7

Experience and Examples of Optimization of Axial Turbines Flow Paths

In this chapter, as an example of practical use of the developed theory of optimal design of axial turbines flow paths, the results of the studies, related to the optimization of parameters of flow path of the high pressure cylinders (HPC) of 220, 330 and 540 MW capacities turbines, operating at nominal mode, as well as examples of optimization turbo-expander and low pressure turbine of gas turbine unit, taking into account the mode of its operation, are presented. The entire complex of calculation research was conducted using mathematical models of flow path (FP) of axial turbines, described in Chapter 2.

In addition, in the studies variants of mathematical models of FP "with the specified profiles" [38] were also used, which allowed with more accuracy determine geometric characteristics of turbine cascades, in particular, the inlet geometric angles of working and nozzle cascades, that are changing with the changing of stagger angles of the profiles. The latter had a significant impact on the amount of additional losses related to the incidence angle of inlet flow of working fluid.

7.1 Multi-Criterion Optimization of HPC of Powerful Steam Turbines at Nominal Operational Mode

7.1.1 A Preliminary Study of Influence of Quality Criteria Weights Coefficients on the Optimization Results

Practice of the optimal design of axial turbines cylinders has showed that when optimizing steam turbine cylinder with extraction of working fluid for regeneration and heat supplying at least two criteria – the efficiency of the cylinder flow path and its capacity must be taking into account [38, 40-42].

Using the convolution of quality criteria in accordance with (1.37) allows efficiently solve the multi-criterion optimization problems corresponding the Pareto front.

As an example of the effectiveness of the use of convolution (1.37) the results of the optimization of HPC FP of a powerful steam turbine by two criteria - power and cylinder efficiency for different values of the weight coefficients μ_i are presented in Table 7.1 and Fig. 7.1.

Table 7.1 *Optimization results with different weight coefficients of the optimization criteria for power (μ_N) and efficiency (μ_{η_d}).*

The optimization task number	μ_N	μ_{η_d}	***N*, MW**	η_d **, %**
1	0	1	124.398	82.49
2	0.2	0.8	124.981	82.23
3	0.4	0.6	125.844	81.77
4	0.5	0.5	126.436	81.07
5	0.6	0.4	126.804	80.15
6	0.8	0.2	127.173	78.50
7	1	0	127.288	77.82

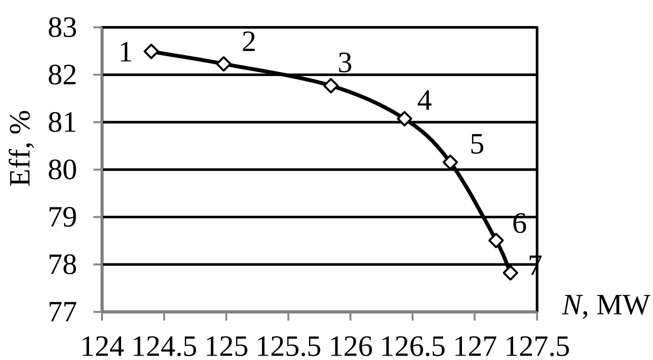


Figure 7.1 *Pareto front solutions of the optimization task with two criterions for HPC FP powerful steam turbine.*

Numbers on the curve corresponds to the numbers of optimization problem in the Table 7.1.

7.1.2 Optimization of HPC Parameters of the 220 MW Capacity Turbine for Nuclear Power Plant

The number of optimization parameters – 33:

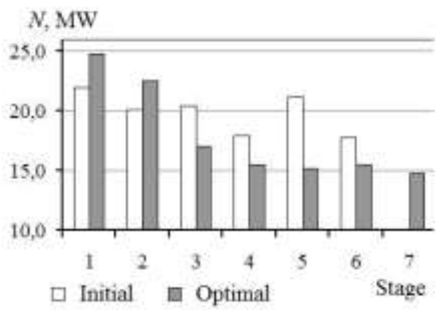
- level 1 (cylinder) - optimized for 19 parameters:
  - Root diameter and height of the nozzle blades of the first stage of the cylinder.
  - Meridional disclosing of the channels of the nozzle and working cascades.
  - Effective exit angles of the nozzle and working cascades of all turbine stages.
- 2-nd level (stage) - optimized for 14 parameters:
  - The number of the blades in the nozzle cascades for all turbine stages.
  - The number of the blades in the working cascades for all turbine stages.

Quality criteria applied when optimizing – the criterion vector that inclu-des the normalized values of internal relative efficiency of the cylinder (η_{oi}) and its power (N) with equal weight coefficients.

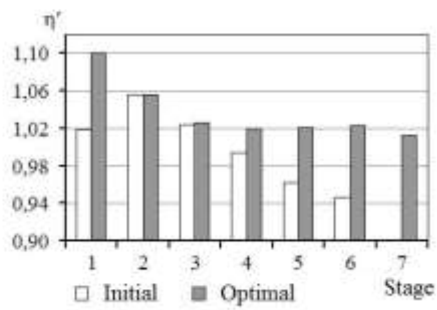
The results of the optimization of the HPC FP of the 220 Mw capacity turbine [39] are listed in Table 7.2 and in Fig. 7.2, where η_d – Moliere diagram efficiency of FP; η' – the ratio of efficiency of the stages to Moliere diagram efficiency of the initial variant of the cylinder; η_{oi} – internal efficiency of FP; $\Delta\eta_{oi}$ – gain of the internal efficiency of the optimal FP; N – power; ΔN – the power gain of the optimal variant of the HPC FP.

Table 7.2 *The integral indicators of initial and optimal variants of FP.*

Variant of HPC FP	η_d	η_{oi}	***N*, MW**	$\Delta\eta_{oi}$ **, %**	**Δ*N*, kW**
1 Initial, 6 st.	0.7836	0.7690	119.425	0	0
2 Optimal, 7 st.	0.8096	0.8011	125.375	3.21	5949.45
3 Final, 7 st.	0.8063	0.7961	124.824	2.71	5399.06



a



b

Figure 7.2 *A comparison of the power (a) and (b) efficiency of the initial and optimal variants of stages of HPC FP 220 MW capacity turbine.*

Improvement of the quality indicators of the optimized FP obtained through:

- rational distribution of the cylinder heat drop, having in its disposal, between the stages;
- some decreasing of the axial speed components and ensuring closer to axial outlet working fluid from the stages, resulting in reducing the exit velocity losses;
- reducing the incidence angles, that provides the improving efficiency of the nozzle and working cascades;
- increasing the mean diameter of the stages, that led to obtaining the optimal values of the ratio of the velocities (u/C_0);
- reducing the specific weight of the losses near the hub and the shroud boundaries by increasing the height of the blades;

- the optimal value of the nozzle and working cascades relative pitch, which also led to an increase of their effectiveness.

The final variant is obtained by optimization taking into account the technological restrictions on the production of the flow path parts. This explains the slight decreasing of efficiency and cylinder capacity compared to the best option without restrictions.

The optimal variant of HPC FP of the 220 MW capacity turbine for nuclear power plant is obtained, which characterized by high perfection levels of aerodynamic indices, providing a boost of power on 5.4 MW, of internal efficiency on 2.71% and Moliere diagram efficiency on 2.27% as compared to the initial version of FP.

7.1.3 Optimization of High-Pressure Cylinder Parameters of the 330 MW Capacity Turbine

The number of optimization parameters – 55:

- level 1 (cylinder)-optimized for 44 parameters:
  - Root diameter and height of the nozzle blades of the first stage of the cylinder.
  - Meridional disclosing of the channels of the nozzle and working cascades.
  - Effective exit angles of the nozzle and working cascades of all turbine stages.
- 2-nd level (stage)-optimized for 11 parameters:
  - The number of the blades in the working cascades for all turbine stages.

Quality criteria applied when optimizing – the criterion vector that inclu-des the normalized values of Moliere diagram efficiency of the cylinder (η_d) and its power (N) with equal weight coefficients.

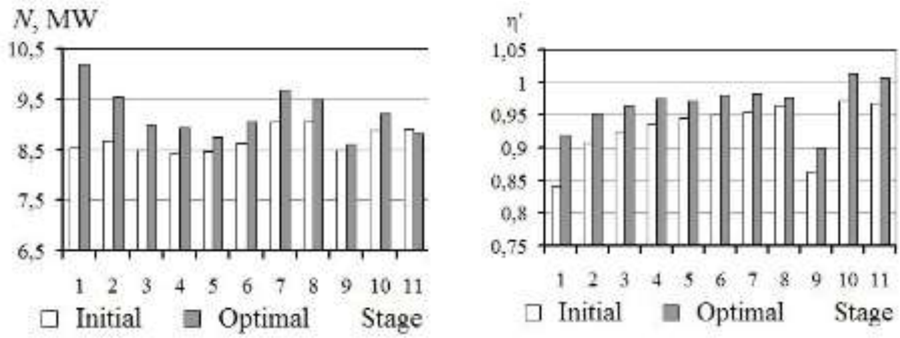
The results of the optimization of the HPC FP of the turbine 330 MW capacity turbine are listed in Table 7.3 and in Fig. 7.3, where η_d – Moliere diagram efficiency of FP; η' – the ratio of efficiency of the stages to Moliere diagram efficiency of the initial variant of the cylinder; η_{oi} – internal efficiency of FP; $\Delta\eta_{oi}$ – gain of the internal efficiency of the optimal FP; N – power; ΔN – the power gain of the optimal variant of the HPC FP.

Table 7.3 *Integral indicators of initial and optimal variant of HPC FP.*

Variant of HPC FP	η_d	η_{oi}	***N*, MW**	$\Delta\eta_{oi}$ **, %**	**Δ*N*, kW**
Initial	0.8595	0.8119	95.573	0	0
Optimal	0.8989	0.8656	101.773	5.37	6200.0

Improvement of the quality indicators of the optimized FP obtained through:

- more rational distribution of the cylinder heat drop, having in its disposal, between the stages;
- application of the optimal configuration of meridional shape of FP with a slightly reduced heights blades;
- increasing value of the effective nozzle exit angles, providing the reduction of the incidence angles on the working cascades;
- improving the efficiency of working cascades through the optimal choice of stagger angles and numbers of the blades, resulting in a significant reduction of losses from the incidence angle;
- reducing the degree of reaction level of the stages and, as a consequence, reducing the losses from root and radial leakages.



a *b*

Figure 7.3 *Comparison of the power (a) and (b) efficiency of the stages of initial and optimal variants of HPC FP of the 330 MW capacity turbine.*

Practical application of the developed optimization theory provided the solution of the task: the optimum variant HPC PF of the 330 MW capacity turbine was obtained, which characterized by high perfection levels of aerodynamic indices, providing a boost of power on 6.2 MW, of the relative internal efficiency on 5.76% and Moliere diagram efficiency on 3.94% in comparison with the initial version of FP.

7.1.4 Optimization of the HPC Flow Path Parameters of the 540 MW Capacity Turbine

Features of the initial variant of the HPC FP:

- FP of the 9 stages HPC has high enough quality integral indicators, which have been achieved thanks to the very high level of aerodynamic perfection of the flow path of the cylinder:
  - numbers of the nozzle and working cascades blades are close to the optimal values;

- the inlet flow incidence angles at the nozzle and work cascades are close enough to the possible minimum values given used profiles and blades production technology;
- the root degrees of reaction provide fairly low levels of hub leakages;
- the use of highly effective radial seals has significantly reduced radial leakages.

However, in the construction of FP reserves of possible efficiency gains were identified associated with not quite rationally distribution of disposable heat drop between the cylinder stages and somewhat inflated level of root leakages in first stage.

The number of optimization parameters of HPC FP of the turbine 540 MW capacity – 55:

- level 1 (cylinder) - optimized for 37 parameters:
  - Root diameter and height of the nozzle blades of the first stage of the cylinder.
  - Meridional disclosing of the channels of the nozzle and working cascades.
  - Effective exit angles of the nozzle and working cascades of all turbine stages.

Due to the fact that in the initial variant of the HPC FP number of the nozzle and working cascades blades near by the optimal values, the second level of optimization (stage) was not used in this task.

Quality criteria applied when optimizing – the criterion vector that includes the normalized values of Moliere diagram efficiency of the cylinder (η_d) and its power (N) with equal weight coefficients. The results of the optimization of the HPC FP of the turbine 540 MW capacity are listed in Fig. 7.4, where N – power and η′ – the ratio of efficiency of the stages to Moliere diagram efficiency of the initial variant of the cylinder.

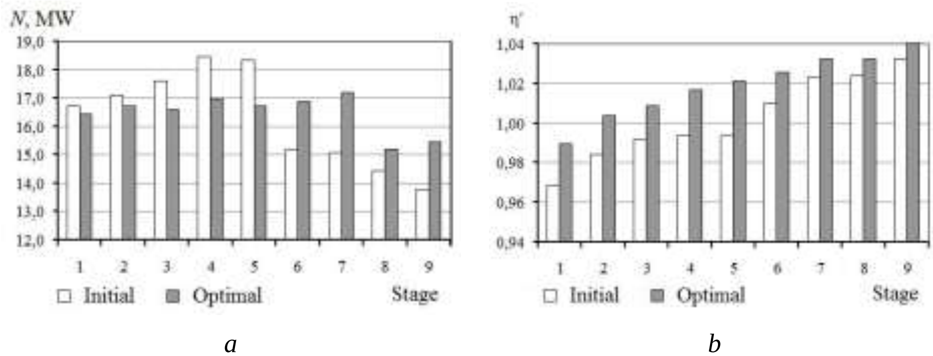


Figure 7.4 *Comparison of the power (a) and efficiency (b) of the stages of initial and optimal variants of HPC FP of the 540 MW capacity turbine.*

Improvement of the quality indicators of the optimized FP obtained through:

- a more rational distribution of the disposal cylinder heat drop, between the stages, thereby improving the integral indicators of the cylinder quality;
- some decrease of axial velocity component and ensuring closer to axial outlet of working fluid from the stages, that reduced the exit velocity losses, improving inlet conditions for nozzles cascades (which led to an improvement in their effectiveness);
- close to optimal values of velocities ratio (u/C_0), obtained by incre-asing the mean diameter of the stages;
- reduction in the share of the losses near the hub and the shroud boundaries associated with increasing the heights of the blades;
- using in 6–9 stages of the blades a highly effective *1MMC* profile (Chapter 5), which provided a good matching flow inlet angles and the

geometric inlet angles of the working cascades, that resulted in increasing their efficiency;

- obtaining the optimal twist laws of the β_{2e} angles at the outlet of the working wheels of 6–9 stages that contributed to the rational distribution of the gas-dynamic parameters along the radius of these stages.

So, the practical application of the developed optimization theory secured the solution of the requested task: the optimum variant of HPC FP of the 540 MW capacity turbine was obtained, which characterized by high perfection levels of aerodynamic indices, providing a boost of power on 1.4 MW, of inner efficiency on 1.52% and Moliere diagram efficiency on 1.63% in comparison with the initial version of FP.

7.2 Optimal Design of the Axial Turbines Flow Paths Taking into Consideration the Mode of Operation

For demonstration of opportunities of the developed complex of the methods, algorithms and mathematical models for solving the problems of optimal design of the turbine units taking onto account their mode of operation [38, 40–42] the results of optimization research of turbine expander flow path and of gas turbine unit GTU GT-750-6M low pressure turbine flow path are presented below.

7.2.1 Optimization of Rendering Turbine Expander Unit (RTEU) Flow Path of 4 MW Capacity With Rotary Nozzle Blades

In gas pipelines, natural gas is transported under the pressure 35–75 atmospheres. Before serving the natural gas to the consumer its pressure must be lowered to the level of pressures local supply systems. At the moment gas distribution stations widely are using technologies of utilization of natural gas let-down pressure before serving the consumer. To extract energy from compressed gas the special rendering turbine expander units (RTEU) are used in which the potential overpressure energy is converted into mechanical work of a rotor rotation of a turbine, which serves as generator drive.

Seasonal unevenness of natural gas consumption, usually caused by environmental temperature, leads to a deeply no projected RTEU operation modes and adversely affect their performance and service life. For example, the gas flow through the flow path of the RTEU during the year may vary in ranges from 0.25–0.35 to 1.05–1.25 from the rated value. The foregoing attests to the relevance and necessity of taking into account the factor variability of operation loads during the selection of the basic geometric parameters of the RTEU FP.

This section provides results of optimization of 4-stage flow path of existing design of RTEU taking into account real operation modes of it, using the developed algorithm [40].

Operating conditions of the considered RTEU are characterized by significant monthly uneven mass flow rate of the working fluid through the flow path of the unit with fixed heat drop and rotor speeds:

- full gas pressure at the inlet of FP .... $P_0^* = 1.2$ MPa;
- full gas temperature at the inlet of FP .... $t_0^* = 110\,°C$;
- static gas pressure at the outlet of FP .... $P_2 = 0.19$ MPa;
- the rotor turbine speed.. n = 8000 rpm.

The mass flow rate of natural gas, depending on the operating mode, changed in the range from 4.94 to 20.66 kg/s (the mass flow rate at the design mode is $G_{nom} = 16.66$ kg/s).

At present several ways to regulate the mass flow through the RTEU FP are known. The changing of the walk-through sections of nozzle cascade (NC), thanks to the use of rotary nozzle blades, is the most effective.

It is known that the implementation of the rotary nozzle blades can significantly extend the range of workloads of the turbine installation and improve performance indicators of FP. However, to get the maximum effect from the rotation of the nozzle blades, there is a need to further address the challenge of defining optimal angles α_{1e} for each stage, depending on the operating mode of the RTEU FP.

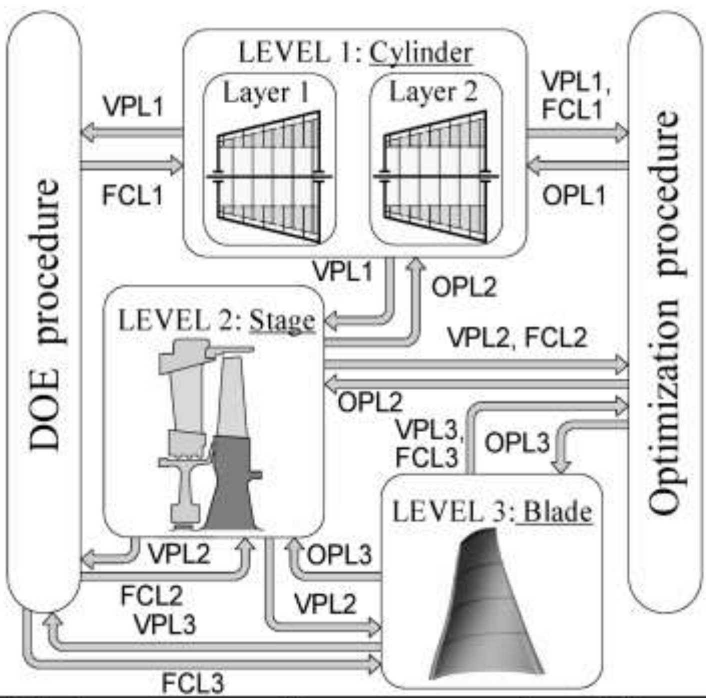
In accordance with the terms of the design, mass flow regulation of the working fluid through the flow path of the RTRU has been carried out by turning of the nozzle blades (changing the outlet angles α_{1e}) of all stages. Optimization was carried out taking into account the 12 operational modes of turbine expander (one month duration of each mode). The mass flows of natural gas through the FP for the specified modes are shown in the Table 7.4.

***Table 7.4** The natural gas mass flows through the RTEU FP for specified operational modes.*

#	1	2	3	4	5	6	7	8	9	10	11	12
G_0, kg/s	18.71	20.66	18.71	10.18	6.33	6.28	4.94	6.14	7.17	10.55	17.57	20.35

Two levels of recursive optimization algorithm (section 1.2.1) – "Cylinder" (Layer 1 and Layer 2) and "Stage" were involved in the optimization process. At the level of "Cylinder" recursive optimization algorithm is called on not only for "Stage" level but for Layer 1 and Layer 2. As can be seen from Fig. 7.5, at the top level "Cylinder" (Layer 1) the vector of varied parameters of created *FMM* has been generated from 16 parameters, one of which is operational mode (the mass flow at the cylinder inlet – G_0) and the remaining 15 are design parameters.

They included effective outlet flow angles from nozzle and blades (α_{1e}, β_{2e}), and average diameters and heights of the blade wheel cascades (D_2 and l_2). Mean diameters and heights of nozzle wheel cascades (D_1 and l_1) for each stage were determined based on values similar to the parameters of the blade wheel cascades taking into account recommendations about overlap size for each RTEU stage. At the below laying level "Stage" for each stage except the first the vector of varied parameters of *FMM* was formed of 9 parameters ($D_2, l_2, \alpha_1, \beta_2, u/C_0, z_{1,2}, b_{1,2}$). For the 1-st stage the dimension of *FMM* vector is equal 8 (angle α_1 isn't a member of *FMM* of the 1-st stage).



Level	VPL	OPL
Cylinder	$d_{1,2}; l_{1,2}; \alpha_1; \alpha_{0g}; \beta_2; \beta_{1g}; P_0; i_0; P_2; u/C_0$	$d_{1,2}; l_{1,2}; \alpha_1; \alpha_{0g}; \beta_2; \beta_{1g}$
Stage	$d_{1,2}; l_{1,2}; \alpha_1; \alpha_{0g}; \beta_2; \beta_{1g}; P_0; i_0; P_2; u/C_0; Z_{1,2}; b_{1,2}; m_{1,2}$	$Z_{1,2}; b_{1,2}; m_{1,2}$
Blade	$\alpha_1; \alpha_{0g}; \beta_2; \beta_{1g}; Z_{1,2}; b_{1,2}; m_{1,2}; r_1; \omega_{1,2}$	$r_1; \omega_{1,2}$

Figure 7.5 *The structure of optimal design technique.*

The sequence of the general optimization task solution looks as follows. Previously, using the DOE theory (paragraph 1.3) the *FMM*s of the level

"Stage" were created in the form of full quadratic polynomials (1.2). The *FMM* of the "Cylinder" level (Layer 1) was build next.

According to a design of experiment matrix from top level "Cylinder" to level "Stage" parametrical restrictions in the form of values $D_2, l_2, \alpha_{1e}, \beta_{2e}, u/C_0$ arrive. Concrete level of these parameters is defined by a current point of the plan of numerical experiment of level "Cylinder" (Layer 1). At level "Stage" taking into account the arrived parametrical restrictions local optimizing tasks by definition of optimal values of blades numbers ($z_{1,2}$) and chords values ($b_{1,2}$) of nozzle and blade wheel cascades of each stage are solved.

The received optimal values of these parameters are passed to the top level "Cylinder" (Layer 2) for calculation of the optimal angles α_{1e} along the FP depending on the mass flow of working fluid at the entrance to the turbine expander.

At the end of the optimization process under optimal values of "Cylinder"-level parameters, except values of chords and numbers of blades, inlet metal angles of nozzle and blade wheel cascades of each stage are specified. The values of the specified angles are defined taking into account a weight part of quality criterion of each operational mode.

As quality criterion for an estimation of the flow path efficiency at the level "Cylinder" the value equal to total work of the cylinder for a selected period of time one year (T)

$$U = \int_{t=0}^{t=T} N_{cyl}(t)\,dt\,, \tag{7.1}$$

defined according to the developed mathematical model (section 2.2.3), was used.

Given the assumption that the duration of the modes is the same, this criterion was reduced to the sum of the "regime" cylinder capacity ($\sum_{i=1}^{n} N_{cyl}^{i}$, where n is the number of modes). To assess the quality criterion at "Stage" level the internal relative efficiency of the corresponding stage was used.

Since this task was solved for the FP with standard type of the nozzles profiles H-2, changing the angle α_{1e} takes into account and corresponding changing of the inlet metal angle of the nozzle wheel cascade (α_{0g}). When calculating the losses, associated with incidence angles at the inlet of the cascade, the influence of the blade's inlet flow angle on the losses in accordance with experimental data was taken into account.

Inlet metal angles of the blade wheel cascade for each stage were determined by averaging their values across 12 modes of operations taking into account weight proportion of quality criterion of each mode.

The values of the "basic" design parameters, obtained by solving the general optimization task, are listed in the Table 7.5.

The received distributions of angles α_1 for each stage of the flow path as functions of mass flow change are presented in Fig. 7.6. Apparently from Fig. 7.6 optimal curves of angles differ greatly from the linear curve received at uniform simultaneous turn of nozzles.

***Table 7.5** Results of optimal design along stages of the turbine expander.*

Parameter	Stage number				Stage number			
	Prototype				Optimal design			
	1	2	3	4	1	2	3	4
D_1, m	0.48	0.48	0.48	0.48	0.481	0.483	0.489	0.498
D_2, m	0.48	0.48	0.48	0.48	0.482	0.484	0.49	0.499
l_1, m	0.0305	0.035	0.0425	0.051	0.029	0.036	0.045	0.056
l_2, m	0.031	0.0375	0.0465	0,056	0.032	0.039	0.049	0.06
β_2, degree	22	25.7	29.1	34	21.7	25.52	28.43	34.15
z_1	54	54	46	46	54	58	48	49
z_2	69	69	53	53	69	78	61	59
b_1, mm	35.099	35.099	42.118	42.118	35.345	35.257	42.034	42.761
b_2, mm	30.809	30.809	40.15	40.15	33.25	30.179	39.187	40.754
β_{1g}, degree	30.75	35.68	44.03	53.72	38.21	32.27	38.97	48.31

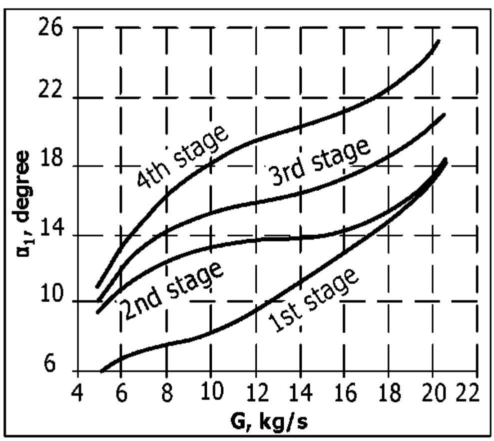


***Figure 7.6** Optimal distribution of angles α_1 along the flow path subject to mass flow.*

Efficiency of an initial design of the flow path with synchronous turn of all nozzles and efficiency of the design received as result of optimal design with the optimal law of angles α_1 change by operation modes are presented in Fig. 7.7. The efficiency of the received flow path essentially surpasses efficiency of initial flow path on all operation modes (Fig. 7.7). Significant improvements in efficiency has been observed in the low mass flow modes of operation (up to 5%), as well as to the modes of mass flow greater than 18 kg/s. Additional generation of electricity for operating cycle is equal to 914.793 MWh (3.64%).

It is obvious, that it is impossible to create the flow path equally well working in a range of loadings from 30 to 125% of the nominal. So the efficiency of any flow path on modes with low mass flows remains at low enough level due to the great values of incidence angles, negative degrees of reaction, a substantial redistribution of disposable heat drop, offset u/C_0 of the stages aside from optimal values.

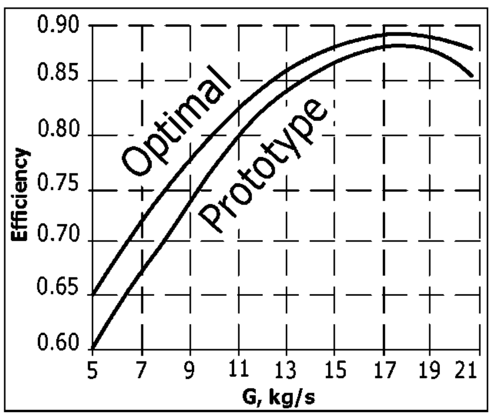


Figure 7.7 *Efficiencies of turbine expanders.*

The gain of optimal variant, in comparison with initial variant of design, on modes with low mass flows is provided by selection of optimal angles α_1 for all nozzle cascades along the flow path. As can be seen from Fig. 7.6 for optimal variant of RTEU FP, when small mass flow rate, value of the 1-st stage angle α_{1e} significantly lower compared to the values of the same angles of subsequent stages, that increases its heat drop and value of output velocity from the nozzle cascade (velocity c_1 close to the speed of sound M_{c_1} = 0.997).

Despite some deterioration in the effectiveness of 1-st stage, this solution allowed unload the subsequent stages and significantly improve their work conditions (positive degree of reaction on the mean radius of the second and third stages has been achieved) and get a positive final outcome.

On operation modes with the mass flow close to or surpassing on-design, increase of efficiency of the flow path became possible due to selection of an optimal combination of "base" design parameters ($D_{1,2}, l_{1,2}, \beta_{1g}, \beta_{2e}, z_{1,2}, b_{1,2}$) for each stage. This helped to reduce the losses associated with the inlet of the working fluid on the cascades and exit velocity losses, as well as to improve the efficiency of the nozzle and blade wheel cascades. Also on the considered operation modes there is a redistribution of heat drops between the stages: reducing load of 1-st and 4-th stages and increasing load of 2-nd and 3-rd.

7.2.2 Optimal Design of Gas Turbine Flow Path Considering Operational Modes

In the current section the example of applying developed methods and algorithms for the solution of the problem of optimization of gas turbine flow path taking into account the modes of operations is given. As the object of study the gas turbine installation GT-750-6M was chosen [40]. This *GTU* is used at the compressor station as a driver of gas-compressor unit. Selection of the specified unit is linked to the fact that such installations are quite widespread in the gas transportation system of Ukraine and more than 80% of them exhausted its resource.

In addition, the authors had at their disposal all the necessary project documentation and the results of the field tests of the manufacturer that was the necessary condition for optimization and the validation of the computational research results.

Optimization of FP of the low-pressure turbine installation GT-750M was carried out taking into account the actual operating loads and the inclusion in consideration of the thermal scheme (TS) of installation.

A direct one-dimensional flow model through the axial turbines FP (section 2.2.3) and the procedure of thermal schemes calculation of *GTU* (section 2.5) were involved in this case. A screenshot of a window of the specialized CAD system with active project of GT-750M installation is presented at Fig. 7.8. One-dimensional mathematical model of the turbine stages group is used in the process of solving common optimization tasks and to build the universal characteristics of the gas turbines, and the model of thermodynamic processes in thermal schemes of *GTU* – for thermodynamic calculation of the unit's thermal cycle (TC) for real operating modes.

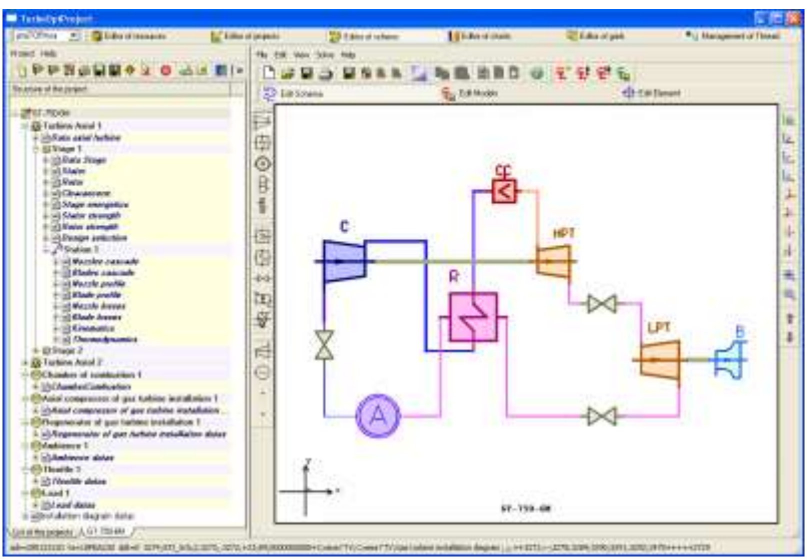


Figure 7.8 *Project of GT-750M installation in a specialized CAD system environment.*

Thermal cycle scheme consists of the following main elements: compressor (C); combustion chamber (CC); high pressure turbine (HPT), located on the same shaft with compressor; free power turbine low pressure (LPT); regenerator (R); external consumer of net power – natural gas blower (B).

As can be seen from Fig. 7.8, GT-750-6M is a split-shaft gas turbine unit with waste-heat recovery.

Such a scheme, thanks to good surging characteristics, is more flexible, reliable and cost-effective in terms of variable operating mode and can be equally well applied for driving propeller, for ground transportation, for blast furnace production etc. When operating on the gas pipeline such a gas turbine unit can provide any mode of operation of the gas pipeline without throttling at the suction and without pressure lowering of the blower.

For operation modeling of the compressor and turbine, while calculating on the various modes the universal characteristics were used. Moreover, the characteristic of the compressor was built according to the manufacturer's data but turbines characteristics were obtained using specialized CAD system.

Fields on the characteristics of high and low pressure turbines covering ranges of operating modes of FP, obtained by calculating the GT-750-6M unit thermal scheme for one calendar year of real modes of operation.

Calculations have showed that area of the work of the HPT FP is close to the on-design regime, but LPT works in more wide range of operating modes.

The problem of flow path geometrical parameter multi-mode optimization with consideration of the thermal scheme of the unit is difficult and extremely labor-intensive. At present, in the available literature, recommendations and examples of the solution of optimization problems in similar papers are practically not existent. Considering the above, for the purpose of the development of approaches to finding solutions to specified problems, preliminary research directed at the consideration of the influence of the efficiency of high and low pressure flow paths of GT-750-6M on its integral characteristics (fuel consumption, *GTU* efficiency, cycle initial parameters, etc.) have been carried out.

The increase of the efficiency of gas turbines flow paths is one of the preferable methods of increasing GTU efficiency and useful power. However, as studies have shown, in some cases the increase of the efficiency of gas turbine separately used in the thermal scheme within modernization does not produce the expected effect. It is connected with features of the configuration of turbines within GTU, and also with the interaction of turbines with other elements of the thermal scheme. The influence of gas turbines flow paths efficiency on GTU performance parameters using a GT-750-6M unit (Fig. 7.8) is considered as an example.

Increasing the efficiency of HPT

As can be seen from Fig. 7.8, HPT is located on the same shaft as the axial compressor and provides its work. The mass flow rate, temperature and pressure of combustion products behind HPT must be in strict conformity with the values necessary for generation by LPT power, set by the external consumer (the natural gas blower) in the current operation mode. An increase of HPT efficiency in the specified operating conditions of the turbine does not lead to the predicted improvement of the performance parameters of the turbine unit. For example, when saving the unit operation mode (useful power, the power turbine rotor speed and the air parameters), the increase of HPT efficiency leads to an increase of its power. The additional power of HPT is transmitted through the shaft to the axial compressor, which leads to the redistribution of the main parameters of the gas-turbine cycle, namely:

- the increase of power for compressor drive causes an increase in compressor rotor speed, which causes an increase of the air flow rate and a slight increase of the compression ratio (compressor efficiency decreases because of the displacement of the compressor and HPT joint operation line takes place);

- the new air flow rate and pressure at the compressor outlet are superfluous for this thermal cycle and cause a fall in combustion products at the combustion chamber outlet, which inevitably leads to a decrease in cycle thermodynamic efficiency.

The specified changes in the unit's thermal scheme nullify the effect expected from HPT flow path optimization.

Increasing the efficiency of LPT

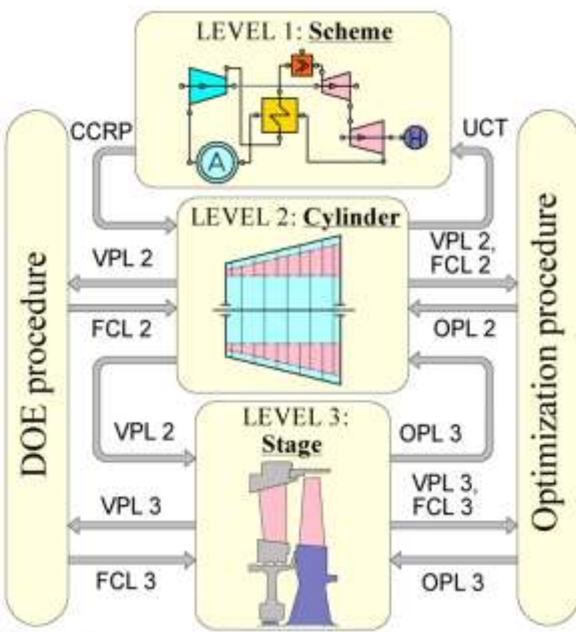
The calculations show that the increase of LPT efficiency has a favorable effect on the performance parameters of the GT-750-6M and allows getting increase the net power while maintaining fuel consumption or fuel economy while maintaining power, given to the external consumer. Considerable deviations of the gas-turbine cycle parameters from design are not observed in this case.

Thus, an increase in the efficiency of LPT flow path is the most rational variant of the GT-750-6M unit modernization. The specified modernization does not lead to an essential redistribution of the parameters of the gas-turbine cycle and therefore does not touch the expensive elements of the unit such as the compressor, combustor, regenerator and supercharger.

It is worth to note that these studies were carried out for the GT-750-6M unit but research results and conclusions are valid for all *GTUs* with a similar thermal scheme.

For the optimization of geometrical parameters of GT-750-6M LPT flow path, taking into account the actual modes of operation, three upper levels of developed recursive algorithm optimization, described in Chapter 1, were involved. The distribution of the tasks and interaction between the local design levels are depicted in Fig. 7.9.

The highest level in the hierarchy of the design process "Scheme" is intended to calculate the distributions of parameters of GTU cycle (pressure, temperature, capacity, and cost) between elements in the scheme, as well as to determine the integral indicators of the unit at the off-design operation modes. As can be seen from Fig. 7.9, from the level "Scheme" to the level "Cylinder" the sets of mode parameters come that uniquely identify modes of the FP operation (consumption of combustion products at the entrance to the FP – G_0, full gas pressure at the inlet of FP – P_0^*, full gas temperature at the inlet to FP – T_0^*, full gas pressure at the outlet of the FP – P_2^*, turbine shaft speed – n).



Level	VPL	OPL
Cylinder	$d_{1,2}; l_{1,2}; \alpha_1; \alpha_{0g}; \beta_2; \beta_{1g}; P_0^*; h_0^*;$ $P_2; P_2^*; G_0; n; u/C_0$	$d_{1,2}; l_{1,2}; \alpha_1; \alpha_{0g}; \beta_2; \beta_{1g}$
Stage	$d_{1,2}; l_{1,2}; \alpha_1; \alpha_{0g}; \beta_2; \beta_{1g}; P_0^*; h_0^*;$ $P_2; u/C_0; n; Z_{1,2}; b_{1,2}; m_{1,2}$	$Z_{1,2}; b_{1,2}; m_{1,2}$

Figure 7.9 *The structure of optimal design technique.*

At the "Cylinder" level optimal values of basic geometrical parameters such as mean diameters of the nozzle and blade wheel cascades (D_1, D_2), the heights of the nozzles and the blades (l_1, l_2), inlet/outlet flow angles in both absolute and relative motions for nozzle and blades wheel cascades ($\alpha_1, \alpha_{0g}, \beta_2, \beta_{1g}$) were defined.

As a functional limitation at the level of "Cylinder" the flow rate of combustion products at the entrance to the LPT was chosen, that should match to the flow rate through the initial FP of the unit. For assessing the quality criterion in the process of optimization the value equal to the total work of the gas turbine (GT) for one year of operation was used.

At the next level "Stage" the optimal values of the numbers of the nozzle and rotor blades (z_1, z_2) for their cascades were found, and optimized parameters on the "Cylinder" level were used as parametric constraints. Quality criterion is the internal efficiency of the stage.

A thermodynamic calculation of the *GTU* schemes procedure (section 2.5) is used as the mathematical model at the "Scheme" level. At the "Cylinder" and "Stage" levels a procedure for direct one-dimensional calculation of the axial turbines FP (section 2.2.3) is applied. When the optimal solution at the level of "Cylinder" was found, using direct one-dimensional model of FP, the universal characteristics of well-designed LPT are build. These characteristics are returning to the "Scheme" level for calculation of integral characteristics of the *GTU*.

Three iterations for refining the optimal solution were conducted during computation. The optimization task was solved taking into account 177 real operation modes of the *GTU*. Each mode corresponds to unit operation for 24 hours. Unit loading for the considered period varied in a range from 52 to 73% of the on-design mode, equal to 6 MW.

The calculations has shown that in the on-design operation mode of the *GTU* the gain of *LPT* useful capacity, without mass flow rate increase, was 1.5% (93.1 kW). Efficiency increase after optimization is caused by a decrease in the losses in nozzle and rotor cascades, exit energy losses, and a reduction of leakages in radial clearance. Therefore, in the on-design mode the velocity coefficient for nozzle and rotor cascades of an optimal flow path increased by 0.4 and 0.6% respectively, the absolute velocity downstream rotor (c_2) decreased by 22%, and the leakage in radial clearance decreased by 2.7%. There was an increase of heat drop for nozzle cascades and a decrease of heat drop for rotor cascades (reaction decreased from 0.478 to 0.368). When the optimal design of the turbine works within the thermal scheme of the studied unit, the reduced value of velocity c_2 leads to a corresponding decrease of total pressure losses in the exhaust diffuser.

The optimum values of variable parameters, obtained through the optimization, are shown in the Table 7.6.

Table 7.6 *Results of optimal design of the GT-750-6M high pressure turbine.*

Parameter	**Initial design**	**Optimal design**
1. Nozzle mean diameter – D_1, m	0.970	1.046
2. Blade wheel mean diameter – D_2, m	0.972	1.050
3. Nozzle blade height – l_1, m	0.210	0.203
4. Working blade height – l_2, m	0.211	0.222
5. Inlet metal angle of nozzle cascade – α_{0g}, deg	90.00	94.54
6. Inlet metal angle of blade wheel cascade – β_{1g}, deg	47.33	47.93
7. Outlet effective angle of nozzle cascade – α_1, deg	20.67	19.00
8. Outlet effective angle of blade wheel cascade – β_2, deg	25.18	24.12
9. Number nozzle blades – z_1, pcs	48	41
10. Number rotor blades – z_2, pcs	60	70

As the result of the optimization the efficiency increment depending on the operation mode of *GTU* is from 0.09 to 0.27%. The fuel economy (of natural gas) for *GTU* with optimal *LPT* flow path depending on operation modes is given in Fig. 7.10. The total fuel economy for the considered period of 177 days amounted to 50831 kg.

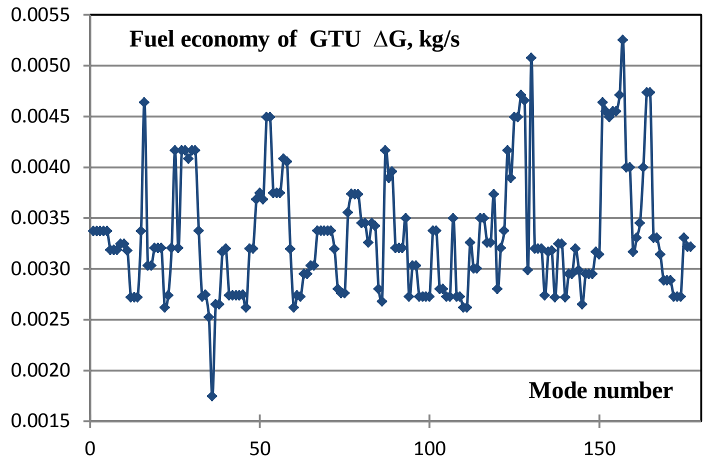


Figure 7.10 *Fuel economy for the GT-750-6M with optimal LPT by operation modes.*

Before performing the work of such complexity, as the above examples of optimal design of multi-stage cylinders, the authors made a huge amount of the work related to the verification of the developed and implemented mathematical models as well as proposed methods of optimization.

It should be emphasized that the criteria of the calculation results is an experiment. Full-scale experimental investigation of powerful turbines is very expensive. However, at one of the thermal power plants the test of turbine 200 MW capacity was conducted in a wide range of operational modes.

Comparison of results of the calculation research of the HPC FP turbines with experimental data obtained as a result of field tests of the same turbine in a wide range of operating modes, have strongly affirmed that used in optimization designed and implemented mathematical models have high accuracy and adequately simulate physical processes of flow of the working fluid in axial turbine flow path.

According to the results of the conducted studies one important conclusion can be formulated.

The further improvement of the indicators level of the quality of existing and newly designed advanced multi-stage axial turbine installations is possible only using the most modern methods and software systems, capable of solving tasks of a multilevel object-oriented multi-criterion and multi-parameter optimization of the flow paths of axial turbines, taking into account their operational mode.