Optimization of the Flowing Part of the Turbine K-310-240 Based on the Object-Oriented Approach

Olena Avdieieva(✉), Oleksandr Usatyi, and Iryna Mykhailova

National Technical University “Kharkiv Polytechnic Institute”,
2 Kyrpychova Street, Kharkiv 61002, Ukraine

Abstract. This article describes the application of the optimization methodology of a complex technical system using the K-310-240 turbine as an example based on a block hierarchical approach. The methodology for optimizing the flow part of powerful steam turbines has been developed taking into account operating conditions. The complex hierarchical structure of the optimization task is implemented in CAD “Turboagregat”, which is based on the principles of a single integrated information space by adding new optimization objects. To organize effective information exchange, the process of optimal design is implemented using recursive bypass of optimization levels. Application of the methodology for solving a two-level multi-parameter and two-criteria optimization problem allowed us to find the optimal combination of 55 design parameters of the K-310-240 turbine, while increasing the absolute efficiency by 0.83% and the turbine power by 6.179 MW (~1.87%) regarding the prototype. By calculation, the mutual influence of turbine objects on its optimal characteristics was identified and evaluated.

Keywords: Object-oriented approach · Cylinder · Steam turbine · Blade and nozzle cascades

1 Introduction

In the world, the demand for electricity is growing every year. At the moment, there is a huge amount of work in the field of renewable energy, but all this cannot replace the already existing turbine park, which generates the bulk of all electricity in the world. Therefore, the design of new and modernization of existing steam turbines is still an urgent task in the energy sector.

At the moment, vast experience has already been accumulated in the field of optimal design of multi-cylinder turbine units, samples of flow parts (FP) of each cylinder having rather high technical and economic indicators have been created. Further search for reserves to increase the efficiency of steam turbines is possible only if a powerful computing techniques along with new methods and approaches implemented in the framework of modern computer aided design systems (CAD).

J. Machado et al. (Eds.): icieng 2021, LNME, pp. 201–213, 2022.
https://doi.org/10.1007/978-3-030-79165-0_20

2 Literature Review

There are many works devoted to optimization of steam and gas turbines [1–9], in which various methods and algorithms are used: genetic algorithm [10–12], surrogate modeling [13, 14], bee colony algorithm [15], DOE methods [16, 17].

At the moment there are many methods, algorithms for finding the optimal solution and also a large number of software complexes [1, 10, 13, 14]. No exception is the software package CAD "Turboagregat", aimed at finding the optimal solution for complex technical systems (CTS). The problem of optimal design of such a system, taking into account constraints and inequalities in general form, can be represented as follows:

$$\begin{gathered}
\vec{Y}_{opt}\left(\vec{x}_k^{opt}\right) = \max \vec{Y}(\vec{x}_k), \vec{x}_k \in X, \vec{v}(\vec{x}_k) \in V, \\
\vec{Y}\left(\vec{Y}_1(\vec{x}_k), \vec{Y}_2(\vec{x}_k), \ldots \vec{Y}_n(\vec{x}_k)\right), \\
N_{X\min} \leq |X| \leq N_{X\min} < \infty, N_{V\min} \leq |V| N_{V\min} < \infty,
\end{gathered} \tag{1}$$

where $\vec{Y}$ is the vector of objective functions; $\vec{x}_k$ is a vector of constructive parameters; $\vec{v}$ is the vector of functional constraints; V, X-regions of existence of functional and constructive constraints; $N_{V(\min,\max)}$, $N_{X(\min,\max)}$ - the boundaries of the regions of existence of the corresponding constraints.

The solution (1) is the extremum of the objective function that satisfies the constraints. A well-known fact is that CTS are basically either hierarchically structured constructions or various schematic solutions in which the elements of the circuit can also have their own structure. That is why for solving the problem (1) of the CTS, appropriate methodologies, methods and algorithms are required.

One of the methodologies for the search for the optimal design of the flow section of a turbo-aggregate was proposed in [18] (Fig. 1).

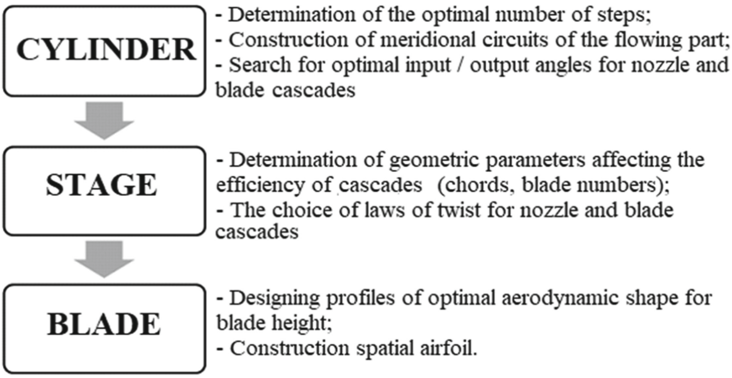


Fig. 1. Distribution of tasks by optimization levels

The paper [18] describes a three-level block-hierarchical approach for optimizing a cylinder of a turbine. The disadvantage of this approach is the lack of accounting for the operation of the regulatory system in conjunction with the rest of the flowing part. This became the basis for developing a methodology for the integrated optimization of the flowing part of powerful steam turbines using an object-oriented approach [19, 20]. This methodology is universal for CTS and was used in obtaining the results of optimization of the turbine K-310-240, given in this article.

3 Research Methodology

As an object of research, take the flowing part of the turbine K-310-240 produced by PJSC "Turboatom". In Fig. 2, consider the structure of the object in question from the point of view of the object-oriented approach.

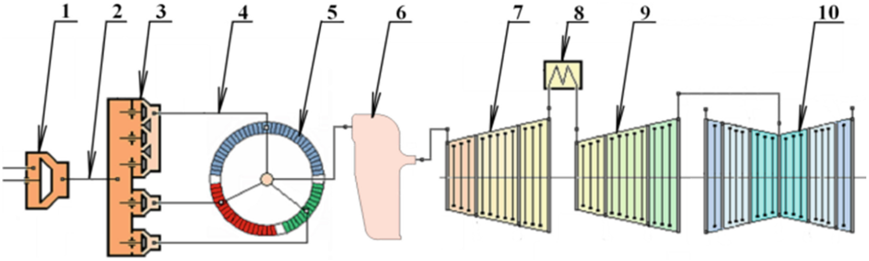


Fig. 2. Diagram of the flowing part of the turbine K-310-240: 1 - shut-off valve (NVD); 2 - stop valve line (NVD); 3 - box with control valves (SPR); 4 - segment pipelines (NVD); 5 - segments of the control stage (NVD); 6 - equalization chamber (EC); 7 - the cylinder of a high pressure (the Cylinder); 8 - high pressure cylinder (Cylinder); 9 - medium pressure cylinder (Cylinder); 10 - Low-pressure cylinder (Cylinder)

Elements that make up the structure can be divided into three objects according to their purpose. The first object is a "nozzle vapor distribution" (NVD), which includes a stop valve, a check valve line, a box with control valves, segment pipelines and a regulating stage (segments of the control stage). To the second object can be attributed, the link between the NVD and the rest of the flowing part - equalization chamber (EC), which is designed to equalize the flow at the entrance to the first stage of the high-pressure cylinder. The third object - "Cylinder" - included cylinders of high, medium and low pressure (HPC, MPC, LPC). Each of the objects, except the second one, can be divided into objects subordinate to it. Division into sublevels can be carried out until the simplest optimization object is determined.

Figure 3 shows the hierarchical structure of the information model of the structural diagram of the flowing part of a steam turbine. From the block diagram it is seen that the highest (zero) level is the turbine itself. At the first level there are previously described heterogeneous objects with their subordinate hierarchy. Each of the optimization objects has its own mathematical model and a quality assessment system.

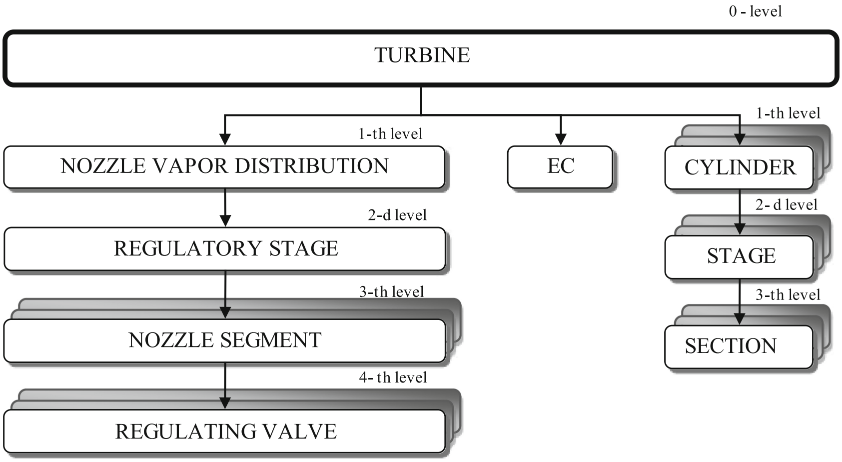
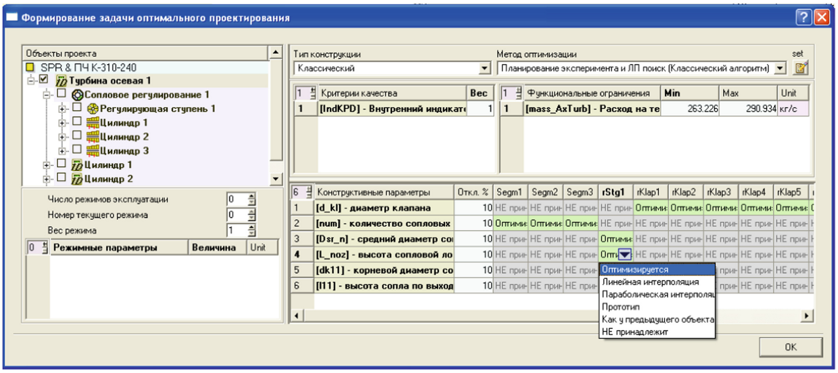


Fig. 3. Block diagram of the information model of the flowing part of the steam turbine

Mathematical models of objects of different levels used in the program complex are given in [19]. The proposed structure of the solutions to the optimization problem is implemented in such a way that it is possible to solve the optimization problem of the whole object (a powerful steam turbine) and its individual parts (NVD, HPC, MPC, LPC, separate stage, separate blade, etc.).

As a method of search optimization in the optimization subsystem, pseudo-random sequences of LPτ numbers are used. At optimizing levels, when searching for optimal solutions for each point from the set of points of the LPτ sequence, the FMM of the functional constraints is calculated. Therefore, for the points that satisfy these constraints, the FMM of the quality criteria is calculated. This optimization algorithm allows solving multicriterial problems using the convolution of the vector quality criterion. Applying the convolution of the criteria for the proposed method in solving optimization problems for various combinations of weight coefficients, we find the points farthest from the origin, thus obtaining a set of unmodified solutions corresponding to the Pareto front.

The algorithm is constructed in such a way that when choosing the optimal solution, both the solutions obtained in the computation process, the calculation of the experimental mathematical model, and the 5 best solutions using the LPτ search are involved. The software complex CAD “Turboagregat” is implemented on the principles of a single integrated information space and implies a hierarchically structured format for describing information models of optimal design objects. According to the proposed methodology of optimal design of the flowing part of powerful steam turbines in the CAD “Turboagregat” created the highest level of “Turbine” with its opera. In Fig. 4 from the window for forming the optimization task for the highest level of the “Turbine”. The left part of the figure shows the structure of the project. When selecting the level of interest in the rest of the window, it becomes possible to perform optimized parameters, functional constraints, quality criteria, parameter settings, design type and optimization method. It is also seen from the figure that you can select a suitable condition that determines the status of the optimized parameter.



Формирование задачи оптимального проектирования

Объекты проекта
- SPR & ПЧ K-310-240
  - ☑ Турбина осевая 1
    - ☐ Сопловое регулирование 1
      - ☐ Регулирующая ступень 1
      - ☐ Цилиндр 1
      - ☐ Цилиндр 2
      - ☐ Цилиндр 3
    - ☐ Цилиндр 1
    - ☐ Цилиндр 2

Число режимов эксплуатации: 0
Номер текущего режима: 0
Вес режима: 1

0	Режимные параметры	Величина	Unit

Тип конструкции: Классический
Метод оптимизации: Планирование эксперимента и ЛП поиск (Классический алгоритм)

1	Критерии качества	Вес
1	[IndKPD] - Внутренний индикат	1

1	Функциональные ограничения	Min	Max	Unit
1	[mass_AxTurb] - Расход на те	263.226	290.934	кг/с

6	Конструктивные параметры	Откл. %	Segm1	Segm2	Segm3	rStg1	rKlap1	rKlap2	rKlap3	rKlap4	rKlap5
1	[d_kl] - диаметр клапана	10	НЕ прин	НЕ прин	НЕ прин	НЕ прин	Оптими:	Оптими:	Оптими:	Оптими:	Оптими:
2	[num] - количество сопловых	10	Оптими:	Оптими:	Оптими:	НЕ прин	НЕ прин	НЕ прин	НЕ прин	НЕ прин	НЕ прин
3	[Dsr_n] - средний диаметр со	10	НЕ прин	НЕ прин	НЕ прин	Оптими:	НЕ прин	НЕ прин	НЕ прин	НЕ прин	НЕ прин
4	[L_noz] - высота сопловой ло	10	НЕ прин	НЕ прин	НЕ прин	Опти	НЕ прин	НЕ прин	НЕ прин	НЕ прин	НЕ прин
5	[dk11] - корневой диаметр со	10	НЕ прин	НЕ прин	НЕ прин			прин	НЕ прин	НЕ прин	НЕ прин
6	[l11] - высота сопла по выход	10	НЕ прин	НЕ прин	НЕ прин			прин	НЕ прин	НЕ прин	НЕ прин

Fig. 4. The dialog for forming the optimization task of a steam turbine

Optimization of the turbine K-310-240 was carried out according to the scheme in Fig. 5, where as the object of optimization of the first level is a turbine, and at the second level, objects such as NVD, HPC, MPC and LPC are optimized. At each level, the problem is solved in accordance with the above algorithm.

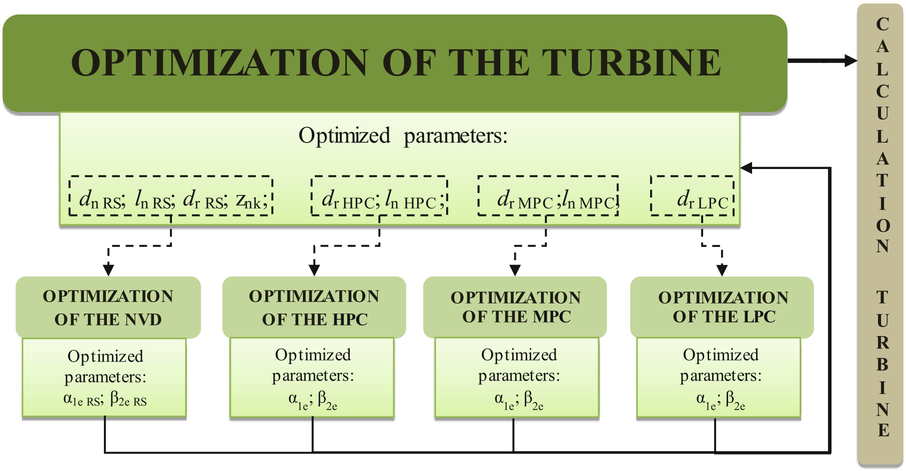


Fig. 5. Turbine optimization diagram

At the first level of the "Turbine" 16 parameters are optimized. These include the main parameters taken from the lower level: diameters of control valves ($d_{r\ RS}$); number of nozzle channels in each segment (z_{nk}); average diameter of the regulating stage ($d_{n\ RS}$); length of the nozzle blade of the regulating stage ($l_{n\ RS}$); the root diameter of the directing device of the first pressure stage of the HPC, the MPC and the LPC (d_{rCHP}, d_{rMPC}, d_{rLPC}); the height of the guide vane blade of the first pressure stage of the HPC and the MPC ($l_{n\ HPC}$, $l_{n\ MPC}$).

At the second level of "NVD" and "Cylinder" 39 parameters are optimized: the effective yield angles from all nozzle and blades grids except for the effective exit angles from the nozzle grilles of the first stages of the cylinders that ensure the throughput of the cylinders.

For the first level of optimization, the following objective functions are selected: absolute efficiency, turbine power and in equal weight fractions absolute efficiency and turbine power. At the second level, the Optimization Cylinder for HPC, MPC and LPC, the search for optimal solutions is carried out using the same goal functions as in the first approach. Optimization at the level of "NVD" was carried out by three separate objective functions: efficiency of the control stage; the power of the regulating stage; efficiency and power of the regulating stage.

When evaluating the efficiency of the initial design and solving the optimization problem, the following methods for estimating energy losses were used:

- to estimate the profile energy losses in the gratings - the Craig and Cox methods with the KhPI corrections;
- for estimation of secondary energy losses in lattices - the method of G.Yu. Stepanova;
- to estimate the energy losses from periodic nonstationarity - the technique of S.Z. Kopelev;
- To calculate the losses associated with radical leaks, the methodology given in the technical guidance materials was chosen;
- to assess the moisture losses of steam - the GE methodology;
- to determine the amount of moisture to be removed as a result of separation, the algorithms described in the book of G.A. Filippova, O.A. Povarov and V.V. Pryakhin.

The integral characteristics of the initial version of the turbine K-310-240, obtained as a result of the design studies and are given in Table 1.

Table 1. Integral characteristics of the original version of the turbine K-310-240

Parameter	Value	Parameter	Value
Absolute efficiency of the cycle	0,4441	Turbine power, MW	330,577
Efficiency NVD	0,5817	Power RS, MW	10,5111
Efficiency of RS	0,7367	Power of HPC, MW	88,7690
Efficiency of HPC	0,8098	Power of the MPC, MW	136,434
Efficiency of MPC	0,8587	Power of the LPC, MW	47,4315
Efficiency of LPC	0,7819	Theoretical work of the cycle, kJ	1380,11

- Thus, for each optimized object four tasks were solved:
- "prototype" - calculation of the prototype;
- "η" - optimization by the quality criterion of the efficiency of the optimized object;
- "N" - optimization by the criterion of quality of the power of the optimized object;

- "η + N" - optimization by the objective function, which includes the quality criterion of efficiency and the quality criterion of the power of the optimized object in equal weight fractions.

4 Results

In accordance with the methodology and algorithm described previously, a comprehensive optimization of the steam turbine K-310-240 for various target functions has been carried out, the integral characteristics are given in Table 2.

Table 2. Integral characteristics of the turbine

Parameter	Results of calculations			
	Prototype	η	N	η + N
Absolute efficiency of the cycle, ηa	0,4441	0,4525	0,4521	0,4524
Increase in the absolute efficiency of the cycle, Δηa,%	0	0,84	0,8	0,83
Turbine power N, MW	330,58	336,43	336,96	336,76
Capacity increase ΔN, MW	0	5,853	6,379	6,179

Such integral parameters of the turbine as the absolute efficiency of the cycle and the power of the turbine are contradictory, therefore, in the presence of selections in the flowing part of the turbine, the use of the two-criterion objective function ensures finding the best constructive solutions in terms of power quality and turbine efficiency (Table 2).

The distribution of the power gain and the level of absolute efficiency values for the turbine objects are shown in Figs. 6 and 7, respectively. The least influence on the increase in turbine power is provided by the MPC, and the largest is by HPC (Fig. 7).

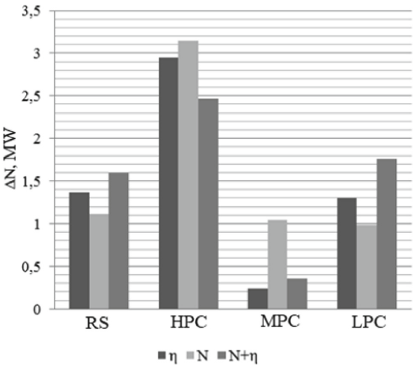


Fig. 6. Increase in the capacity of turbine objects relative to the prototype for various objective functions

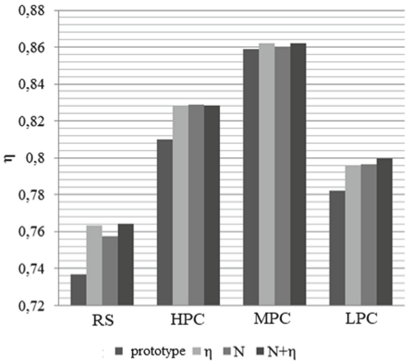


Fig. 7. Power efficiency of turbine objects depending on the objective function

The values of the optimized parameters as a result of solving optimization problems are presented in Tables 3, 4, 5 and 6. The change in the diameters of the control valves is associated with an increase in the heights of the valve lifts that result from minimizing throttle losses and the need to skip the required flow. Redistribution of the number of nozzles by segments is associated with a change in the flow area of the nozzle channels of the segments, caused by a change in the diameter and height of the nozzle grid of the regulating stage.

Table 3. The values of the optimized parameters at the level of “Turbine” (the first level)

Parameter	Results of calculations			
	Prototype	η	N	η + N
Number of channels in segment I	40	48	49	49
Number of channels in segment II	23	19	18	18
Number of channels in segment III	15	11	11	11
Diameter 1-th of the valve, m	0,0750	0,0713	0,0745	0,0741
Diameter 2-d of the valve, m	0,0750	0,0713	0,0751	0,0747
Diameter 3-th of the valve, m	0,1120	0,1065	0,1131	0,11191
Diameter 4-th of the valves, m	0,1120	0,1065	0,1104	0,1117
Diameter 5-th of the valve, m	0,1250	0,1188	0,1216	0,1207
Diameter 6-th of the valve, m	0,1250	0,1188	0,0126	0,1230
Average diameter of the nozzle cascades of the regulating stage, m	1,1750	1,1610	1,170	1,1615
Height of nozzle blade, m	0,0230	0,0225	0,023	0,0225
Root diameter of the nozzle cascade of the first stage of the HPC, m	0,982	0,944	0,950	0,9585

(*continued*)

Table 3. (*continued*)

Parameter	Results of calculations			
	Prototype	η	N	η + N
Root diameter of the nozzle cascade of the first stage of the MPC, m	1,202	1,202	1,202	1,202
Root diameter of the nozzle cascade of the first stage of the LPC, m	1,620	1,703	1,732	1,749
Height of nozzle blade of the first stage of the HPC, m	0,022	0,0225	0,023	0,023
Height of nozzle blade of the first stage of the MPC, m	0,081	0,081	0,081	0,081

Table 4. Optimized parameters of HPC (the second level)

Parameter	Type task	Stage number							
		1	2	3	4	5	6	7	8
Angle α_{1e}, degree	Prototype	13,83	13,85	13,90	13,95	14,03	14,08	14,15	14,28
	η	14.14	13,84	13,93	14,04	13,66	13,93	13,54	14,24
	N	13.16	13,18	13,67	13,69	14,01	14,11	13,86	14,33
	η + N	13.65	13,45	13,32	13,45	13,93	13,51	14,10	13,49
Angle β_{2e}, degree	Prototype	21,17	21,22	21,27	21,33	21,45	21,53	21,63	21,77
	η	22,65	21,85	22,35	22,49	22,3	22,61	21,92	22,52
	N	20,98	20,96	22,32	22,07	22,54	23,04	22,65	22,55
	η + N	22,34	21,93	21,35	21,61	21,84	21,84	22,13	21,47

Table 5. Optimized parameters of MPC (the second level)

Parameter	Type task	Stage number										
		1	2	3	4	5	6	7	8	9	10	11
Angle α_{1e}, degree	Prototype	13,3	13,4	14,15	13,7	15,27	15,53	14,9	17,02	15,65	16,07	17,32
	η	13.34	13,26	13,94	13,57	15,09	15,32	14,72	16,91	15,82	15,85	17,19
	N	13.13	13,36	14,03	13,62	15,13	15,68	15,11	17,23	15,80	16,17	17,17
	η + N	13.27	13,27	14,01	13,56	15,11	15,38	14,75	16,85	15,49	15,91	17,14
Angle β_{2e}, degree	Prototype	20,58	20,57	20,5	21,28	21,22	21,08	20,8	24	21,07	21	20,57
	η	21,29	20,85	20,85	21,06	20,90	20,79	20,51	23,65	20,75	20,52	20,28
	N	20,82	20,97	21,13	21,87	21,39	21,22	20,84	24,21	21,35	20,92	20,50
	η + N	21,31	20,87	20,91	21,28	21,00	20,87	20,59	23,76	21,17	20,82	20,46

Table 6. Optimized parameters of LPC (the second level)

Parameter	Type task	Stage number			
		1	2	3	4
Angle α_{1e}, degree	Prototype	14,1	15,33	17,65	17,583
	η	13.55	14,486	17,65	17,583
	N	13.24	14,618	17,65	17,583
	η + N	13.18	14,442	17,65	17,583
Angle β_{2e}, degree	Prototype	20,283	18,9	18,283	26,183
	η	19,151	19,165	18,283	26,183
	N	19,528	19,934	18,283	26,183
	η + N	19,13	19,429	18,283	26,183

With regard to the optimized geometric parameters of the MPC, as a result of optimization, the root diameter of the nozzle cascade of the first stage of the HPC decreased, and the root diameter of the nozzle cascade of the first stage of the LPC increased. The height of the nozzle cascade of the first stage of the HPC after optimization has increased slightly.

The increase in power, as noted earlier, is achieved due to the redistribution of the heat transfer along the pressure steps of the flowing part of the turbine, therefore, consider the distributions of heat differences in the cylinders shown in Figs. 8, 9 and 10.

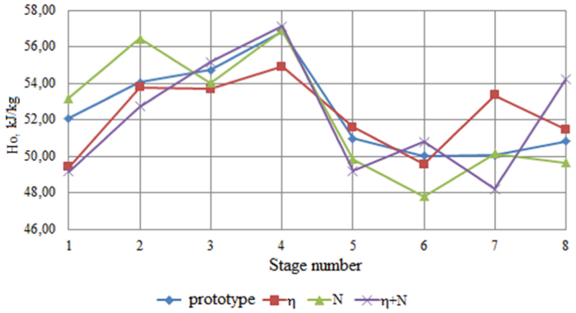


Fig. 8. Distribution of the available heat transfer along the HPC stages

Depending on the objective function, the curves for the variation of the heat transfer along the HPC and LPC steps have a similar character, except for the first stage of the LPC, where the changes are caused by abrupt changes in the effective exit angle from the nozzle array.

Proceeding from the fact that the best design option is adopted as a result of optimization of the turbine based on the two-criterion objective function, we compare the distribution of the heat drop of the HPC in this variant with the prototype. The heat

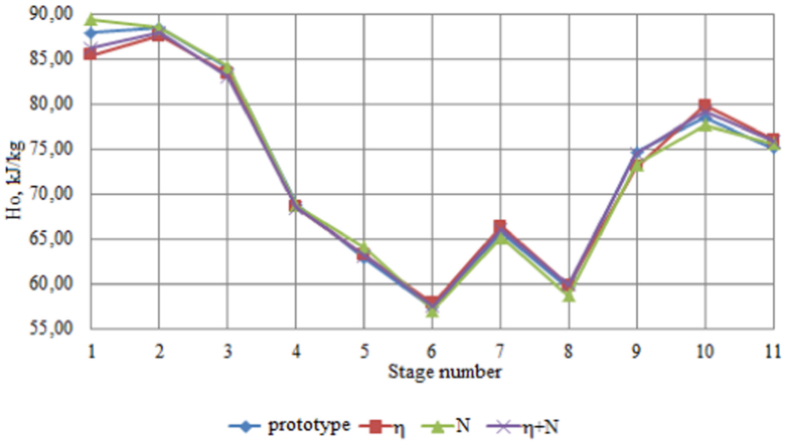


Fig. 9. Distribution of the available heat transfer along the MPC stages

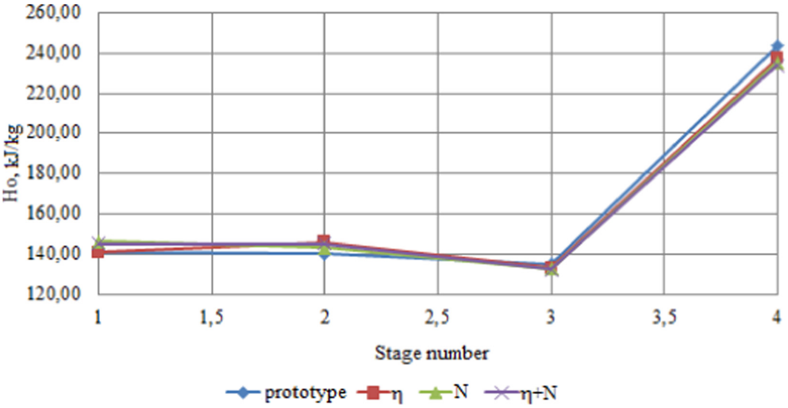


Fig. 10. Distribution of the available heat transfer along the LPC stages

transfer at the fourth stage is almost the same, in contrast to the other stages. At the 1st, 2nd, 5th and 7th stages the heat transfer of the received structure is lower than that of the prototype. Despite this, the power gain was ~2.5 MW due to the increase in heat dissipation of the 3.6 and 8 stages, as well as the power efficiency and flow rate in these stages.

In addition, the increase in power is also affected by the increase in power efficiency due to a significant decrease in radical and radial leakage, caused by a decrease in the degree of reactivity. A slight increase in the efficiency of the nozzle cascades also affects the efficiency of the turbine.

Based on the results obtained and the comparative analysis, depending on the objective function, the distribution of the integral characteristics of the turbine according to its objects is very diverse.

5 Conclusions

The proposed object-oriented approach for complex optimization of the flowing part of a powerful turbine implemented in the CAD “Turboagregat” has shown its effectiveness in the example of the turbine K-310-240.

For the first time, the mutual influence of the turbine objects on its optimal characteristics was identified and assessed.

Application of the universal methodology for CTS has shown its effectiveness in multi-level and multi-criteria optimization of the turbine K-310-240 in the composition, which includes different types of objects. As a result of complex optimization of this turbine, its power was increased by 6,179 MW (~1.87%), and the increase in the absolute efficiency of the cycle was 0.83% relative to the prototype.

To obtain a simultaneous increase in two quality indicators, such as efficiency and power as an objective function, it is necessary to take them in equal parts.

Analysis of the obtained results shows that the optimization carried out not only leads to a change in the geometric parameters, but also to the redistribution of heat drops between the stages of the pressure cylinder, which in turn contributes to an increase in the efficiency of the drive, cylinder in the stages, which have higher values of efficiency and flow.

References

1. Xu, C., Amano, R.S.: A turbomachinery blade design and optimization procedure. In: Proceedings of ASME Turbo Expo 2002, pp. 927–935. Amsterdam, The Netherlands (2002)
2. Smith, R.W.: Steam turbine cycles and cycle design optimization: combined cycle power plants. Advances in Steam Turbines for Modern Power Plants, pp. 57–92. Woodhead Publishing (2017)
3. Cao, L., Si, H., Lin, A., Li, P., Li, Y.: Multi-factor optimization study on aerodynamic performance of low-pressure exhaust passage in steam turbines. Appl. Therm. Eng. **124**, 224–231 (2017)
4. Shao, S.: Aerodynamic optimization of the radial inflow turbine for a 100kw-classmicro gas turbine based on metamodel-semi-assisted method. In: Proceedings of ASME Turbo Expo 2013: Turbine Technical Conference and Exposition. Volume 6B: Turbomachinery, V06BT37A032. San Antonio, Texas, USA (2013)
5. Nowak, G.: Pareto multicriteria optimization of airfoil cooling system. In: Proceedings of the 8th European Turbomachinery Conference, Graz (2009)
6. Turner, M.G., Park, K. [at alias]: Framework for multidisciplinary optimization of turbomachinery. In Proceedings of ASME Turbo Expo: Power for Land, Sea, and Air. Volume 7: Turbomachinery, Parts A, B, and C, pp. 623–631. Glasgow, UK (2010)
7. Goulos, I., Hempert, F., Sethi, V., et al.: Rotorcraft engine cycle optimization at mission level. Proc. ASME Turbo Expo: J. Eng. Gas Turbines Power. **135**(9), 091202 (2013) (GT2013-95678)
8. Wu, Y., Li, B., Teng, J., et al.: Automated design optimization and experimental validation for intermediate casing duct of aeroengine. In: Proceedings of ASME Turbo Expo: Turbine Technical Conference and Exposition. Volume 6B: Turbomachinery. San Antonio, Texas, USA. V06BT43A004, GT2013-94137 (2013)

9. Lytvynenko, O., Tarasov, O., Mykhailova, I., Avdieieva, O.: Possibility of using liquid-metals for gas turbine cooling system. In: Ivanov, V., Pavlenko, I., Liaposhchenko, O., Machado, J., Edl, M. (eds.) Advances in Design, Simulation and Manufacturing III. DSMIE 2020. Lecture Notes in Mechanical Engineering. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-50491-5_30
10. Horn, J., Nafpliotis, N., Goldberg, D.E.: A niched pareto genetic algorithm for multiobjective optimization. In: Proceedings of the First IEEE Conference on Evolutionary Computation, IEEE World Congress on Computational Intelligence, IEEE Service Center, vol. 1, pp. 82–87. New Jersey, Piscataway (1994)
11. Qin, X., Chen, L., Sun, F., Wu, C.: Optimization for a steam turbine stage efficiency using a genetic algorithm. Appl. Therm. Eng. **23**(18), 2307–2316 (2003)
12. Safari, A., Lemu, H. G., Assadi, M.: A novel combination of adaptive tools for turbomachinery airfoil shape optimization using a real-coded genetic algorithm. In: Proceedings of ASME Turbo Expo: Turbine Technical Conference and Exposition. Volume 6B: Turbomachinery. San Antonio, Texas, USA. V06BT43A003 (2013)
13. Ogaday, W., Moore, W., Mala-Jetmarova, H., Gebreslassie, M., Tabora, G.R., Belmont, M.R., Savic, D.A.: Comparison of multiple surrogates for 3D CFD model in tidal farm optimization. Procedia Eng. **154**, 1132–1139 (2016)
14. Mehmani, A.: Uncertainty-integrated surrogate modeling for complex system optimization. Ph.D. thesis, Syracuse University (2015)
15. Yang, X., Liu, BO., Cao, Z.: Opposition-based artificial bee colony algorithm application in optimization of axial compressor blade. In: Proceedings of ASME Turbo Expo, GT2013-95177 (2013)
16. Usatyi, O., Avdieieva, O., Maksiuta, D., Tuan, P.: Experience in applying DOE methods to create formal macromodels of characteristics of elements of the flowing part of steam turbines. In: AIP Conference Proceedings, vol. 2047, no. 1, p. 020025, (2018)
17. Kelin, A., Larin, O., Naryzhna, R., …Vodka, O., Shapovalova, M.: Mathematical modelling of residual lifetime of pumping units of electric power stations. Advances in intelligent systems and computing, 1113 AISC, pp. 271–288 (2020)
18. Boiko, A., Govorushchenko, Y.: Optimization of the Axial Turbines Flow Paths. Science Publishing Group, New York, NY 10018, U.S.A. (2016)
19. Boiko, A.V., Usaty, A.P., Avdieieva, O.P.: Methodology of the object-oriented complex optimization of the flow passes of powerful steam turbines taking into consideration the variable operation mode. NTU “KhPI” Bulletin: Series “Power and Heat Engineering Processes and Equipment”, vol. 13, pp. 5–10 (2014)
20. Avdieieva, O., Usatyi, O., Vodka, O.: Development of the typical design of the high-pressure stage of a steam turbine. In: Ivanov, V., Pavlenko, I., Liaposhchenko, O., Machado, J., Edl, M. (eds.) Advances in Design, Simulation and Manufacturing III. DSMIE 2020. Lecture Notes in Mechanical Engineering. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-50491-5_26