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COMPREHENSIVE METHODOLOGY FOR TURBOEXPANDER UNITS FLOW PARTS DESIGNING

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The author's comprehensive methodology for designing the flow parts of turboexpander units, the main elements of which are a centripetal turbine and a centrifugal compressor, is presented. The methodology includes mathematical methods and models of various levels of complexity, from one-dimensional to spatial ones, as well as experimental research. The calculation of three-dimensional viscous flow is performed using the method of numerical integration of the averaged Navier-Stokes equations and Menter's differential turbulence model. The spatial shape of the turbine and compressor is described using the method for which the initial data is given as a limited number of parameterized values. An example of the developed flow part, which has high gas-dynamic efficiency in a wide range of operating modes and corresponds to the best world analogues in terms of its characteristics, is given. It is shown that the calculated gas-dynamic characteristics are in satisfactory agreement with the experimental data. A database of highly efficient flow parts of turbines and compressors, which are used as prototypes in the creation of new modern turboexpander units, has been created.

Keywords*: turboexpander, gas pipeline, natural gas, turbo-compressor, flow part.*

Introduction

In Ukraine, the problem of restoring, ensuring and further increasing of energy efficiency, energy security and energy independence, which are the basic components of the entire economy and defense capability, is acute [1].

To solve these problems, Ukraine applies a number of measures, including actively increasing its own production of natural gas [2]. After extraction, before transportation, the gas must undergo special preparation, in particular "drying" [3], during which water and hydrocarbon fractions capable of condensing at low temperatures are separated. These days, the following technologies are used for these purposes: low-temperature separation (LTS) [4], absorption two-column units for drying from water vapor [5], column unit for drying from hydrocarbon vapor [6], turboexpander units (TEU) [7].

Low-temperature separation is based on reducing the gas temperature during flow throttling [8]. This results in a decrease in temperature and partial condensation of water vapor and "heavy" hydrocarbons. Depending on the gas composition, its temperature, initial and final pressures, the temperature drop is 2.5–3.0 °C/MPa.

Absorption two-column unit for drying from water vapor consists in the absorption of water vapor by a concentrated diethylene glycol [9] or triethylene glycol [10] (absorbents) solutions in a column-type apparatus. It provides deep water vapor drying under conditions of high gas pressure and low flow temperatures. It does not provide drying of hydrocarbon vapors and requires the use of absorbent recovery equipment (desorber). Desorption of the absorbent is an energy-intensive process, carried out in a column-type apparatus. The apparatus assembly includes an evaporator, condenser, heat exchangers, and pumping equipment.

Column unit for drying from hydrocarbon vapor works on the principle of absorption of hydrocarbon vapors by an absorbent (consists mainly of heavy liquid hydrocarbons) [11] in a column-type apparatus. It provides deep drying of hydrocarbon vapors under conditions of high gas pressure and low flow temperatures. It does not provide drying from water vapor and requires the use of absorbent recovery equipment.

Various methods of absorbent recovery are possible, but all of them are energy-intensive. It is possible to carry out the process in sequentially installed column-type apparatuses. The used equipment includes saturated absorbent heating furnaces, condensers, heat exchangers, and pumping equipment.

Gas drying using expanders does not require energy consumption [12]. Depending on the gas composition, its temperature, initial and final pressures, the temperature drop is 10–12 °C/MPa. Provides electricity generation or compression of the gas after it is dried.

In addition, the use of expanders in gas drying has an advantage compared to traditional technologies.

1. Provides deeper cooling compared to LTS technology.
2. Has a lower cost compared to absorption drying equipment.
3. Does not require additional energy consumption.
4. There are no operating costs compared to glycol drying.
5. It has smaller dimensions compared to absorption plants, which is important for the conditions of existing industries, in which production areas are limited, and the creation of additional areas is a long process associated with significant difficulties.

An example of a TEU block is shown in Fig. 1.

The basic element of the TEU is a turbo-compressor in which the compressor and turbine are located on the same shaft. In the turbine, the gas expands and cools down, after which the condensed gas components are separated and removed. The power obtained in the turbine is fed through the shaft to the compressor. In the compressor, the "dried" gas is compressed and, if necessary, fed to a pressure compressor, after which it can be sent to the gas transportation system.

The efficiency of the turbo-compressor determines how much fuel will be saved to drive the pressure compressor, as well as how much of expensive gas condensate will be obtained, which determines the efficiency and cost-effectiveness of the technological process as a whole.

Among Ukrainian enterprises engaged in the development and production of TEU, first of all, PJSC "Turbogaz" stands out [13]. Thanks to cooperation with specialists from institutes of the National Academy of Sciences of Ukraine and high school, the products of PJSC "Turbogaz" meet or exceed the best world standards in terms of their characteristics. To achieve this, when creating TEU, complex theoretical, computational and experimental methods are used and the latest innovative solutions are implemented [14–17].

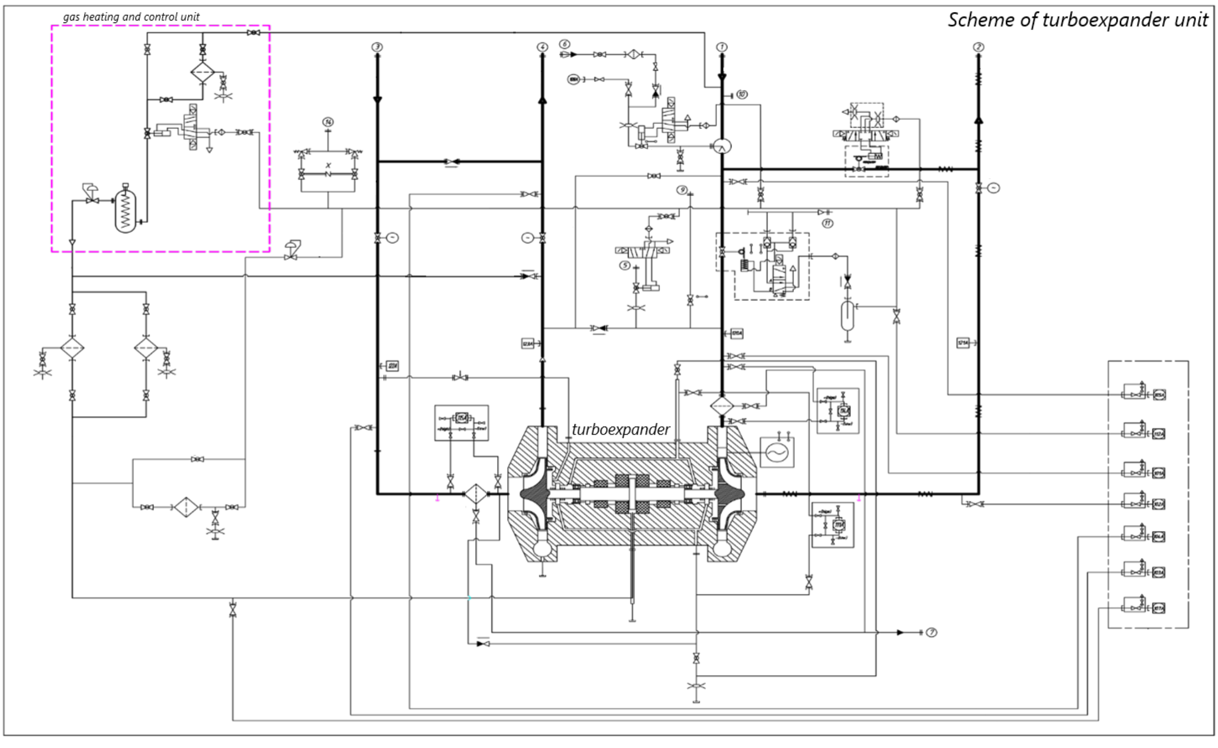


Fig. 1. TEU block scheme

A comprehensive methodology for designing the flow parts of a TEU turbo-compressor, namely the flow parts of centripetal turbines and centrifugal compressors, is presented in the paper. The methodology includes mathematical methods and models of various levels of complexity, from one-dimensional to spatial ones, as well as experimental research.

General algorithm for the TEU flow parts designing using methods of different levels of complexity

The design of the flow parts of centripetal turbines and centrifugal compressors is carried out by stages. The algorithm for such designing is shown in Fig. 2.

At the first step, a preliminary calculation of the flow part geometric characteristics is carried out using fairly simple methods based on solving one-dimensional or quasi-axisymmetric equations [18, 19].

Based on the obtained geometric characteristics, a complete three-dimensional geometry is created, for which analytical profiling methods of flow parts are used. Those methods allow the creation of turbine and compressor stages of both axial, radial-axial and axial-radial types.

The given algorithm for the flow part designing can be automated. To do this, it is necessary to algorithmize the process of results analyzing and generating new values of varying parameters (geometric characteristics of the flow part) using methods for solving optimization problems. When using this approach, depending on the number of varying parameters, it takes from several hundred to several thousand iterations. Nowadays, there are software complexes based on the application of local or global extremum search methods for optimizing the flow parts of turbines and compressors [20, 21]. Their main drawback is that, to ensure acceptable costs of computing resources (primarily in terms of time), spatial calculations are performed on "very coarse" mesh for a fairly limited number of varying parameters. That is why their full use in the design and modernization of flow parts is very limited. In the examples considered in this paper, the analysis of results and decision to change the varying parameters were performed in the "manual" mode. In this case, the result and the number of iterations depend on the specialist's qualifications. Usually, to obtain the final form of one stage, several dozen three-dimensional calculations are required, which, firstly, is noticeably less compared to "automated" algorithms, and secondly, it allows the "full" use of complex spatial flow models.

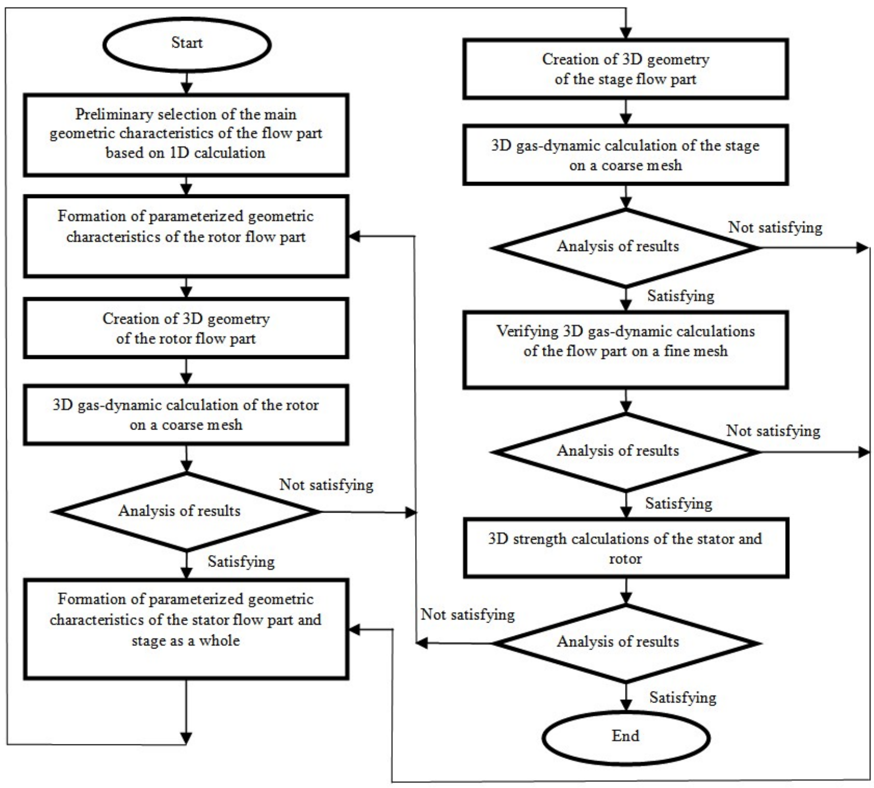


Fig. 2. Flowchart of the flow part design algorithm

In order to obtain a complete spatial form and more accurate gas-dynamic characteristics of the flow part, the methods of design and calculation developed by the authors of this paper are used [22, 23].

The main advantage of radial-axial and axial-radial turbomachine stages compared to axial designs is high performance and relatively small dimensions. Unlike axial turbomachines, for which there are proven approaches to blade profiling, based on the use of standard profiles or on the construction of profiles according to generally recognized methods, including parameterized values, there are no generally recognized approaches for radial-axial and axial-radial turbomachines.

An original method of analytical profiling of radial-axial and axial-radial types rotors is used in the paper [24, 25]. Its use in combination with numerical modeling of three-dimensional viscous flows allows to significantly accelerate the process of effective flow parts (FP) designing.

As of now, computational fluid dynamics (CFD) is an important tool for designing and modernizing turbomachines, which allows to analyze three-dimensional flow, evaluate the efficiency of the flow part and choose ways to improve it.

The Navier-Stokes equations, averaged according to Favre-Reynolds [26] with correct boundary conditions, describe one of the most complex forms of flows in a continuous medium without taking into account various physicochemical transformations, namely: spatial, compressible, viscous, turbulent and unsteady flow in the entire range of operating parameters. At the current level of development of CFD and computer technology, it is most appropriate to use the two-parameter differential SST Menter turbulent viscosity model [27], built on the basis of the Wilcox k–ω model, for turbulent effects modeling.

An important component of numerical models of spatial flows is the method of describing the properties of working medias. For this purpose, equations of state are used, the choice of which significantly affects the reliability of the obtained results. As of now, the Benedict-Webb-Rubin equations [28] most accurately describe the real thermodynamic properties of working medias, but the problem with their direct use is that the computational time consumption increases by almost two orders. A much less expensive approach is when the closure functions are determined by interpolation from pre-calculated tables of thermodynamic parameters. To reduce the dimensionality of tables without reducing the interpolation accuracy, a new interpolation-analytical approach for complex functions approximation is used [29, 30]. For turbine and compressor designing problems, in many cases it is sufficient to use the simpler Tamman equation of state [31] with the choice of constants corresponding to the change in the thermodynamic parameters of the working media in the range of the unit operating modes [18].

The above calculation and design models are implemented in the IPMFlow software package, which is a development of the FlowER and FlowER-U packages [22, 32, 33].

Examples of the developed TEU compressors and turbines flow parts

The problem of the compressor flow part designing is complex and multifactorial, requiring consideration of various factors, such as ensuring operating characteristics, efficiency, reliability, cost, compliance with various restrictions, manufacturability, etc.

An important component of the design is gas-dynamic calculations and obtaining the spatial shape of the compressor and turbine flow part and its operating characteristics on their basis. The starting point for this is initial data obtained on the basis of previous assessments, experience and technical requirements:

– geometrical restrictions;

– ranges of operating parameters (gas-dynamic parameters at the inlet and outlet, mass flow rate, rotor rotation speeds, etc.);

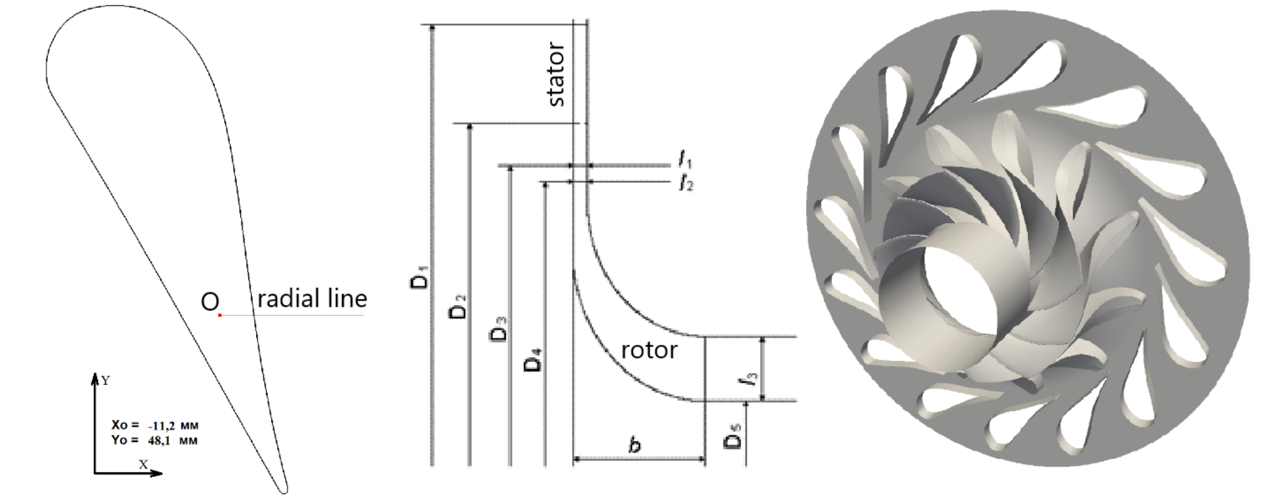
– data for determining the constants of the Tamman equation of state (if necessary);

– characteristics that need to be achieved (power, efficiency, etc.).

The results of the TEU turbine and compressor flow parts development, provided for a real project with the code name "740", are given below.

Fig. 3 shows the designed turbine flow part. The rotor blade has a spatial shape with a complex circular lean of the leading edge. Complex lean prevents or significantly reduces flow separations on the peripheral shroud.

Fig. 4 shows a visualization of the flow at nominal operating modes.



a b c

Fig. 3. Turbine flow part:
a – stator blade profile; b – meridional section; c – isometry

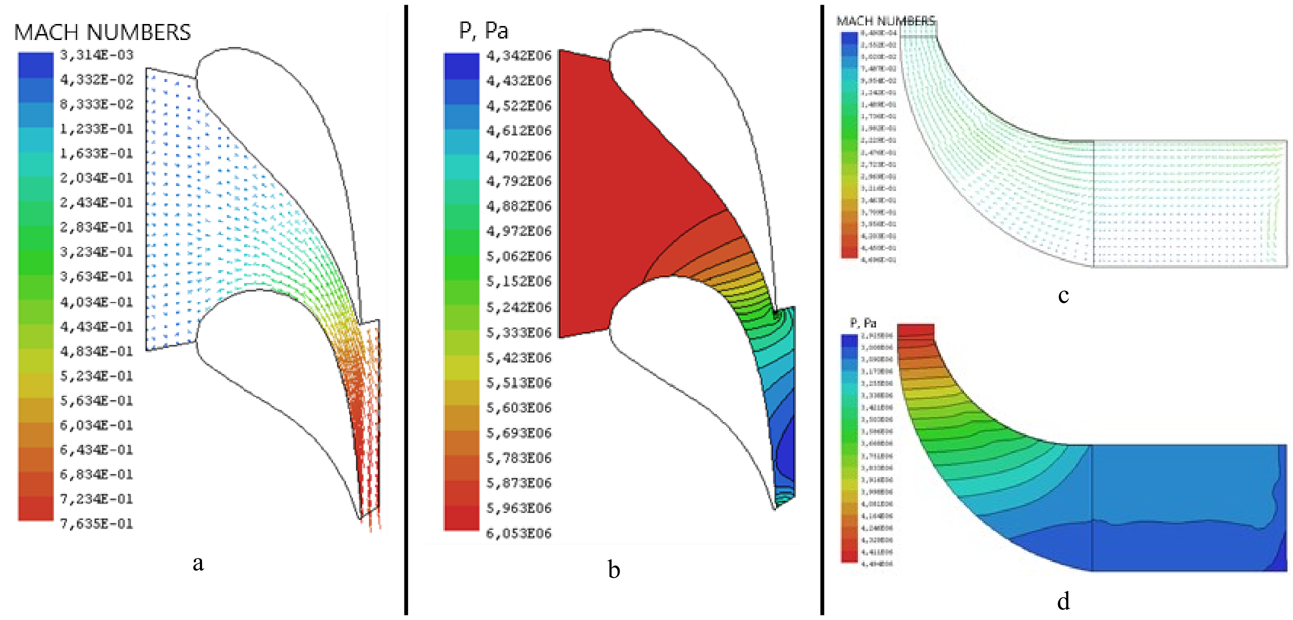


Fig. 4. Flow visualization. Middle section. Nominal mode:
a, c – velocity vectors; b, d – isolines of static pressure;
a, b – stator tangential section; c, d – rotor meridional section

Based on the results of computational research, it can be concluded that a favorable flow pattern is observed. There are no flow separations.

Fig. 5, 6 show the integral characteristics of the turbine.

The given results indicate that the developed flow part has a high level of aerodynamic perfection in the entire range of operating modes. The nominal operating mode corresponds to the maximum values of the turbine efficiency, and even at low rotational speeds the turbine efficiency is satisfactory.

Fig. 7 shows the designed compressor flow part. Just like in the case of a turbine, the rotor has a spatial shape with a complex circular lean of inlet edge, which prevents or significantly reduces flow separation on the peripheral shroud.

Fig. 8–10 show a visualization of the flow at the nominal and two "extreme" operating modes.

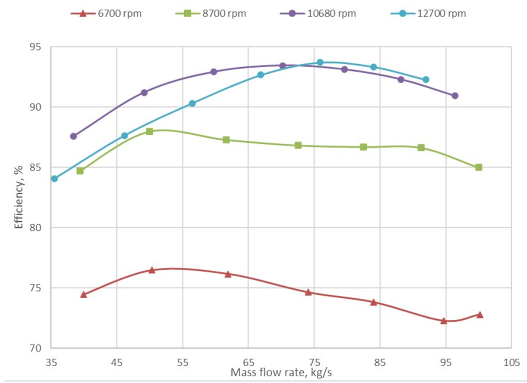


Fig. 5. Dependence of efficiency on mass flow rate

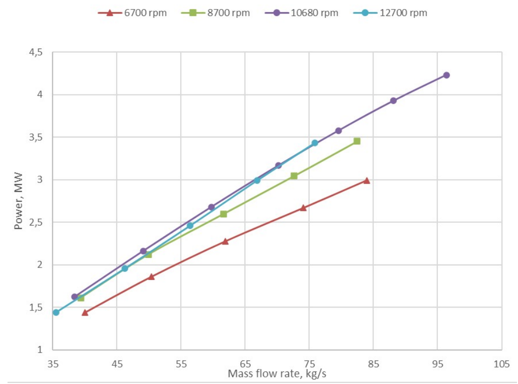
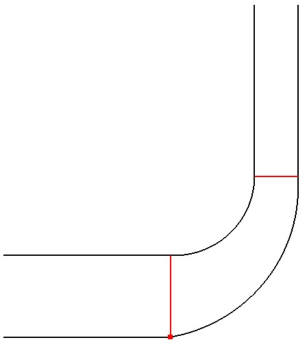


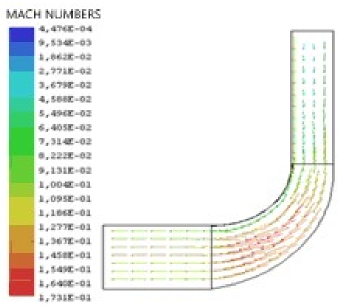
Fig. 6. Dependence of power on mass flow rate



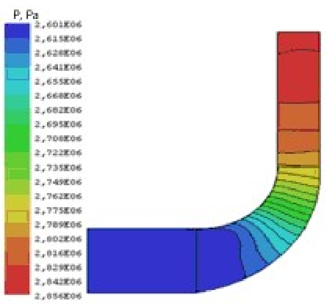
a

b

Fig. 7. Compressor flow part: a – meridional section; b – rotor isometry

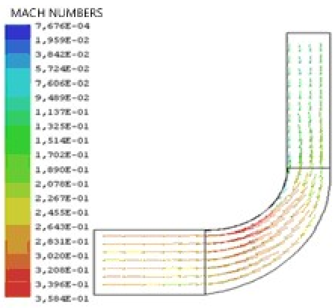


a



b

Fig. 8. Flow visualization. Mid-meridional section. Minimum inlet pressure and rotor speed:
a – velocity vectors;
b – isolines of static pressure



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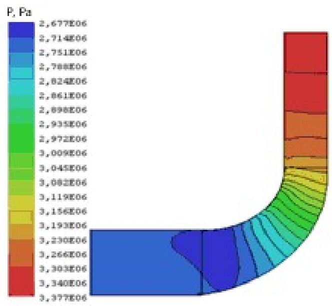
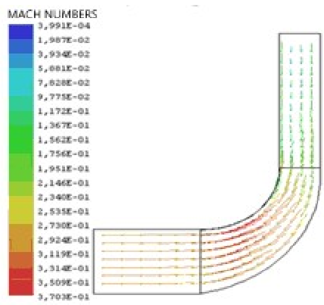


b

Fig. 9. Flow visualization. Mid-meridional section. Nominal mode:
a – velocity vectors;
b – isolines of static pressure



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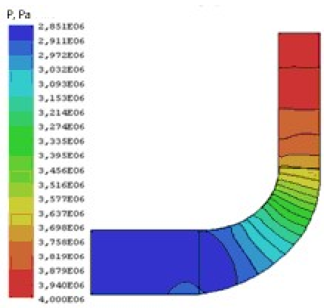

b

Fig. 10. Flow visualization. Mid-meridional section. Maximum inlet pressure and rotor speed:
a – velocity vectors;
b – isolines of static pressure

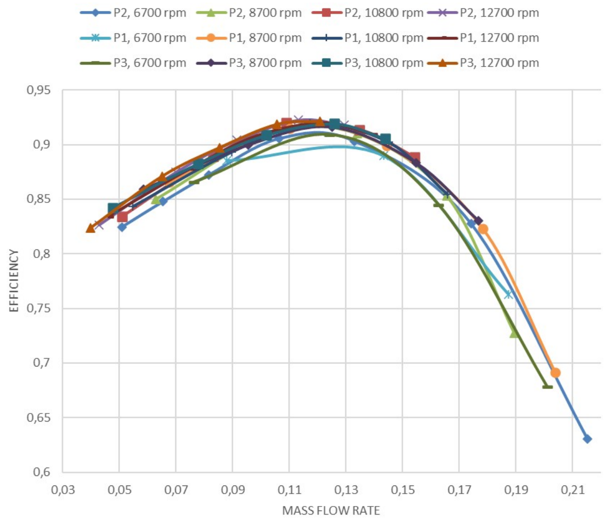

Fig. 11. Dependence of efficiency on the mass flow rate

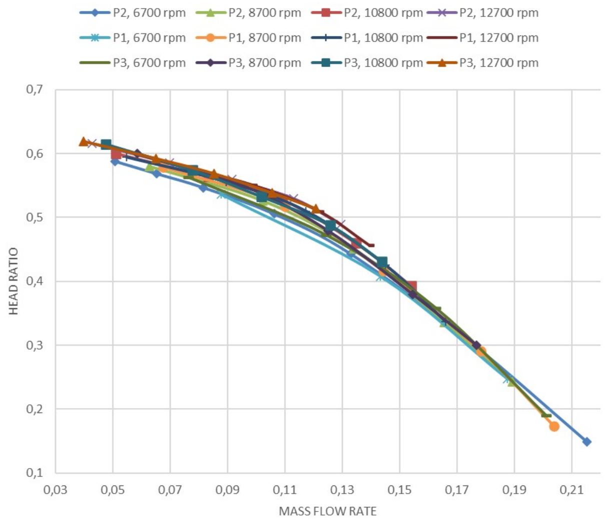

Fig. 12. Dependence of the theoretical head ratio on the mass flow rate

First of all, it should be noted that based on the results of computational research, it can be concluded that a favorable flow pattern is observed in most of the compressor operating mode range. Flow separations occur only at the certain operating mode ranges.

Fig. 11, 12 show the integral dimensionless characteristics of the compressor, and Fig. 13 shows the dependence on which the predicted limits of the onset of surge and blockage are indicated.

The given research results indicate that the developed flow part has a high level of aerodynamic perfection and provides a satisfactory flow pattern in the entire range of considered operating modes, both design and non-design ones. The nominal operating mode corresponds to the maximum values of the compressor efficiency.

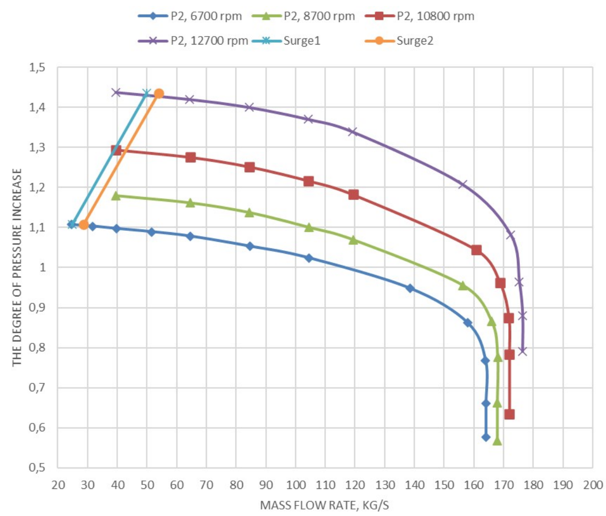

Fig. 13. Dependencies of the degree of total pressure increase on the mass flow rate of the compressor

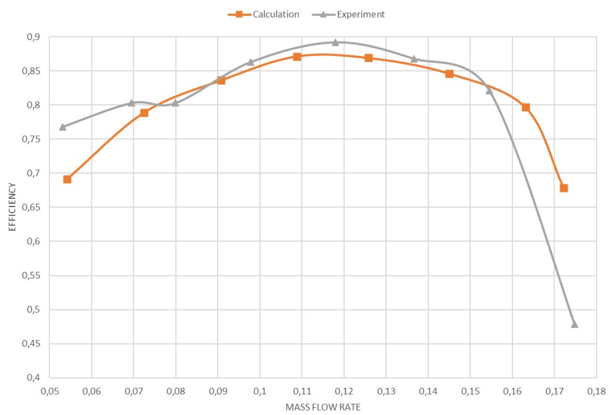

Fig. 14. Compressor efficiency – comparison of calculations and experimental results

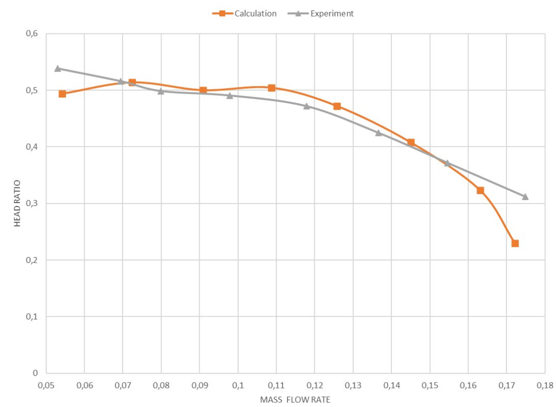

Fig. 15. Compressor head ratio – comparison of calculations and experimental results

Fig. 14, 15 show a comparison of the results of computational research of spatial flow in the project "740" compressor flow part with the results of the compressor experimental research in the aerodynamic laboratory of PJSC "Turbogaz". The calculation was performed using air as the working medium.

The obtained calculation results are in satisfactory agreement with the experimental data, which indicates the high accuracy and reliability of the flow part design methodology presented in the paper.

According to the described methodology, a fairly large number of centripetal turbines and centrifugal compressors have been developed and implemented, photographs of some rotors are shown in Figs. 16, 17.

From the given examples of rotors, it can be seen that they have a complex spatial shape, can be made with a complex lean of edges, intermediate blades and, if necessary, have a special coating.

Based on the gained experience, PJSC "Turbogaz" created a unique base of turbines and compressors (Figs. 18–20), which are used as prototypes in the creation of modern, highly efficient new TEUs flow parts.

Fig. 16. Examples of developed and implemented TEU turbine rotors

Fig. 17. Examples of developed and implemented TEU compressor rotors

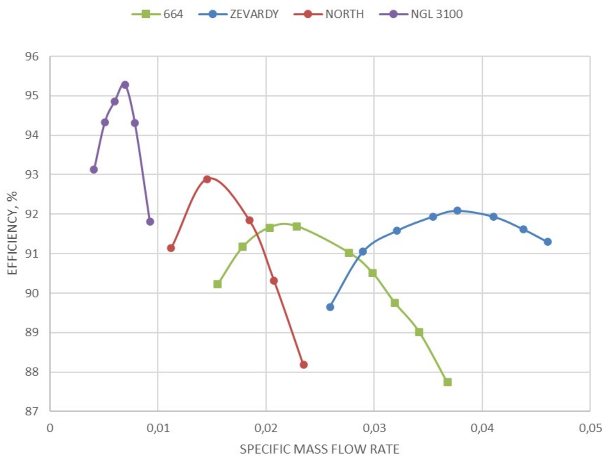

Fig. 18. Database of PJSC "Turbogaz". Efficiency of developed turbines

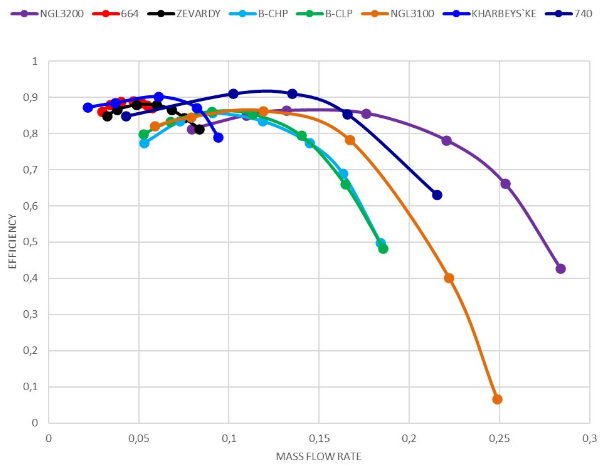

Fig. 19. Database of PJSC "Turbogaz". Efficiency of developed compressors

Conclusions

A comprehensive methodology for the centripetal turbines and centrifugal compressors flow parts designing, which includes mathematical methods and models of various levels of complexity, from one-dimensional to spatial ones, as well as experimental studies, has been developed.

Using the example of the turbine and compressor of the "740" project, it is shown that the proposed methodology makes it possible to create TEU flow parts, which have high gas-dynamic efficiency in a wide range of operating modes and, in terms of their characteristics, correspond to the best world analogues.

It is shown that the calculated gas-dynamic characteristics of the compressors are in satisfactory agreement with the experimental data.

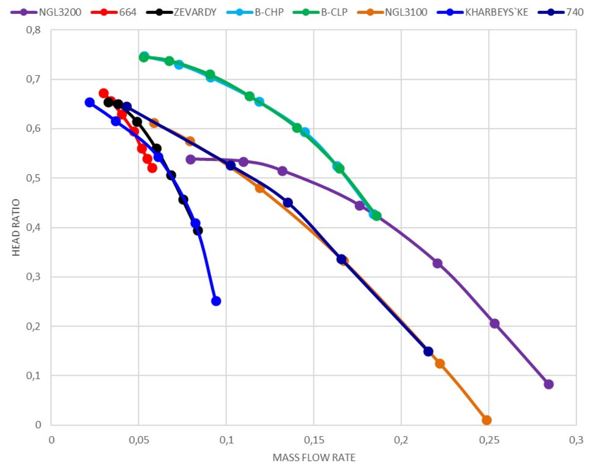

Fig. 20. Database of PJSC "Turbogaz".
Head ratio characteristics of the developed compressors

A unique database of highly efficient turbines and compressors flow parts, which are used as prototypes in the creation of new modern TEUs, has been created.

References

1. Boichenko, S., Dokshyna, S., Shkilniuk, I., Yakovlieva, A., Levandovskyi, I., Kuberskyi, I., & Zaporozhets, A. (2024). Increasing the level of energy security of Ukraine by reducing import dependence of oil products. In: Boichenko S., Zaporozhets A., Shkilniuk I., Yakovlieva A. (eds). *Modern Technologies in Energy and Transport II*. Studies in Systems. Decision and Control. Springer, Cham, vol. 574, pp. 67–77. https://doi.org/10.1007/978-3-031-76650-3_5.
2. (2024). *Monitorynh naftohazovydobuvnoho sektoru* [Monitoring of the oil and gas sector]. Report for November 2024. Association of Gas Extracting Companies of Ukraine: official website (in Ukrainian). https://agpu.org.ua/analityka/monitorynh/monitorynh-naftohazovydobuvnoho-sektoru-3-9-11-2024.
3. Wosu, C. O. (2024). Design and performance analysis of an industrial absorber for the dehydration of natural gas using triethylene glycol. *Journal of Engineering Research Innovation and Scientific Development*, vol. 2, no. 3, pp. 40–49. https://doi.org/10.61448/jerisd23245.
4. Zhu, L., Wang, D., Liu, G., & Liu, H. (2022). Oiling low temperature separation process for dehydration and dehydrocarbon of natural gas and practical application. *Science and Technology for Energy Transition*, vol. 77, article No. 8. https://doi.org/10.2516/stet/2022005.
5. Rasi, S., Läntelä, J., & Rintala, J. (2014). Upgrading landfill gas using a high pressure water absorption process. *Fuel*, vol. 115, pp. 539–543. https://doi.org/10.1016/j.fuel.2013.07.082.
6. Khurmamatov, A. M. & Auesbaev, A. U. (2023). Analysis of the operating mode of the existing desorber and its modernization using additional contact devices. *Nafta-Gaz*, no. 6, pp. 412–419. https://doi.org/10.18668/NG.2023.06.05.
7. Aghai, R. (2003). Turboexpander technology evaluation and application in natural gas processing. *Proceedings of Eighty-Second Gas Processing Association Annual Convention*. San Antonio, Texas.
8. Baccanelli, M., Langé, S., Rocco, M. V., Pellegrini, L. A., & Colombo, E. (2016). Low temperature techniques for natural gas purification and LNG production: An energy and exergy analysis. *Applied Energy*, vol. 180, pp. 546−559. https://doi.org/10.1016/j.apenergy.2016.07.119.
9. Murodov, A., Xabibullaev, S., Maxmudov, N., Daminov, T., & Qarshiyev, A. (2023). Creation of technology for desalination of saturated diethylene glycol substance in East Berdak gas complex preparation plant. *E3S Web of Conference*, vol. 434, article No. 02026. https://doi.org/10.1051/e3sconf/202343402026.
10. Chidiebere, O. O., Inyang, U. E., & Oboh, I. O. (2023). Modelling and optimization of natural gas dehydration system using triethylene glycol. *Journal of Engineering Research and Reports*, vol. 24, iss. 12, pp. 89−102. https://doi.org/10.9734/jerr/2023/v24i12862.
11. Orymbetov, E., Orymbetova, G. E., Khussanov, A. E., Orymbetov, T. E., & Orymbetov, B. E. (2022). Sectioning of petroleum gas adsorption drying. Series of geology and technical sciences. *News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences*, vol. 3 (453), pp. 155–165. https://doi.org/10.32014/2022.2518-170x.187.
12. Bloch, H. P. (2017). Subject Category 43 – Turboexpanders. *Petrochemical Machinery Insights*, pp. 657−660. https://doi.org/10.1016/B978-0-12-809272-9.00043-8.
13. (2025). Projects of PrJSC "Turbogaz". PrJSC "Turbogaz": official website. https://turbogaz.com.ua/uk/projects.

14. Moiseiev, S. V., Novikov, M. K., Burniashev, A. V., Pakki, H. V., Tkachuk, M. A., Lvov, H. I., Kravchenko, S. O., & Podrieza, S. M. (2023). *Rozroblennia proryvnykh tekhnolohii zmitsnennia elementiv turbodetandernykh ustanovok* [Development of breakthrough technologies for strengthening of turbo-expansion installations elements]. *Visnyk Natsionalnoho tekhnichnoho universytetu «KhPI». Seriia: Mashynoznavstvo ta SAPR – Bulletin of the National Technical University «KhPI» Series: Engineering and CAD*, no. 1, pp. 53–67 (in Ukrainian). https://doi.org/10.20998/2079-0775.2023.1.06.
15. Tkachuk, M., Lvov, G., Kravchenko, S., Moiseiev, S., Novikov, M., Burniashev, A., Pakki, G., & Podrieza, S. (2023). Substantiating promising technical solutions for turbo- expander power plants based on the research into working processes and states. *Eastern-European Journal of Enterprise Technologies*, vol. 4, no. 7 (124), pp. 98–105. https://doi.org/10.15587/1729-4061.2023.285865.
16. (2021). Moiseiev, S. V., Burniashev, A. V., Plakhotnyk, V. V., & Borysenko, O. V. *Dotsentrova turbina* [Centrifugal turbine]: Patent for invention No. 123415. State Register of Inventions of Ukraine. Published 03/31/2021, Bulletin No. 13/2021 (in Ukrainian). https://sis.nipo.gov.ua/uk/search/detail/1585827/.
17. (2021). Moiseiev, S. V., Burniashev, A. V., Plakhotnyk, V. V., & Borysenko, O. V. *Rehulovanyi soplovyi aparat dotsentrovoi turbiny* [Adjustable nozzle apparatus of a centrifugal turbine]: Patent for invention No. 123333. State Register of Inventions of Ukraine. Published 03/17/2021, Bulletin No. 11/2021 (in Ukrainian). https://sis.nipo.gov.ua/uk/search/detail/1483943/.
18. Rusanov, A. V. & Yershov, S. V. (2008). *Matematicheskoye modelirovaniye nestatsionarnykh gazodinamicheskikh protsessov v protochnykh chastyakh turbomashin* [Mathematical modeling of non-stationary gas-dynamic processes in flow parts of turbomachines]. Kharkiv: IPMash of NAS of Ukraine, 275 p. (in Russian).
19. Bilan, A. V. & Bilan, V. N. (2006). *Avtomatizirovannoye proyektirovaniye lopatok parovykh turbin* [Automated design of steam turbine blades]. *Kompressornoye i energeticheskoye mashinostroyeniye – Compressor and Power Machine Industry*, no. 3 (5), pp. 66–68 (in Russian).
20. Goldberg, D. E. (1989). Genetic Algorithms in Search, Optimization, and Machine Learning. USA, MA, Boston: Addison-Wesley Longman Publishing Co., Inc., 412 p.
21. Thevenin, D. & Janiga, G. (2008). Optimization and Computational Fluid Dynamics. Springer-Verlag Berlin Heidelberg, 294 p. https://doi.org/10.1007/978-3-540-72153-6.
22. Rusanov, R., Klonowicz, P., Rusanov, A., Lampart, P., Jedrzejewski, L., & Witanowski, L. (2015). Methods for designing of axial turbines for ORC cogeneration unit working with MDM. *NTU "KhPI" Bulletin: Power and heat engineering processes and equipment*, no. 15, pp. 86−100. https://doi.org/10.20998/2078-774X.2015.15.11.
23. Rusanov, A. V. (2013). *Ispolzovaniye sovremennykh kompyuternykh tekhnologiy dlya sozdaniya vysokoeffektivnykh protochnykh chastey radialno-osevogo tipa* [Using modern computer technologies to create highly efficient radial-axial flow parts]. *Kompressornoye i energeticheskoye mashinostroyeniye – Compressor and Power Machine Industry*, no. 2 (32), pp. 4–9 (in Russian).
24. Rusanov, A. V., Shatravka, O. I., & Kosyanova, A. I. (2009). *Profilirovaniye radialno-osevykh turbin s ispolzovaniyem sovremennykh kompyuternykh tekhnologiy* [Profiling of radial-axial turbines using modern computer technologies]. *Vostochno-Yevropeyskiy zhurnal peredovykh tekhnologiy – Eastern-European Journal of Enterprise Technologies*, vol. 4, no. 4 (40), pp. 58–62 (in Russian). https://doi.org/10.15587/1729-4061.2009.21037.
25. Rusanov, A. V., Rusanov, R. A., Pashchenko, N. V., & Chuhai, M. O. (2018). Analytical method of profiling axial-radial compressor impellers. *Journal of Mechanical Engineering – Problemy Mashynobuduvannia*, vol. 21, no. 4, pp. 4−13. https://doi.org/10.15407/pmach2018.04.004.
26. Anderson, D. A., Tannehill, J. C., & Pletcher, R. H. (1997). Computational Fluid Mechanics and Heat Transfer. Taylor and Francis: Milton Park, UK, 816 p.
27. Menter, F. R. (1994). Two-equation eddy-viscosity turbulence models for engineering applications. *AIAA Journal*, vol. 32, no. 8, pp. 1598–1605. https://doi.org/10.2514/3.12149.
28. Benedict, M., Webb, G. B., & Rubin, L. C. (1940). An empirical equation for thermodynamic properties of light hydrocarbons and their mixtures I. Methane, ethane, propane, and n–butane. *Journal of Chemical Physics*, vol. 8, iss. 4, pp. 334–345. https://doi.org/10.1063/1.1750658.
29. Rusanov, A. V. (2013). *Interpolyatsionno-analiticheskiy metod ucheta real'nykh svoystv gazov i zhidkostey* [Interpolation-analytical method of taking into account real properties of gases and fluids]. *Vostochno-Yevropeyskiy zhurnal peredovykh tekhnologiy – Eastern-European Journal of Enterprise Technologies*, vol. 3, no. 10 (63), pp. 53–57 (in Russian). https://doi.org/10.15587/1729-4061.2013.14864.
30. Rusanov, A. V., Lampart, P., & Rusanov, R. A. (2014). *Interpolyatsionno-analiticheskaya approksimatsiya modifitsirovannogo uravneniya sostoyaniya Benedikta-Vebba-Rubina dlya ucheta realnykh svoystv rabochikh tel v trekhmernykh raschetakh* [Interpolation-analytical approximation of the modified Benedict-Webb-Rubin equation of state to take into account the real properties of working bodies in three-dimensional calculations]. *Kompressornoye i energeticheskoye mashinostroyeniye – Compressor and Power Machine Industry*, no. 3, pp. 18–23 (in Russian).

31. Tammann, G. (1895). Ueber die Abhängigkeit der volumina von Lösungen vom druck [On the dependence of the volumes of solutions on pressure]. *Zeitschrift für Physikalische Chemie – Journal of Physical Chemistry*, vol. 17U, no. 1, pp. 620–636 (in German). https://doi.org/10.1515/zpch-1895-1738.
32. Yershov, S., Rusanov, A., Gardzilewicz, A., & Lampart, P. (1999). Calculations of 3D viscous compressible turbomachinery flows. *Proc. 2nd Symp. on Comp. Technologies for Fluid/Thermal/Chemical Systems with Industrial Applications, ASME PVP Division Conf*., 1–5 August 1999, Boston, USA, PVP, vol. 397 (2), pp. 143–154.
33. Rzadkowski, R., Zywica, G., Kaczmarczyk, T. Z., Koprowski, A., Dominiczak, K., Szczepanik, R., & Kowalski, M. (2020). Design and investigation of a partial admission radial 2.5-kW organic Rankine cycle micro-turbine. *International Journal of Energy Research*, vol. 44 (14), pp. 11029–11043. https://doi.org/10.1002/er.5670.

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Комплексна методологія проєктування проточних частин турбодетандерних установок

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Представлено авторську комплексну методологію проєктування проточних частин турбодетандерних агрегатів, основними елементами яких є доцентрова турбіна і відцентровий компресор. Методологія включає математичні методи і моделі різних рівнів складності – від одновимірних до просторових, а також експериментальні дослідження. Розрахунок тривимірної в'язкої течії виконується за допомогою методу чисельного інтегрування осереднених рівнянь Нав'є-Стокса і диференційної моделі турбулентності Ментера. Опис просторової форми турбіни і компресора здійснюється з використанням методу вихідних даних, для якого існує обмежена кількість параметризованих величин. Наведено приклад розробленої проточної частини, яка має високу газодинамічну ефективність у широкому діапазоні режимів роботи і за своїми характеристиками відповідає кращим світовим аналогам. Показано, що розрахункові газодинамічні характеристики задовільно співпадають з експериментальними даними. Створено базу даних високоефективних проточних частин турбін і компресорів, які використовуються як прототипи при створені нових сучасних турбодетандерних установок.

***Ключові слова**: турбодетандер, газопровід, природний газ, турбокомпресор, проточна частина турбомашини.*

Література

1. Boichenko S., Dokshyna S., Shkilniuk I., Yakovlieva A., Levandovskyi I., Kuberskyi I., Zaporozhets A. Increasing the level of energy security of Ukraine by reducing import dependence of oil products. In: Boichenko S., Zaporozhets A., Shkilniuk I., Yakovlieva A. (eds). *Modern Technologies in Energy and Transport II*. Studies in Systems. Decision and Control. Springer, Cham, 2024. Vol. 574. P. 67–77. https://doi.org/10.1007/978-3-031-76650-3_5.
2. Моніторинг нафтогазовидобувного сектору. Асоціація газовидобувних компаній України. Звіт за листопад 2024 р. Асоціація газовидобувних компаній України: офіційний вебсайт. 2024. https://agpu.org.ua/analityka/monitorynh/monitorynh-naftohazovydobuvnoho-sektoru-3-9-11-2024.
3. Wosu C. O. Design and performance analysis of an industrial absorber for the dehydration of natural gas using triethylene glycol. *Journal of Engineering Research Innovation and Scientific Development*. 2024. Vol. 2. No. 3. P. 40–49. https://doi.org/10.61448/jerisd23245.
4. Zhu L., Wang D., Liu G., Liu H. Oiling low temperature separation process for dehydration and de-hydrocarbon of natural gas and practical application. *Science and Technology for Energy Transition*. 2022. Vol. 77. Article No. 8. https://doi.org/10.2516/stet/2022005.
5. Rasi S., Läntelä J., Rintala J. Upgrading landfill gas using a high pressure water absorption process. *Fuel*. 2014. Vol. 115. P. 539–543. https://doi.org/10.1016/j.fuel.2013.07.082.
6. Khurmamatov A. M., Auesbaev A. U. Analysis of the operating mode of the existing desorber and its modernization using additional contact devices. *Nafta-Gaz*. 2023. No. 6. P. 412–419. https://doi.org/10.18668/NG.2023.06.05.
7. Aghai R. Turboexpander technology evaluation and application in natural gas processing. *Proceedings of Eighty-Second Gas Processing Association Annual Convention*. San Antonio, Texas. 2003.

8. Baccanelli M., Langé S., Rocco M. V., Pellegrini L. A., Colombo E. Low temperature techniques for natural gas purification and LNG production: An energy and exergy analysis. *Applied Energy.* 2016. Vol. 180. P. 546−559. https://doi.org/10.1016/j.apenergy.2016.07.119.
9. Murodov A., Xabibullaev S., Maxmudov N., Daminov T., Qarshiyev A. Creation of technology for desalination of saturated diethylene glycol substance in East Berdak gas complex preparation plant. *E3S Web of Conference*. 2023. Vol. 434. Article No. 02026. https://doi.org/10.1051/e3sconf/202343402026.
10. Chidiebere O. O., Inyang U. E., Oboh I. O. Modelling and optimization of natural gas dehydration system using triethylene glycol. *Journal of Engineering Research and Reports*. 2023. Vol. 24. Iss. 12. P. 89−102. https://doi.org/10.9734/jerr/2023/v24i12862.
11. Orymbetov E., Orymbetova G. E., Khussanov A. E., Orymbetov T. E., Orymbetov B. E. Sectioning of petroleum gas adsorption drying. Series of geology and technical sciences. *News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences*. 2022. Vol. 3 (453). P. 155–165. https://doi.org/10.32014/2022.2518-170X.187.
12. Bloch H. P. Subject Category 43 – Turboexpanders. *Petrochemical Machinery Insights*. 2017. P. 657−660. https://doi.org/10.1016/B978-0-12-809272-9.00043-8.
13. Проекти ПрАТ «Турбогаз». ПрАТ «Турбогаз»: офіційний вебсайт. 2025. https://turbogaz.com.ua/uk/projects.
14. Моісеєв С. В., Новіков М. К., Бурняшев А. В., Паккі Г. В., Ткачук М. А., Львов Г. І., Кравченко С. О., Подрєза С. М. Розроблення проривних технологій зміцнення елементів турбодетандерних установок. *Вісник Національного технічного університету «ХПІ». Серія: Машинознавство та САПР*. 2023. № 1. С. 53−67. https://doi.org/10.20998/2079-0775.2023.1.06.
15. Tkachuk M., Lvov G., Kravchenko S., Moiseiev S., Novikov M., Burniashev A., Pakki G., Podrieza S. Substantiating promising technical solutions for turbo- expander power plants based on the research into working processes and states. *Eastern-European Journal of Enterprise Technologies*. 2023. Vol. 4. No. 7 (124). P. 98–105. https://doi.org/10.15587/1729-4061.2023.285865.
16. Патент на винахід № 123415 «Доцентрова турбіна». Моісеєв С. В., Бурняшев А. В., Плахотник В. В., Борисенко О. В. Державний реєстр винаходів України. Опубліковано 31.03.2021, бюл. № 13/2021. https://sis.nipo.gov.ua/uk/search/detail/1585827/.
17. Патент на винахід № 123333 «Регульований сопловий апарат доцентрової турбіни». Моісеєв С. В., Бурняшев А. В., Плахотник В. В., Борисенко О. В. Державний реєстрі винаходів України. Опубліковано 17.03.2021, бюл. № 11/2021. https://sis.nipo.gov.ua/uk/search/detail/1483943/.
18. Русанов А. В., Ершов С. В. Математическое моделирование нестационарных газодинамических процессов в проточных частях турбомашин. Харьков: ИПМаш НАН Украины, 2008. 275 с.
19. Билан А. В., Билан В. Н. Автоматизированное проектирование лопаток паровых турбин. *Компрессорное и энергетическое машиностроение*. 2006. № 3 (5). С. 66–68.
20. Goldberg D. E. Genetic Algorithms in Search, Optimization, and Machine Learning. USA, MA, Boston: Addison-Wesley Longman Publishing Co., Inc., 1989. 412 p.
21. Thevenin D., Janiga G. Optimization and Computational Fluid Dynamics. Springer-Verlag Berlin Heidelberg, 2008. 294 p. https://doi.org/10.1007/978-3-540-72153-6.
22. Rusanov R., Klonowicz P., Rusanov A., Lampart P., Jedrzejewski L., Witanowski L. Methods for designing of axial turbines for ORC cogeneration unit working with MDM. *NTU "KhPI" Bulletin: Power and heat engineering processes and equipment.* 2015. No. 15. P. 86−100. https://doi.org/10.20998/2078-774X.2015.15.11.
23. Русанов А. В. Использование современных компьютерных технологий для создания высокоэффективных проточных частей радиально-осевого типа. *Компрессорное и энергетическое машиностроение*. 2013. № 2 (32). С. 4−9.
24. Русанов А. В., Шатравка О. И., Косьянова А. И. Профилирование радиально-осевых турбин с использованием современных компьютерных технологий. *Восточно-Европейский журнал передовых технологий*. 2009. № 4. С. 58−62. https://doi.org/10.15587/1729-4061.2009.21037.
25. Rusanov A. V., Rusanov R. A., Pashchenko N. V., Chuhai M. O. Analytical method of profiling axial-radial compressor impellers. *Journal of Mechanical Engineering – Problemy Mashynobuduvannia*. 2018. Vol. 21. No. 4. P. 4−13. https://doi.org/10.15407/pmach2018.04.004.
26. Anderson D. A., Tannehill J. C., Pletcher R. H. Computational Fluid Mechanics and Heat Transfer. Taylor and Francis: Milton Park, UK, 1997. 816 p.
27. Menter F. R. Two-equation eddy-viscosity turbulence models for engineering applications. *AIAA Journal*. 1994. Vol. 32. No. 8. P. 1598–1605. https://doi.org/10.2514/3.12149.
28. Benedict M., Webb G. B., Rubin L. C. An empirical equation for thermodynamic properties of light hydrocarbons and their mixtures I. Methane, ethane, propane, and n–butane. *Journal of Chemical Physics*. 1940. Vol. 8. Iss. 4. P. 334–345. https://doi.org/10.1063/1.1750658.

29. Русанов А. В. Интерполяционно-аналитический метод учета реальных свойств газов и жидкостей. *Восточно-Европейский журнал передовых технологий.* 2013. № 3/10 (63). С. 53−57. https://doi.org/10.15587/1729-4061.2013.14864.
30. Русанов А. В., Лампарт П., Русанов Р. А. Интерполяционно-аналитическая аппроксимация модифицированного уравнения состояния Бенедикта-Вебба-Рубина для учета реальных свойств рабочих тел в трехмерных расчетах. *Компрессорное и энергетическое машиностроение*. 2014. № 3. С. 18−23.
31. Tammann G. Ueber die Abhängigkeit der volumina von Lösungen vom druck. *Zeitschrift für Physikalische Chemie.* 1895. Vol. 17U. No. 1. P. 620−636. https://doi.org/10.1515/zpch-1895-1738.
32. Yershov S., Rusanov A., Gardzilewicz A., Lampart P. Calculations of 3D viscous compressible turbomachinery flows. *Proc. 2nd Symp. on Comp. Technologies for Fluid/Thermal/Chemical Systems with Industrial Applications, ASME PVP Division Conf.*, 1–5 August 1999, Boston, USA, PVP. 1999. Vol. 397 (2). P. 143–154.
33. Rzadkowski R., Zywica G., Kaczmarczyk T. Z., Koprowski A., Dominiczak K., Szczepanik R., Kowalski M. Design and investigation of a partial admission radial 2.5-kW organic Rankine cycle micro-turbine. *International Journal of Energy Research*. 2020. Vol. 44 (14). P. 11029–11043. https://doi.org/10.1002/er.5670.