RESULTS OF EXPERIMENTAL AND COMPUTATIONAL STUDIES FOR STEAM TURBINE EXHAUST HOODS APPLYING A WIDE-MODE DEFLECTOR

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Abstract. *Research of exhaust hoods operation combined with the turbines' last stages at reduced volume flow rates is of high scientific importance. With a decrease of load in the diffusers, flow passage the bushing circulation zone of the separated flow increases, which affects the efficiency of the turbine outlet part. During the first phase, an aerodynamic experiment was executed, that studied an outlet hood model of the powerful steam turbine, as well as the turbine's last stage. Based on the results of the experiment carried out in wide operating modes range of the turbine last stage, it was determined that the installation of a wide-mode deflector at the inlet to the diffuser allows to reduce the separated circulation flows and the nonuniform flow in the outlet hood, as well as to reduce the total loss coefficient. During the second phase, computational studies were performed that used CFD four design forms of an axial-radial diffuser, distinguished by presence or absence of deflectors. It was determined that in the studied range of operating modes, all design forms of the diffuser with a wide-mode deflector have a positive effect on the flow – the total loss coefficient decreases and the efficiency of the turbine outlet part increases respectively, while the dimensions of the bushing circulation zone significantly decrease. The research results can be used both in the development of new exhaust hoods designs and in the modernization of the operated turbines flow path.*

Keywords: *circulation zone, diffuser, loss coefficient, operating mode.*

Introduction

Nowadays, many powerful steam turbines are operating at reduced volume flow rates for a long time [1]. The flow pattern in these operating modes contains flow separation from the diffuser walls of the outlet hood and developed circulation zones. This pattern significantly affects the turbine efficiency and the blade row reliability of the steam turbine's last stage. Therefore, the study of the turbine exhaust hoods operation within a wide operating modes range and the improvement of their aerodynamic characteristics is contemporary and is a promising method to increase the efficiency of turbomachines. This research contains comparative results of experimental and computational studies of steam turbine exhaust hoods using a wide-mode deflector. The aim of the given computational study is to confirm the effectiveness of the wide-mode deflector installation, and to verify performed calculations.

Numerous studies about the operation of the "last stage with exhaust hood" steam turbine compartment are aimed at investigating the three-dimensional flow fields in the diffuser and finding ways to improve their characteristics. Various options are proposed in order to reduce the exhaust hood resistance by optimizing its geometry parameters [2-5]. Several works [6-9] are dedicated to the investigating and finding possible ways to decrease the flow parameters circumferential nonuniformity downstream of the turbine's last stage by changing the flow path of the stage and improving characteristics of an axial-radial diffuser, and to minimize the separated flows [10-12].

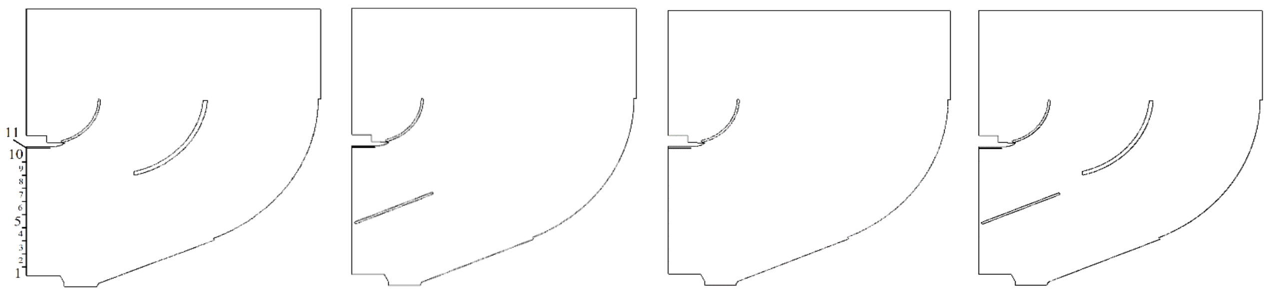
Efficiency increase is achieved by optimizing the design of the turbine's last stage and by modifying the geometry of the turbine's outlet diffuser [13].

On the other hand, the available literary sources in this research area are very limited. According to experimental studies of the low pressure cylinder's last stages of a steam turbine [14, 15], the low load operating mode of the last stages is characterized by streamlines contraction to the flow path periphery and the formation of a wide root zone of the separated flow, the size of which increases as the load decreases. Concurrently, the speed of the reverse steam flow in the circulation zone is quite high, which, due to the removal of moisture from the condenser, leads to the erosion of the rotor blades trailing edges of the turbine's last stage [16-18]. Recent studies of the flow in the exhaust hoods under low load operating modes allowed developing several designs with movable and fixed elements for more efficient flow control in a wide range of operating modes [3, 12, 19-20].

Research methodology

The research was executed in two steps. At first, aerodynamic experimental studies were performed to investigate the axial-radial diffuser models of the outlet hood of a powerful steam turbine, as well as its last stage. The "last stage and diffuser" compartment of a powerful steam turbine, made on a scale of 1:10, was studied at the air turbine stand. Three diffusers designs were tested, that had the same external and internal contours, but different elements inside the flow part: type 1 - with a toroidal deflector, type 2 - without any deflectors, type 3 - with a wide-mode deflector. The flow parameters were measured in four sections I, II, III, IV (Fig. 2, a) along the diffuser (I - inlet, IV - outlet). The experiments were executed in three operating modes of the last stage with *U/C* = 0.6; 0.74; 1.22-1.28 (*U/C* is operating mode characteristic parameter, circumferential to fictitious velocities ratio), that corresponded to the relative volume flow rate of the working fluid *GV2* ~ 1, 0.8 and 0.55. The influence of *U/C* on the compartment efficiency η_{com} and on the total loss coefficient ς_t with its components, internal and leaving losses, was determined.

Secondly, computational studies were performed using the ANSYS Fluent software for similar diffuser models under the same operating modes. The boundary conditions at the diffuser inlet corresponded to the experimental distribution downstream the last stage. Four designs of axial-radial diffusers were studied, where a rectangular mesh is built with clustering near the wall surfaces. The inlet section of the diffusers up to the shroud is divided into 11 segments to simulate the distribution of parameters behind the last stage (Fig. 1). The flow pattern in the flow part, as well as loss coefficients were determined.



Design 1 **Design 2** **Design 3** **Design 4**

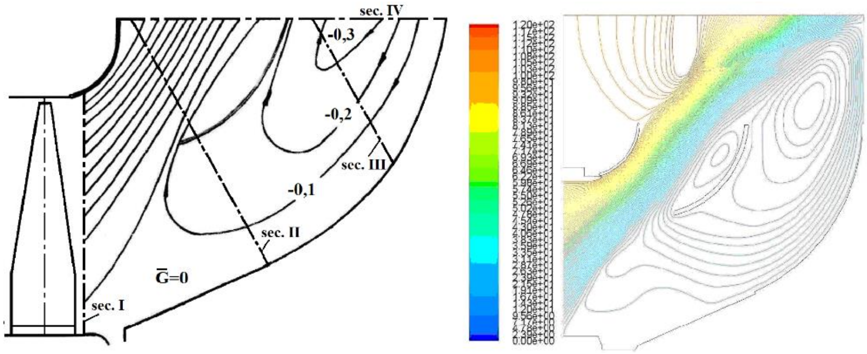
Figure 1. Models of diffusers

Results

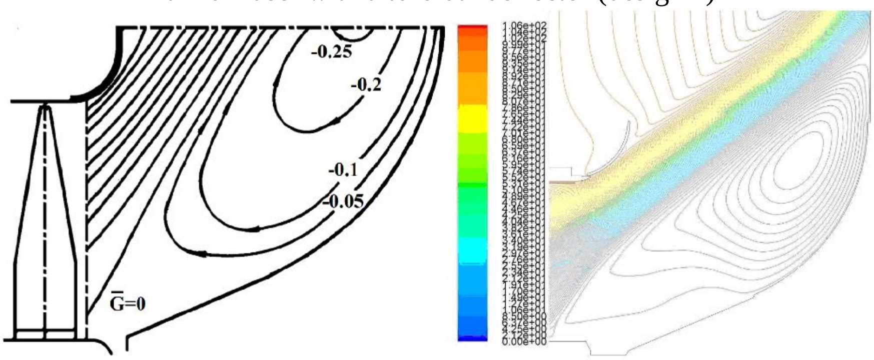
A) Experimental studies

The influence of the last stage operating modes *U/C* on the flow in the diffuser flow path, the compartment efficiency η_{com} and losses was determined. In design mode *U/C* = 0.6, the flow at the outlet of the last stage is close to axial, the flow is contracted to the diffuser peripheral contour due to the leakage flow through the radial clearance of the rotor blade. Total loss coefficients are the same for both designs, but the values of their components are different: with a deflector installed, the leaving losses are reduced, which is compensated by the increase in internal losses. In the outlet section of design 3, the streamlines are more rarefied near the internal contour. This flow is associated with an additional diffuser effect that occurs in the channel under the deflector.

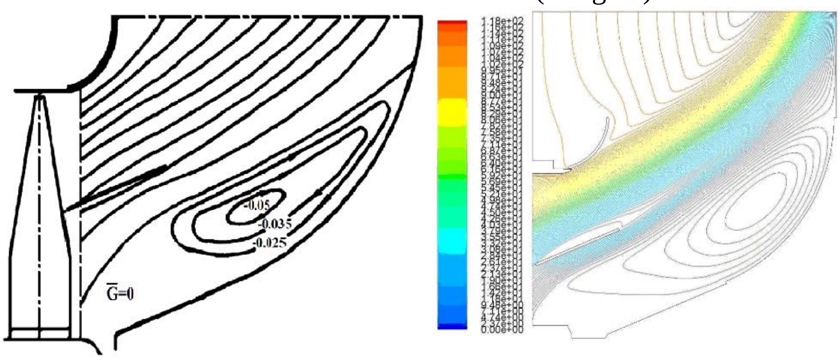
In the mode *U/C* = 0.74 in a diffuser 2, a flow separation from the internal contour appears, which is followed by a circulating flow from section II to section IV. More than 1.5% of the total flow rate of working fluid through the stage is involved in the circulating motion. With a deflector installed, no significant changes in the flow pattern are observed, however, the size of the circulation zone and the circulating flow rate decrease by 1.6 times.



a – diffuser with a toroidal deflector (design 1)



b – diffuser without deflector (design 2)



c – diffuser with a wide-mode deflector (design 3)

Figure 2. Flow in diffuser designs 1, 2 and 3 at operating modes *U/C* = 1.22-1.28

In the operating mode *U/C* = 1.22, the circulation zone in design 2 takes more than half of the diffuser area and extends beyond the outlet section IV. Up to 25% of the total flow rate of the working fluid through the stage is involved in the circulation motion (Fig. 2, b). The streamlines are contracted to the diffuser peripheral contour. In design 3, the resistance of the diffuser with a deflector decreases and the last turbine stage operates in the mode *U/C* = 1.28 (Fig. 3). The circulating zone does not expand beyond the outlet section, and the flow rate of the circulating working fluid is only 5% of the total flow rate of active flow.

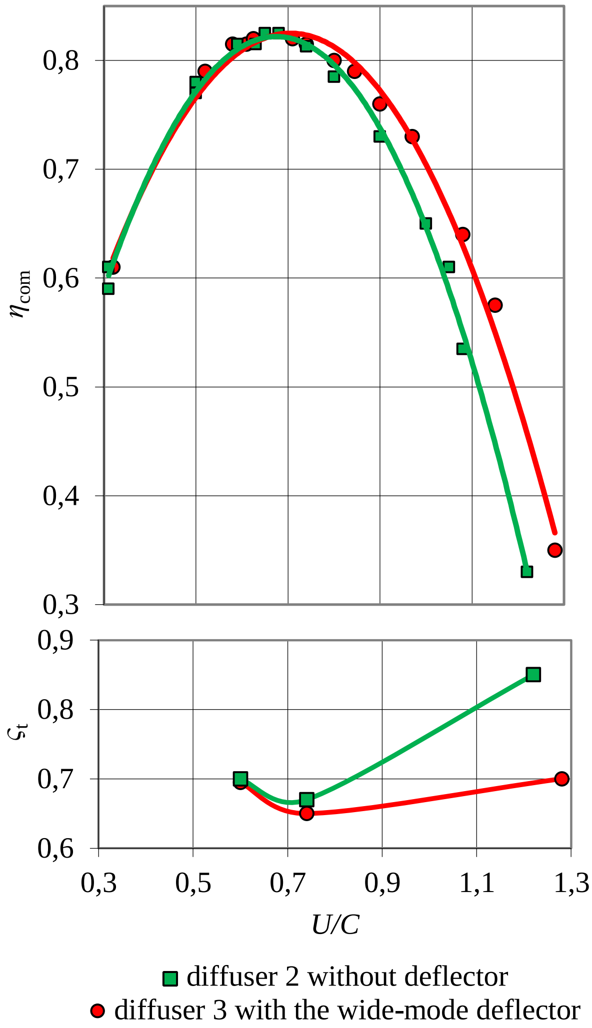


Figure 3. Dependence of total loss coefficient and efficiency on *U/C* ratio

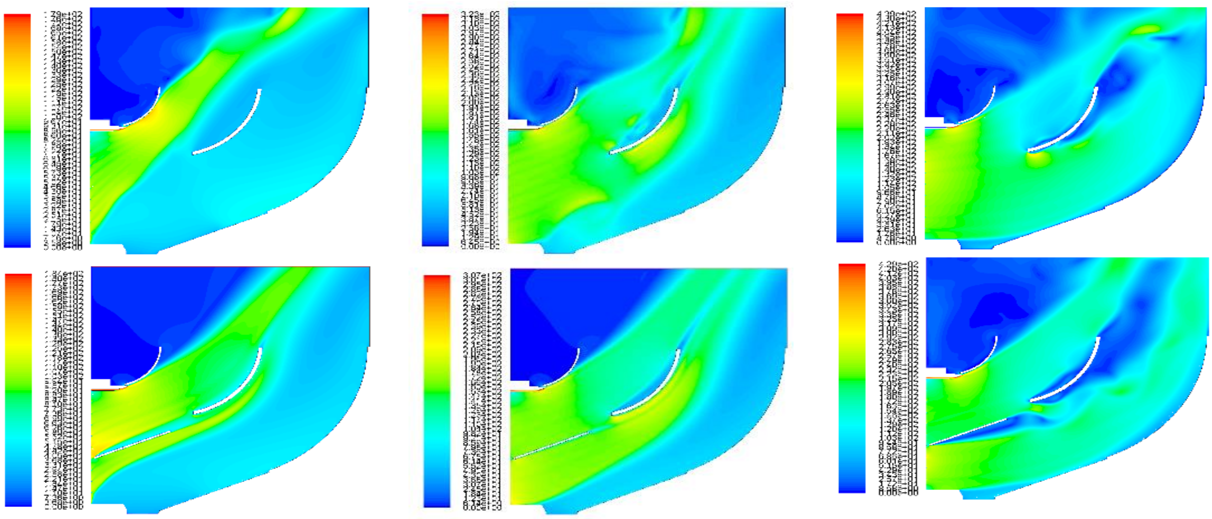
The installation of the deflector leads to a change in the flow pattern in the diffuser. At the periphery of section I, the speed decreases, and it increases in the central zone. In sections II and IV, the flow becomes more uniform, and the circulation zone decreases due to the powerful flow jet formed under the deflector. In section IV of the diffuser with a deflector, the distribution of the flow rate component of velocity is almost uniform. The interaction of the flow with the deflector leads to a twofold increase in internal losses, however, at the same time, the leaving losses decrease by more than 2 times, and leading to a relatively low value of the ς_t. The use of a fixed wide-mode deflector in the diffuser makes it possible to keep the efficiency η_{com} at an unchanged level in the operating modes *U/C* = 0.3...0.74, and to increase it by reducing the total loss coefficient in the operating modes *U/C* > 0.74.

B) Computational studies

Four models of axial-radial diffusers were studied. The first three models, 1st, 2nd and 3rd designs, are similar to the diffusers that were studied at the air turbine stand. The 4th design of the diffuser - with toroidal and wide-mode deflectors Fig. 1 was studied for the first time. The idea was to test the performance of the wide-mode deflector under the conditions of an already existing standard toroidal deflector installed in the exhaust turbine hoods.

The Fig. 2 shows the comparison of the calculated equal flow rates lines distribution with experimental ones in the operating mode *U/C* = 1.22-1.28 of 1, 2 and 3 diffuser designs. The flow performance of the 1st diffuser design almost does not differ from the one of the 2nd design. The flow velocity near the surface of the external diffuser contour is 1.5 times higher than in other zones due to the flow contraction and curvature changing. The circulation zone takes most part of the diffuser flow channel. Within the 3rd diffuser design the dimensions of the circulation zone decreased by ~ 2.5 times, and the flow rate of the working fluid involved in the circulation motion decreased by ~ 5 times.

The comparative computational study of the modernized diffuser model 4 and the original model 1 was executed Fig. 4. Installation of a wide-mode deflector has little effect on total loss coefficient, but it causes some improvement of the flow in the diffuser when simulating the modes *U/C* = 0.6 and *U/C* = 0.74. In off-design mode *U/C* > 0.74, the wide-mode deflector starts producing a more positive effect on the flow. When simulating the mode *U/C* = 1.28 in the modernized design 4 of the diffuser, the main flow is deflected by a wide-mode deflector to the diffuser bushing, the size of the circulating flow decreases. Concurrently, the total loss coefficient decreases by almost 1.5 times.



a – *U/C* = 1.22-1.28 b – *U/C* = 0.74 c – *U/C* = 0.6

Figure 4. Design distribution of velocity (m/s) in diffuser's design 1 (top row) and design 4 (bottom row) in transient operating modes

Conclusions

A computational model of the diffuser was tested, which makes it possible to reliably and efficiently simulate complex distributions of boundary conditions at the inlet to the diffuser of the exhaust hood, especially when simulating variable operating modes of the turbine last stage. Comparison with experiment showed that the flow pattern in various diffusers designs is adequately simulated even in off-design operating modes with flow separations and developed circulation zones.

The results of aerodynamic experimental and computational studies of axial-radial diffusers of the steam turbine exhaust hood show that the installation of a wide-mode deflector in the diffuser has a positive effect on the flow in the diffuser at variable operating modes. At the off-design modes, such a modernization can significantly reduce the size of the circulating zones and the total loss coefficient.

References

1. ZAYCEV, M., SLABCHENKO, O.: Modernizatsiya TsND turbin K-300-240 elektrostantsiy Ukrainy [Modernization of the K-300-240 steam turbine LPC at Ukraine's electric power plants]. In: Power Engineering and Electrification, 1996, 4, pp. 6-9.
2. GRIBIN, V., MITROKHOVA, O., PARAMONOV, A., REVENKO, A. Numerical investigations the effect of the overall dimensions on the efficiency of steam turbine exhaust

hood. In: *AIP Conference Proceedings 2047 (1)*. Pilsen: American Institute of Physics, 2018.

3. GRIGORYEV, E., ZARYANKIN, A., ROGALEV, A., GARANIN, I. Issledovanie i aerodinamicheskoe sovershenstvovanie vykhlopnogo patrubka nizkogo davleniya parovoi turbiny [Study and aerodynamic improvement of steam turbine low pressure cylinder exhaust nozzle]. In: *Vestnik IGEU*, 2017, 2, pp. 18-26.
4. GALAEV, S., RIS, V., SMIRNOV, E., BABIEV, A. Experience gained from designing exhaust hoods of large steam turbines using computational fluid dynamics techniques. In: *Thermal Engineering*, 2018, 65, pp. 352–361.
5. MUNYOKI, D., SCHATZ, M., VOGT, D. Numerical investigation of the influence of hood height variation on performance of low pressure steam turbine exhaust hood. In: *Proceedings of the ASME Turbo Expo 2018*. Oslo: ASME Turbo Expo, 2018, 8, pp. 11.
6. DING, B., XU, L., YANG, J., YANG, R., DAI, Y. The effect of stage-diffuser interaction on the aerodynamic performance and design of LP steam turbine exhaust systems. In: *Proceedings of the ASME Turbo Expo 2018*. Oslo: ASME Turbo Expo, 2018, 8, pp. 11.
7. SIDOROV, A., GOLIKOV, A., POLNIKOVA, T. Vliyaniye diffuzora na okruzhnuyu neravnomernost davleniya gaza v vykhodnom patrubke turbiny [Diffuser effect on circumferential gas pressure non-uniformity in the exhaust manifold of a steam turbine]. In: *Izvestiya vysshikh uchebnykh zavedeniy. Mashinostroyeniye*, 2015, 6 (663), pp. 20-25.
8. MITROKHOVA O., GRIBIN V., PARAMONOV A., GURYANOVA A., REVENKO A. Numerical simulation of 3D flow in the diffuser exhaust hood of the high-power steam turbine. In: *AIP Conference Proceedings 2189 (1)*. Pilsen: American Institute of Physics, 2019.
9. HOZNEDL, M., ŽIVNÝ, A., MACÁLKA, A., KALISTA, R., SEDLÁK, K., BEDNÁŘ, L., TAJČ, L. The pressure field at the output from a low pressure exhaust hood and condenser neck of the 1090 MW steam turbine: experimental and numerical research. In: *Proceedings of the ASME Turbo Expo 2018*. Oslo: ASME Turbo Expo, 2018, 8, pp. 11.
10. YIN, M., YANG, C., MENG, L., YAN, W., ZHUHAI, Z., LI, J., FENG, Z. Numerical analysis on the swirl flows in the exhaust hood of steam turbine and optimization design. In: *Proceedings of the ASME Turbo Expo 2016*. Seoul: ASME Turbo Expo, 2016, 8, pp. 9.
11. TABATA, S., FUKUSHIMA, H., SEGAWA, K., ISHIBASHI, K., KUWAMURA, Y., SUGISHITA, H. Experimental and numerical investigations of steam turbine exhaust hood flow field with two types of diffusers. In: *Proceedings of the ASME Turbo Expo 2019*. Phoenix: ASME Turbo Expo, 2019, 8, pp. 11.
12. FU, J., LIU J. Investigations on the improving aerodynamic performances of last stage steam turbine and exhaust hood under design and off design conditions. In: *Journal of Thermal Science*, 2015, 24, pp. 468-477.
13. YUDIN, Y., LAPUZIN, A. Povysheniye effektivnosti vykhlopnykh patrubkov TsND parovykh turbin s pomoshchyu shirokorezhimnogo deflektora [Increasing the efficiency of the exhaust hoods of the steam turbines LPC using a wide-mode deflector]. In: *NTU "KhPI" Bulletin: Power and Heat Engineering Processes and Equipment*, 2005, 6, pp. 60-64.
14. ALYOKHINA, S., ISHCHENKO, M., SLASTON, L., SHERFEDINOV, R. Experimental study of the model compartment of the low-pressure cylinder of K-320-240 turbines of JSC “Turboatom”. In: *Journal of Mechanical Engineering – Problemy Mashynobuduvannia*, 2019, 22 (4), pp. 6-10.
15. SHUBENKO, A., HOLOSHCHAPOV, V., STRELNIKOV, I., RESHYTKO, I. Vliyaniye krupnodispersnoy vlagi na rabochiye protsessy vlazhnoparovykh stupeney turbin [Effect of coarse particle moisture on work process of the wet steam stages of turbines]. In: *Energosberezheniye, Energetika, Energoaudit*, 2014, 11 (130), pp. 28-39.
16. SHUBENKO, A., KOVALSKIY, A., VOROBYEV, Y., KARTMAZOV, G., ROMANENKO, V. Vliyaniye erozii na osnovnyye ekspluatatsionnyye kharakteristiki

rabochey lopatki posledney stupeni tsilindra nizkogo davleniya moshchnoy parovoy turbiny. Chast 1. Prognozirovaniye erozionnoy opasnosti v poslednikh stupenyakh energeticheskikh turbin [Erosion influence on the main operational characteristics of the powerful steam turbine low-pressure cylinder last stage rotor blade. Part 1. Erosion hazard prediction in the power turbines last stages]. In: *Problemy Mashinostroyeniya*, 2009, 12 (4), pp. 7-16.

17. SENOO, S., WHITE, A. Analysis and design of wet-steam stages. In: *Advances in Steam Turbines for Modern Power Plants*, 2017, pp. 165–218.
18. LIN, A., CHANG, X., CAO, L., ZHANG, H., SUN, L. Effect of wet steam on aerodynamic performance of low-pressure exhaust passage with last stage blade. In: *Journal of Applied Fluid Mechanics*, 2019, 12 (6), pp. 1837-1845.
19. YUDIN, Y., SUBOTOVICH, V., LAPUZIN, A., MALYMON, I. Rozrakhunkove aerodynamichne doslidzhennia vykhlopnoho dyfuzora potuzhnoi parovoi turbiny v shyrokomu diapazoni rezhymiv roboty [Numerical aerodynamic investigation of exhaust diffuser for powerful steam turbine in a wide operating modes range]. In: *NTU "KhPI" Bulletin: Power and Heat Engineering Processes and Equipment*, 2020, 1 (3), pp. 5-9.
20. EPIPHANOV, V., GAEV, V., LISYANSKII, A., KIRILLOV, A., NIKOLAEV, M., SMIRNOV, E., ZAJTSEV, D. Effect of deflector vane geometry on performance of large-scale turbine exhaust hood at transonic flow conditions: air-test experiments and 3D numerical simulation. In: *Proceedings of the 5th European Conference Turbomachinery*. Praha: Environmental Science, 2003, pp. 803-812.