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SUBSTANTIATING PROMISING TECHNICAL SOLUTIONS FOR TURBO- EXPANDER POWER PLANTS BASED ON THE RESEARCH INTO WORKING PROCESSES AND STATES

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One of the most rational methods of energy utilization of compressed gas in pipelines is to use turbo-expander installations. In particular, these are autonomous turbo-expander power stations. A fundamentally new concept has been devised to improve the technical and economic performance of this type of machines. This concept is not focused on a separate aspect of the plant’s operation but on their entire set. In particular, physical principles, structures, and technologies were considered as an object of research. First, effective parameters of gas-dynamic flows and heat-mass transfer were determined based on the modeling of work processes. Secondly, progressive designs of turbo-expander units have been created. Thirdly, technologies for the production of parts and assemblies of turbo-expander units have been developed, which combine, unlike the traditional ones, different types of strengthening for contacting parts in their pair. A method of parametric modeling was used to substantiate the technical solutions of the elements of turbo-expander power plants. This makes it possible to determine the technical characteristics of these installations under a certain set of parameters. By purposeful variation, a recommended set of their parameters was determined, which ensure the improvement of the most important technical characteristics. A specialized database was built, which contains an array of information about the regularities of the influence of variation of significant parameters on various characteristics of turbo-expander power plants. Already on this basis, the problems of synthesis of successful technical solutions of turbo-expander power plants are solved. As a result, their high energy efficiency is ensured. Thus, the efficiency of the expander was achieved at the level of 86 % while the resource increased by 20–25 %. All these solutions were implemented in a number of unique turbo-expander units. Their effectiveness has been demonstrated during operation

***Keywords:** discrete-continuous strengthening, contact interaction, stressed-strained state, technical characteristics, turbo-expander, heat and mass transfer*

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1. Introduction

One of the effective ways of using the energy of compressed gas, which is in the gas pipeline, is its utilization at turbo-expander plants, in particular, turbo-expander power plants (TePPs). Despite the fundamentally positive nature of this technique compared to the traditional throttling method, the problem of further increasing the energy efficiency of this technique arises. At the same time, it is traditionally possible to pay attention to certain aspects of the operation of turbo-expander installations. However, a conceptual approach that covers all the most significant aspects appears to be more effective. Accordingly, directions for research and development have been determined.

The first of them concerns the work process in the gas-dynamic flow. This flow passes through the channels and drives the rotary part of the turbine. An important factor is the fact that the working body is not an ideal but a real gas, and with impurities of the liquid phase. Therefore, improved structural solutions of the main elements are needed. First of all, this concerns impellers.

Another important aspect is the technology of manufacturing and strengthening of parts and assemblies of turbo-expander units. It should be noted that traditional technologies have largely exhausted their capabilities in terms of improving the technical characteristics of these installations. Accordingly, it is necessary to devise new, more effective manufacturing and strengthening methods.

2. Literature review and problem statement

Modern turbo-expander units attract the attention of many researchers [1, 2]. In these works, some basic problems of design and research of turbo installations are illuminated, but each is considered separately. At the same time, not all problems were solved in their totality. Thus, there is no single generalized approach to justifying technical decisions at all stages of design and technological preparation of production. This reduces the value of certain successful, but not mutually agreed, solutions. At the same time, in addition to these issues, attention is drawn to certain directions, which are reported in a large number of works. These are, in particular, the problems of heat and mass transfer and hydro-gas dynamics [3, 4]. These issues are considered in more detail in individual aspects in [5–7]. At the same time, work [5] does not take into account the significant changes that have taken place in recent years in the sector of designing turbo-expander installations. As for [6, 7], they mostly use traditional models of hydrogas dynamics, which require development and improvement. And in [8, 9], these fundamental developments and studies are implemented in applied aspects regarding turbo-expander installations.

At the same time, the studies reported in the above-mentioned works should be implemented in specific technical solutions. Works [10, 11] describe precisely the methodology of combining theoretical developments and specific technical solutions. In these works, to a certain extent, structures and processes and conditions in turbo-expander installations are investigated. And papers [12, 13] describe specific solutions regarding utilization and other installations.

At the same time, it should be noted that a full, and most importantly, a comprehensive solution to all problematic issues has not been found. This is due to the fact that there is no research methodology that covers, on the one hand, all stages of the life cycle, and on the other – various processes and conditions that accompany the production and operation of existing installations. In addition, the operating conditions of modern installations and the requirements for them are constantly changing [14].

In order to take into account these features and in contrast to traditional procedures, methods of complex generalized parametric modeling of work processes and states have been devised for such structures [15, 16].

However, these studies do not cover all significant components of the life cycle, but only some of them [17, 18]. That is why the development of this research methodology is needed.

In addition, new models and methods of researching the processes and states of structural elements with various methods of strengthening are also needed [18, 19]. However, emphasis is made in [18] only on the advantages of discrete strengthening. On the contrary, in [19, 20], the authors argue about the advantages of continuous strengthening. In particular, among these methods, microarc oxidation (MAO) attracts attention [21–24]. It should be noted here that in works [21, 22], coatings are optimized only according to certain criteria, in particular, according to frictional properties. The same problems apply to [23, 24] but in relation to residual stresses. Papers [25, 26] describe certain aspects and properties caused by the MAO technology. However, the entire set of their properties is not covered. The method of discrete strengthening is also promising [18]. The combination of these methods is even more promising [27].

As a result of strengthening, a thin layer of coating or coatings is created on the surface of structural elements [27]. The properties of the materials of these layers differ sharply from the properties of the main material [28, 29]. In particular, these and a number of other works describe constructed models of surface layers [29, 30]. Various models can be used to analyze the stressed-strained state of such a composition [31, 32]. These models are based on different approaches [33]. However, such models are not applicable directly for modeling reinforced layers of materials, for example, when applying discrete or continuous strengthening. They need to be improved.

Improved models and methods have been developed for mathematical and numerical modeling of the stressed-strained state of such contacting structural elements [34, 35]. They are based on the one hand, on variational principles, and on the other hand, on numerical methods of boundary and finite elements [36, 37]. These problematic issues are partially resolved in works [38, 39]. But, despite significant progress, the development of these methods and models is necessary for the study of the stressed-strained state of a new class of turbo machine elements.

Finally, we can conclude that there is an urgent need to devise a concept for the study of processes and states, as well as a synthesis of progressive technical solutions for elements of turbo-expander installations.

3. The aim and objectives of the study

The purpose of this work is to determine the possibilities of improving the performance indicators of turbo-expander power stations. This serves as the basis for the synthesis of rational structures and the development of advanced technologies for the manufacture and strengthening of parts and assemblies of these installations.

To achieve the goal, the following tasks were set:

– to develop conceptual solutions for the justification of solutions for structural elements of turbo-expander installations;

– to determine the stressed-strained state (SSS) of discrete-continuously reinforced parts.

4. The study materials and methods

The object of our research is turbo-expander installations, in particular, TePPs.

The hypothesis of the study assumed that the determination of conceptual solutions for the justification of the structural elements of turbo-expander units and the SSS of their strengthened contacting elements could provide an opportunity to obtain solutions that would make it possible to improve the operational properties of TePPs.

The set of physical and mechanical processes in the manufacture and operation of elements of turbo-expander units is considered. This prompts to develop on this basis the concept of substantiation of their promising project solutions.

In order to devise the concept of constructing turbo-expander units, the method of generalized parametric modeling was involved and developed [36]. At the same time, in a generalized form, the model of processes and states in these elements is represented in the form:

$$L(u,p,f,t)=0, \quad (1)$$

where L is an operator that combines partial operators: $L=UL_r$ (L_r, $r=1,2,\ldots$ – operators, for example, of dynamic flows, contact interaction, stressed-strained state, friction, wear, etc.); u – state changes that describe the studied processes and states in these elements; f – external loads; t – time; p – an array of generalized parameters (structural execution, technological and structural parameters, etc.).

The main methodological advantage of model (1) is precisely in its integration of generalized parameters $p=\{p_i\}$, where each of the components p_i determines either given, or varied, or desired components of the general model. At the same time, all partial models of processes and states, which are described by operators L_r, have a single representation. That is, the parameterization is end-to-end, conflict-free, and consistent (regarding different processes and states, as well as different stages of the life cycle). Moreover, on this basis, it is possible to state problems of the synthesis of structural technological solutions, which are described under the array of array p:

$$p{:}T(p)\rightarrow extr, \quad (2)$$

$$H(p,u)\geq[H], \quad (3)$$

where T are the components of the technical characteristics to be maximized (or minimized); H, $[H]$ – correspondingly limited characteristics (strength, weight, efficiency, etc.) and their limiting levels.

The combination of ratios (1) to (3) forms a single platform, on the one hand, for the analysis of processes and states, and, on the other hand, for the synthesis of promising design and technological solutions for elements of turbo-expander installations.

On the basis of the devised methodological base, it is possible to solve a set of all problems for the construction of highly efficient turbo-expander units.

5. Results of investigating the design and technological solutions of turbo-expander installations

5. 1. Conceptual solutions regarding the substantiation of solutions for structural elements of turbo-expander installations

Expander-generators are turbo-expander units in which the mechanical energy of the rotor rotation is used to rotate the shaft of the electric generator and, accordingly, generate electrical energy.

It is proposed to connect the installations to be designed according to the scheme (Fig. 1) in parallel with the operating gas distribution point (GDP) or gas distribution station (GDS). That is, in fact, a new type of GDS is proposed, which fully performs the functions of a conventional GDS and, in addition, produces electricity in an environmentally friendly way.

Improving the technical characteristics of TePPs compared to existing ones is possible through the justification of new technical solutions since the known traditional solutions have reached the "ceiling" of their capabilities. For this purpose, the concept of substantiation of such decisions was devised, which provides for a comprehensive consideration of all aspects of the work of the elements of TePPs.

The concept of substantiation of technical solutions for TePP elements, which outperform existing samples (analogs), is shown schematically in Fig. 2. On the basis of the analysis of technical solutions of analogs and previous versions of TePPs, key problematic aspects that need to be solved are determined. These solutions ("C" in Fig. 2) are based on three components: I – the formation of structural variants of the elements of TePPs; II – development of progressive technological methods for strengthening the elements of TePPs; III – SSS analysis of representative sections of the strengthened elements of TePPs. As a result of the research, technical solutions for TePPs "T" with improved technical characteristics are formed.

In the process shown in Fig. 2, current solutions are constantly exchanged between stages I, II, III. Accordingly, they are purposefully adjusted. As a result, the technical solutions for TePP elements, which outperform analogs, are substantiated. This is confirmed at the stage of their operation.

The basis for improving the efficiency of the work process in turbo-expander installations (Fig. 1) is the justification of the rational parameters of the stator and rotor parts of the turbo-expander (Fig. 3).

Elements of these turbo-expanders work under conditions of interaction with other elements. Therefore, there are problems with ensuring their strength, as well as reducing friction and wear. Design solutions cannot provide a sharp increase in the specified characteristics, and therefore, advanced technological solutions are needed.

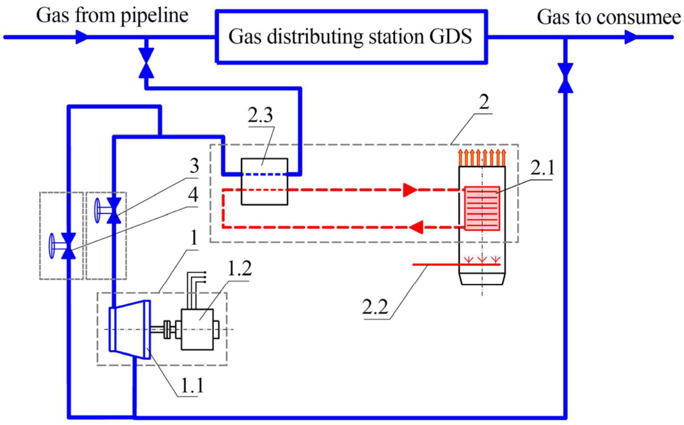


Fig. 1. Schematic connection of TePP to a gas distribution station [10]: 1 — turbo-expander unit; 1.1 — turbo-expander; 1.2 — generator; 2 — heat exchange equipment; 2.1 — heat exchanger (water heating boiler); 2.2 — postburning device; 2.3 — gas-water heater; 3 — unit of the stop-dosing valve; 4 — unit of the bypass-regulating valve

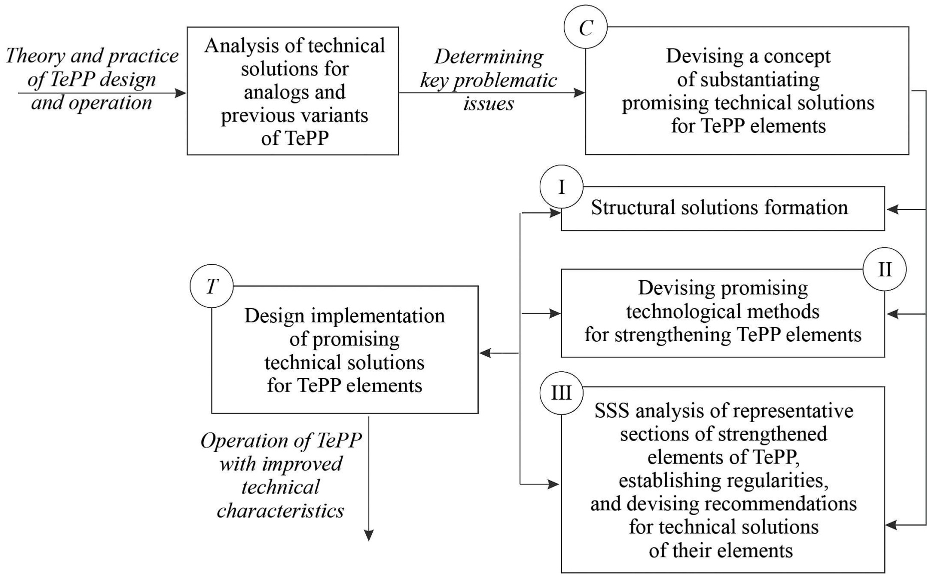


Fig. 2. Algorithm for substantiating technical solutions of TePP elements

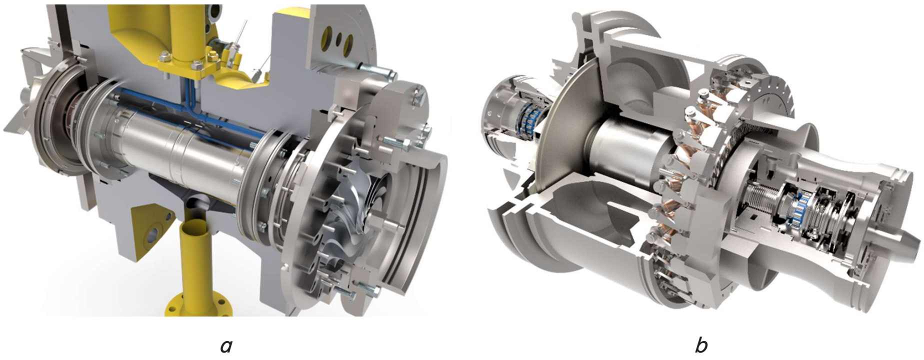


Fig. 3. Variants of structural schemes of turbo-expanders made by PrAT “Turbogaz” [10]: *a* — on rolling bearings; *b* — on sliding bearings

5. 2. Determining the stressed-strained state of discretely-continuously strengthened parts of TePPs

Taking into account that the elements of turbo-expander units work under intense loads, it is necessary to ensure their strength. For this purpose, the stressed-strained state of these elements should be modeled. The operator describing this SSS must also consider the contact interaction. In addition, this operator should take into account certain features of the manufacturing or strengthening technology that are being developed and applied. Thus, continuous, discrete, and discrete-continuous strengthening technologies have been developed and applied to strengthen the elements of turbo-expander installations. The parameters of ion-plasma sputtering, micro-arc oxidation, or electrospark alloying are included in the contact interaction model.

In particular, discrete-continuous strengthening technology was developed to strengthen a conjugate pair of parts, one of which is made of aluminum alloy and the other of cast iron. A layer of aluminum oxide (corundum) is applied to the aluminum part by means of micro-arc oxidation. Archipelagos of discrete strengthening zones indented into the base material are applied to the cast iron part by electrospark alloying [18, 27].

Fig. 4–6 show the interaction diagram and characteristic patterns of the distribution of Mises stresses σ and contact pressure *q* in conjugated pairs of parts subjected to discrete-continuous strengthening. The elastic modulus of the ceramic material (Al_2O_3 layer) E_2 varies compared to the elastic modulus of the aluminum alloy E_1:

$$E_2=\gamma\cdot E_1, \qquad (4)$$

where γ=[0.1; 10] – some coefficient.

Here, E_1=70 GPa. The main material is cast iron with the modulus of elasticity E_4=120 GPa, the material of the discretely strengthened zone is steel, the modulus of elasticity E_3=210 GPa.

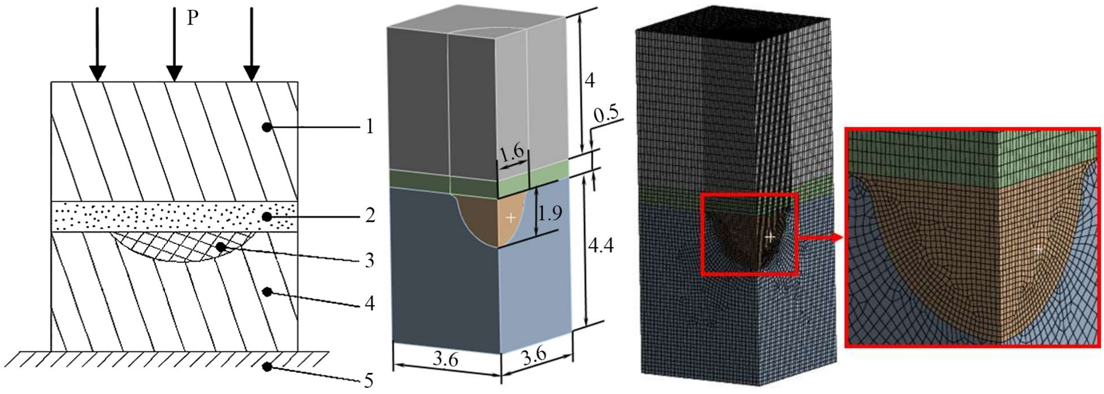


Fig. 4. Representative section in the pair “discretely strengthened part — continuously strengthened part” with dimensions (mm) and a model of ¼ of its symmetrical part: 1 — aluminum alloy; 2 — Al_2O_3 aluminum oxide layer; 3 — discrete reinforced zone; 4 — basic material; 5 — base (hard base)

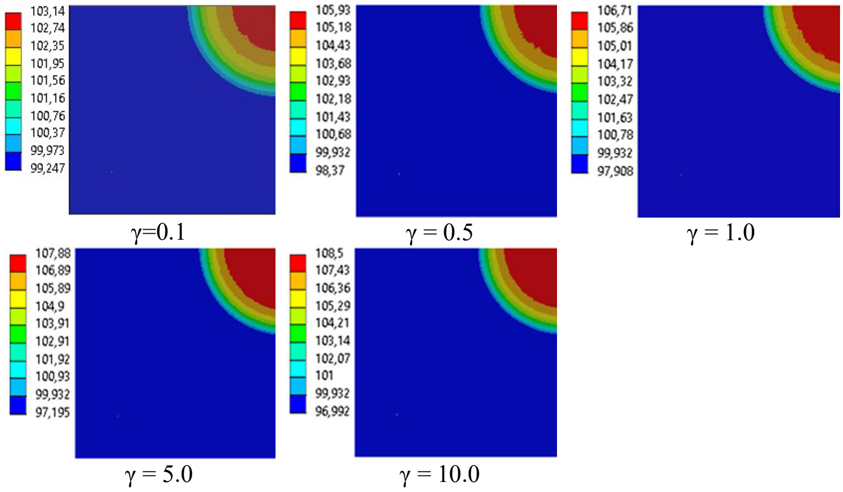


Fig. 5. Distribution of contact pressure *q*, MPa, in a representative section in the pair "discretely strengthened part – continuously strengthened part" under the action of external pressure *p*=100 MPa at different γ

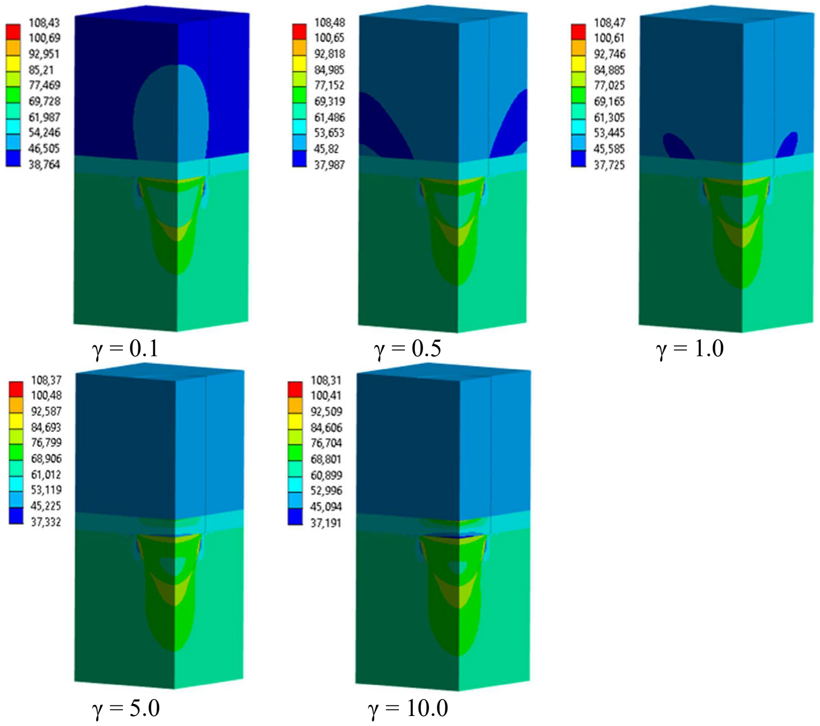


Fig. 6. Distribution of equivalent stresses according to Mises σ, MPa, in the representative section "discretely strengthened part – continuously strengthened part" under the action of an external load of 100 MPa at different γ

The above distributions of contact pressure and stresses (Fig. 5–7) demonstrate their redistribution takes place compared to the initial version (unreinforced parts in contact). At the same time, the stresses are shifted to the strengthened zones of the material. In general, this is a favorable effect for improving the characteristics of strength, wear resistance, and durability.

Thus, compared to the absence of a layer of discretely strengthened ceramics (i.e., γ=1), the character of the contact surface deformation, the contact pressure distribution, and the distribution of equivalent Mises stresses change. In particular, Fig. 8 shows the dependence of the relative level of contact pressure $\overline{q}=q/P$ on the coefficient γ. That is, the greater the modulus of elasticity of the material of the continuous strengthening layer, the higher the contact pressure level in the contact zone with the discrete strengthening zone, and, accordingly, the lower level in the interface with the base material.

Fig. 5 demonstrates that the contact pressure *q* reaches a maximum in the central part of the surface *S*. This contributes to the increase of the overall strength in the system of reinforced bodies. This mechanism is explained by the fact that the material of the strengthened zone has much higher mechanical and physical-mechanical properties than the main material. For example, in the "steel – cast iron" pair, the difference can reach 2–3 times or more. Due to the expansion of the size of the zone of discrete strengthening (Fig. 5, 6), it is possible to redistribute most of the load to this zone, and to reduce it on the main (less strong) material. That is, in general, both elements of the "reinforced zone – main material" composition can be equaled in terms of strength precisely due to the redistribution of force flows. The overall margin of safety can be doubled and higher in this way.

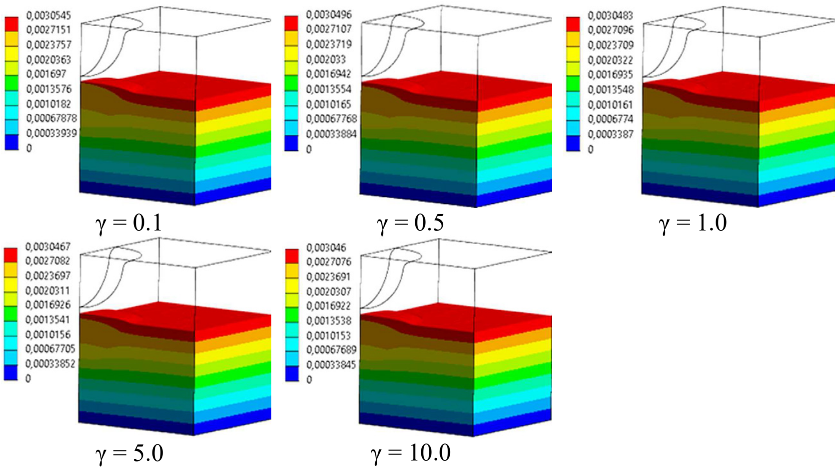
The coefficient of friction in the contact zone of the discretely reinforced material 3 with the ceramic layer 2 can be reduced compared to the similar one, but for the connection "base material 4 – ceramic layer 2", due to the appropriate technological processing. As a result, friction and wear are reduced, as well as the efficiency of the unit, which includes strengthened contacting parts, is improved.

For example, a 20 % redistribution of contact pressure at a 1:3 friction ratio results in a 20 % reduction in friction. At the same time, a two-fold ratio of wear coefficients for these connections leads to a 30 % reduction in total wear.

It should be noted that in each specific case it is necessary to balance the requirements of strength, friction, and wear. For example, one of the rational ones is to set the relative area of the strengthening zone to the total area of the part at the level of 0.65–0.75 [18, 27] and choose the material of the strengthened zone with a three-fold advantage in terms of strength compared to the main material. Accordingly, the regimes of technological operations that ensure such a combination are substantiated.

At the same time, in this case, we are talking about the coordination of these technological solutions with structural solutions, and with the use of not one but two strengthening methods in one combination for the elements of turbo-installations being developed.

Thus, for the elements of the contacting pairs, the loading capacity is increased by 15–20 % and the durability – by 20–25 %. In addition, due to the reduction of all types of losses, the overall efficiency of TePPs with the expander is achieved at the level of 86 %. These indicators are confirmed during TePP operation.



$\gamma = 0.1$ $\gamma = 0.5$ $\gamma = 1.0$

$\gamma = 5.0$ $\gamma = 10.0$

Fig. 7. Patterns of the deformed state (full displacements, mm) of a fragment of discrete-continuous reinforced parts at different γ

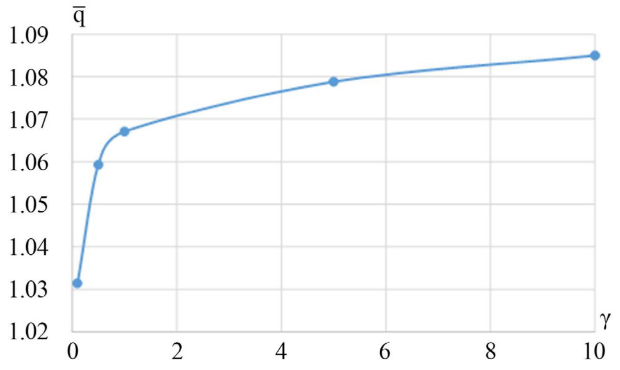


Fig. 8. Dependence of the relative level of contact pressure $\bar{q}$ on the coefficient γ

6. Discussion of results of studying turbo-expander installations

In the course of our research, a new concept of constructing highly efficient design solutions for turbo-expander installations was devised (Fig. 1, 2). This concept is distinguished by a parametric description of the models of processes and states in these installations. This creates advantages in terms of the purposeful variation of current technical solutions for turbo-expander installations in order to achieve improved technical characteristics. Moreover, the partial models of individual processes and states are based on the fundamental principles of solid medium mechanics, thermodynamics, and electromagnetism. This ensures a high degree of adequacy of each of these models in particular and in general. That is, partial models for solving individual analysis problems are united by a single description for solving synthesis problems. This creates additional opportunities for improving the technical characteristics of new-generation turbo-expander units, at each stage of research.

In the course of our research, rational structural solutions for TePP turbo-expanders were determined (Fig. 3).

Based on the analysis of the stressed-strained state of the elements of turbo-installations (Fig. 4–8), the rational parameters of their strengthening have been established. They make it possible to ensure the strength of these elements. This effect was achieved due to the combination of discrete and continuous strengthening technologies. At the same time, the positive effect is achieved due to the redistribution of loads towards stronger elements of the parts. And this, in turn, is caused by the increase in the physical and mechanical properties of the materials of discrete and continuous strengthening zones compared to the properties of the main materials. Subsequently, higher tribomechanical properties of materials of discrete and continuous strengthening zones begin to play a role. Given this, friction is reduced, the efficiency and durability of a pair of strengthened parts increases as a whole.

Despite the significant advantages of the proposed improved approach to investigating the elements of turbo-expander installations, certain shortcomings are inherent in the presented research materials. These shortcomings are due to the fact that the established laws and devised recommendations are valid only for the investigated types of turbo-installations. Additional research is needed for other types. However, the methodological base of research has already been created.

Limitations regarding the application of the implemented advancements and established laws are determined only by the range of variation in the parameters that were included in the calculations. The types of models that were built and used also play a significant role: gas dynamics, heat and mass transfer, energy generation, coating, stressed-strained state, etc. When expanding the set of significant factors, the models should also be expanded.

In general, all results can be applied in further development and research of processes and states in compliance with the basic principles of the relevant scientific fields.

At the same time, it should be noted that the peculiarity of the method proposed in the current work and implemented, in contrast to [1–9], is the interconnectedness of individual stages of research. In addition, building on models [28–34], real, and not model, characteristics of materials of intermediate layers between contacting bodies were considered. This created objective conditions for achieving world-class results of the technical characteristics of the designed turbo-expander units.

7. Conclusions

1. A concept of substantiation of promising technical solutions for the elements of turbo-expander power plants has been devised, which fundamentally differs from existing ones in the full coverage of all significant processes and states and stages of the life cycle. This ensures higher efficiency of research results compared to previous ones. In the applied aspect, its verification was also carried out at separate stages of development and research of turbo-expander installations.

2. In the course of comprehensive studies of the stressed-strained state of discretely-continuously strengthened elements of TePPs, positive effects of improving their strength, reducing friction, and improving durability have been estab-

lished. This results in a 15–20 % increase in load capacity, 20–25 % resource, and up to 86 % efficiency.

All studies, in contrast to traditional setting, were carried out on a single conceptual basis. Owing to this, the higher characteristics of turbo-expander units, confirmed during operation, have been substantiated.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

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