way into aviation [8]. Graphene has

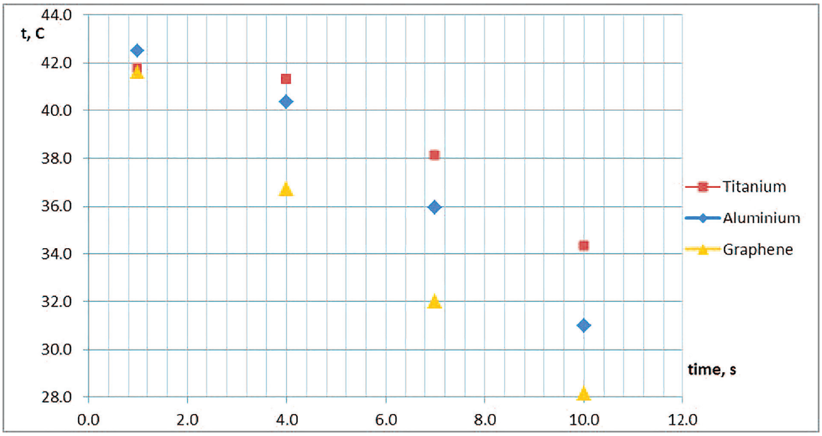

Fig. 13. Results of heat dissipation from titanium, aluminium, and graphene samples

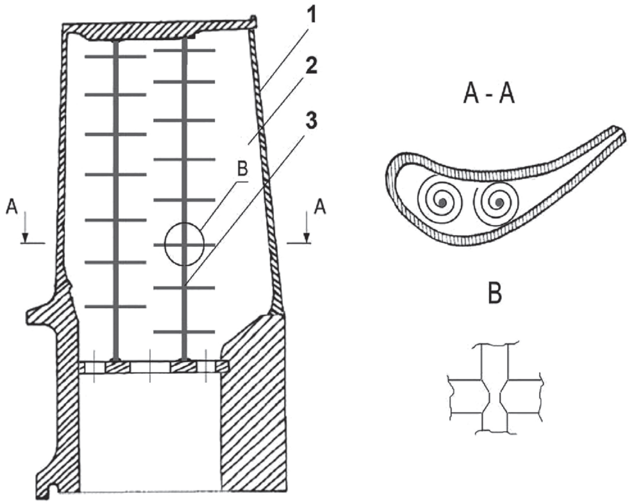

Fig. 14. Turbine blade spirals are attached to two rods. 1 is the blade wall, 2 is the cooling channel, 3 is the rod with spirals; B is the junction where the rod connects to the spiral

a higher level of strength and a higher degree of heat removal from the turbine blades, which in any case will benefit the mining industry.

In the 21st century, there are many new technologies and methods to obtain graphene; we can say that this is a new technical revolution. One of the many ways to create a spiral is to combine many layers of graphene layers using nanotechnology, or, in another way, by exfoliation [9], and obtain a solid model. Then, with the use of wire electric discharge machining (WEDM) [10 small spirals of grapheme can be created, which, in their turn, can be used as a turbulator. Another method is to use electrolysis via chemical vapor deposition at atmospheric pressure on copper [11] and graphite to obtain graphene-coated copper. This method is still being studied, and it may other metals could be coated in the same way.

Other methods of manufacturing graphene turbine blades include special coatings and composites. Graphene coatings have been achieved by other researchers on titanium [12] and copper [13, 14]. In the future, graphene will have important applications in many spheres, and it is logical to say that if there are graphene coatings on metals, there will always be a way to coat other metals with graphene.

As for composites, they are becoming more popular, with research finding it possible to create graphene-metal composites. For example, aluminium-graphene composites [15].

5 Conclusion

The spiral provides a high level of turbulence in the airflow. This, in its turn, provides better heat transfer, even though the spiral is several times lighter than most turbulators.

A higher level of turbulence can be achieved with a $\Delta/b > 1$ ratio. Spiral turbulators can reduce the temperature of turbine blades by about 16—18 percent, which simultaneously increases service life and durability. The proposed design of the blade cooling system will significantly increase the operating temperature of the turbine [16] without reducing the reliability and service life of the blades, which will have a positive effect on the level of efficiency of the entire engine.

A full set of first stage turbine blades could cost 60,000,000 rubles [17]. This includes manufacturing and replacement costs. Any visible burnouts require immediate replacement or re-coating of the burned blades. Given the cost of replacement blades, a complete engine shutdown will also be required for proper inspection and repair. Inspection and maintenance of the engines can result in serious loss of needed power as the engines are at a full stop and cannot be turned on. These factors in the calculation of the economic effect on the costs required for turbine blades made from graphene spiral turbulators.

Improvements in turbine cooling systems help to improve the environmental situation [18] and make a significant contribution to the development of Russia's energy sector [19—25].

The future development of graphene production technology will provide a lightweight and durable turbulator. Graphene has a higher level of strength and a higher degree of heat removal from the turbine blades, which in any case will benefit the mining industry.

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