OPTIMAL DESIGN OF TURBINES TAKING INTO CONSIDERATION THE MODE OF OPERATION

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ABSTRACT

The technique of turbines parameters optimization taking into consideration a variable mode of their operation has been developed. Block-hierarchical representation of design process is used. The hierarchy of local optimization problems is organized by a functional sign and realized in a common information space. The structure of optimization technique is shown, and also the analysis of the data streams uniting these problems in unified process of optimal design is resulted.

By means of the developed technique optimal design of the 4-stage turbine expander with rated power 4 MW has been performed. Results of the design are presented and analyzed.

NOMENCLATURE

Symbols

A - matrix of formal macromodel coefficients
b - blade chord
C_0 - velocity equivalent to heat drop
d - mean diameter
G - mass flow rate
i - enthalpy
l - blade height
m - exponent defining the cascade twist law
n - modes number, factors number of formal macromodel
N_V, N_X - domain boundaries of restrictions existence
Nc, Nr - numbers of design and regime parameters
P - power
p - pressure
$\vec{q}$ - normalized vector $\vec{x}$
r - radius of profile edge
t - time
T - temperature; period of time
u - tangential velocity
u/C_0 - velocity ratio
$\vec{v}$ - vector of functional restrictions
V, X - domains of functional and design restrictions existence
$\vec{x}$ - vector of varied parameters of formal macromodel
Y - response function
Z - blade number
α_{og} - inlet metal angle of nozzle cascade
α_1 - outlet effective angle of nozzle cascade
β_{1g} - inlet metal angle of blade wheel cascade
β_2 - outlet effective angle of blade wheel cascade
ω - wedge angle of profile edge

Indices

0, 2 - inlet and outlet state variables
1, 2 - nozzle or blade wheel; leading or trailing edges
c - constructive
cyl - cylinder
i, j, k, m - integer values for indexation
nom - parameter value at nominal mode
opt - optimal
r - regime

Abbreviations

CAD - computer-aided design
CIS - common information space
DOE - design of experiment
FCLi - formal macromodel coefficients of i-th level
FMM - formal macromodel
OPLi - optimal values of i-th level parameters
RTEU - rendering turbine expander units
OMM - original mathematical model
VPLi - varied parameters of i-th level

INTRODUCTION

The methodology of the majority of modern algorithms of turbines optimal design is based on a principle of constancy of operational loading. Such methods were described by Boiko et al., 2002, Hongde et al., 2007, Kawagishi et al., 2005 and Prado et al., 2005. The parameters that determine an expected level of loading in such algorithms are initially set and play a role of parametrical restrictions during optimization. Variants of flow paths obtained with their help rather effectively work on design nominal modes.

At the same time there is a whole class of turbines, which loadings vary in wide ranges while exploitation, essentially deviating from a design mode that results in appreciable reduction of their integral efficiency. So, for example, power turbines of gas-compressor units within a year often operate in ranges of capacity change from 0,5÷0,6 to 1,05÷1,1 a design mode. The gas mass flow rate through RTEU of the gas-distributing point can vary in ranges from 0,25÷0,35 to 1,05÷1,25 from the nominal mode for the similar period. Ranges of operation modes of steam turbines of power plant are not so wide but they can lead to essential economic losses taking into account absolute levels of their capacities, even insignificant deviations of operation modes from designing modes. The above-stated denotes an urgency and necessity of development of optimization technique and algorithms that are able to consider design stages influence of the probable schedule of operational loading change on totals of turbines efficiency (Boiko et al., 2002, Demeulenaere, 2004). Use of such approach to optimal designing of flow path will allow detecting new reserves of efficiency rise both again created and modernized designs of turbines.

In this paper the technique of the turbines optimal design, taking into consideration the factor of regime parameters changeability while in service is given. During its development the principle of block-hierarchical representation of engineering process (Boiko et al., 2002, Usaty, 1988, Hongde et al., 2007 and Prado et al., 2005) was used, allowing the general optimization problem to reduce to several simpler one. In addition, for optimization of turbines in which rotary nozzle blades design are applied, the parallel computing layer providing definition of optimal laws of stage angles α_1 change as function of level of operational load is entered. Processes of interaction and the information coordination between the local hierarchically-subordinated optimization problems and problems from the parallel computing layer are realized in common information space of CAD "Turboaggregate" (Boiko et al., 2007), that essentially increases efficiency of the general optimization problem solution for a maximum of global objective function achievement.

The number of optimized parameters is about 10n, where n is number of turbine stages. The structure of optimization algorithm and the analysis of information streams between levels and layers of design process are shown. The quality criteria substantiation for local and global optimization tasks is considered.

As an example of the developed technique use the results of the 4-stage RTEU with rated power 4 MW optimal design are presented. The given rendering plant is intended for reduction of natural gas parameters before distribution between consumers. Conditions of operation are characterized by essential monthly non-uniformity of the working fluid mass- flow through a flow path from 50 up to 125 % of rating value with changing pressure upstream plant input.

Comparative numerical investigations have shown, that the turboset design obtained which use the developed optimization technique provides an increase of produced capacity and efficiency (from 0,5 up to 5 %) in the whole range of the mass flow rate change due to an optimal combination of 38 design data.

DESCRIPTION OF OPTIMIZATION TECHNIQUE

Features of consideration of operational load variability

Tasks of optimal design of turbines flow path taking into account operation mode concern to difficult multiparameter and multicriterion tasks. The solution of such tasks with use of an offered technique demands transition from "standard" statement of the optimal design task (the task of conditional global optimization in the presence of restrictions and inequalities) a form (1) to task, allowing consideration the influence of the regime parameters curve (2):

$$\begin{matrix} \vec{Y}^{opt}\left(\vec{x}_c^{opt}\right) = \max \vec{Y}\left(\vec{x}_c\right), \quad \vec{x}_c \in X, \quad \vec{v}(\vec{x}_c) \in V \\ 0 \le |X| \le N_X < \infty, \quad 0 \le |V| \le N_V < \infty \end{matrix} ; \tag{1}$$

$$\begin{matrix} \vec{Y}^{opt}\left(\vec{x}_c, \vec{x}_r = \vec{f}(t)\right) = \max\left(\int_0^T \left(\vec{Y}\left(\vec{x}_c, \vec{x}_r = \vec{f}(t)\right)\right) dt\right), \quad \vec{x}_c \in X, \quad \vec{v}(\vec{x}_c) \in V \\ 0 \le |X| \le N_X < \infty, \quad 0 \le |V| \le N_V < \infty \end{matrix} , \tag{2}$$

where, $\vec{x}_r = \vec{f}(t)$ – a vector of functions of regime parameters change during time.

It should be noted that target functions from $\vec{Y}$, vectors of regime $\vec{x}_r$ and design parameters $\vec{x}_c$ are different for each design level. Distribution of varied parameters on design levels is shown on Fig. 1 (parameters p_0, i_0, p_2, U/C_0, G_0 of them are regime, other parameters - constructive). As target functions at 1st level various parameters can be used, such as power, specific work or efficiency of the cylinder. At 2nd level – stage efficiency, on 3rd – quality criterion of a profile.

For increasing of computing efficiency in algorithms of search optimization replacement of the mathematical models based on laws describing the real physical phenomena and processes in turbine flow path and named original mathematical model (OMM) by their approximated dependences – formal macromodel (FMM) is carried out. For creation FMM of quality criteria and functional restrictions the methods of the DOE theory are used. Application of three-level plans proposed by Box and Behnken, 1960, and saturated plans proposed by Rechtschaffner, 1967, when planning of numerical experiments with OMM allows receiving of FMM in the form of the full square-law polynomial providing exact enough description of response function in chosen hypercube:

$$Y(q) = A_0 + \sum_{i=1}^{n} A_i q_i + \sum_{i=1}^{n} A_{ii} q_i^2 + \sum_{i=1}^{n} \sum_{j=i+1}^{n} A_{ij} q_i q_j . \tag{3}$$

At that, ranges of change of regime parameters select according to supposed (probable) schedule of their change and remain constants in the process of iterations by more precise definition of optimal solution. Ranges of change of constructive components of vector FMM are narrowed in the process of specifying iterations.

Thus, as a result of the planned experiment processing FMM of quality criteria and functional restrictions of a form (3), as functions of geometrical and regime parameters are created.

The account of influence of regime parameters curves on quality criterion of a flow path is reached by integration of FMM, i.e. new FMM coefficients of integrated quality criterion turn out from the following dependence:

$$\begin{aligned} Y(q) = {} & A_0 + \sum_{i=1}^{Nc} A_i q_i + \sum_{j=1}^{Nr} A_j \int_0^1 q_i(t)\,dt + \sum_{i=1}^{Nc-1} \sum_{k=i+1}^{Nc} A_{ik} q_i q_k + \sum_{j=1}^{Nr-1} \sum_{m=j+1}^{Nr} A_{jm} \int_0^1 q_i(t) q_m(t)\,dt + \\ & \sum_{i=1}^{Nc} \sum_{j=1}^{Nr} A_{ij} q_i \int_0^1 q_i(t)\,dt + \sum_{i=1}^{Nc} A_{ij} q_i^2 + \sum_{j=1}^{Nr} A_{jj} \int_0^1 q^2(t)\,dt . \end{aligned} \tag{4}$$

The formal macromodel of a form (4) includes integrals from regime parameters which can be calculated, knowing regime parameters curves ($q_i(t)$) and to transform it to next form:

$$Y_m(q) = A_{0r} + \sum_{i=1}^{Nc}\left(A_{ir}q_i + A_{ii}q_i^2\right) + \sum_{i=1}^{Nc-1}\sum_{k=i+1}^{Nc} A_{ik}q_i q_k\ , \tag{5}$$

where

$$A_{0r} = A_0 + \sum_{j=1}^{Nr}\left(A\int_0^1 q_i(t)\,dt + A_{jj}\int_0^1 q_j^2(t)\,dt\right) + \sum_{j=1}^{Nr-1}\sum_{m=j+1}^{Nr} A_{jm}\int_0^1 q_j(t)\,q_m(t)\,dt\ ; \tag{6}$$

$$A_{ir} = A_i + \sum_{j=1}^{Nr} A_{ij}\int_0^1 q_i(t)\,dt\ . \tag{7}$$

The FMM of a form (5) depends only on geometrical parameters (regime parameters are included integrally into new FMM coefficients) and can be used for an estimation of quality criterion in algorithm of optimal design of turbine flow path working on a variable mode.

Use of DOE theory in optimization technique

Now DOE methods are widely used in optimization algorithms (Kawagishi et al., 2005, Prado et al., 2005). Search of the optimal solution is carried out not on detailed mathematical model, but on its approximation dependence in the form of a full square-law polynomial (3). For creation of formal macromodels (FMM) values of components of vectors of observations are preliminary calculated on original mathematical models (OMM) according to the experiment plan. Each point of the plan represents a corresponding combination of design and regime parameters. Processing of vectors of supervision according to DOE allows creating FMM of criterion functions and functional restrictions.

Naturally in algorithms of search optimization it is possible to use OMM, however, as test rated researches have shown, use of FMM allows reducing time of search of optimal solutions approximately by two orders.

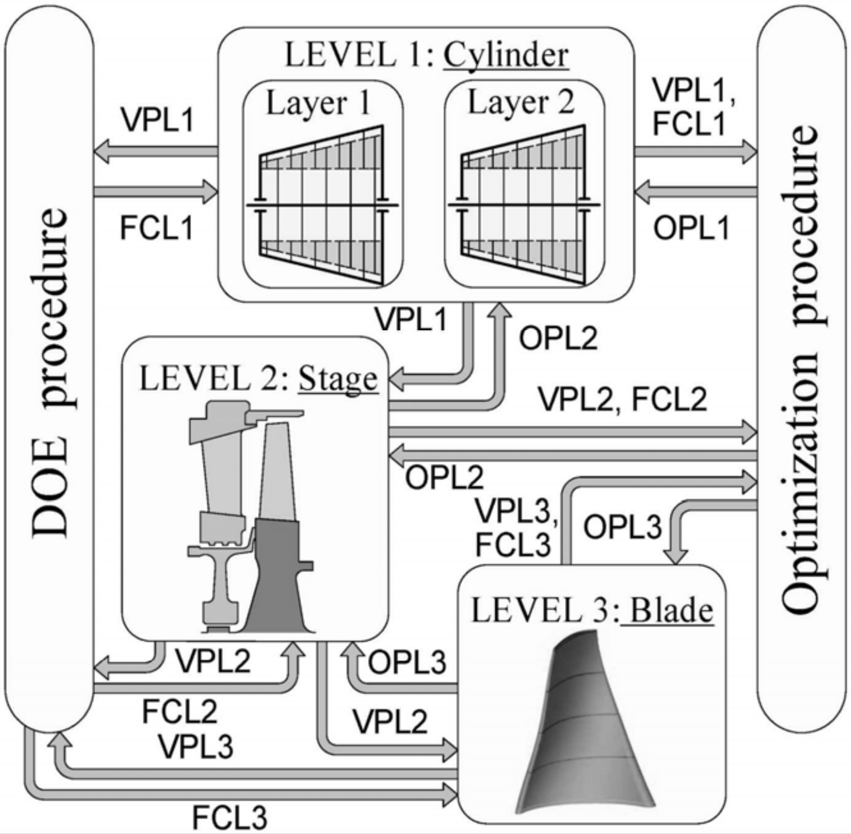
Description of optimal design technique

Process of optimal design was realized with use of recursive traversing of optimization levels (Fig. 1). Thus, at each recursion level are created corresponding FMM of criterion functions and functional restrictions by means of DOE methods. Recursion process is organized so, that the state of design parameters vector of higher level design object in each point of numerical experiment of this level depends not only on values of component of its FMM vector, but also on results of the solution of optimization tasks of below laying level. Thus, during transfer downwards on hierarchy, the information generated by means of DOE methods is used, and during transfer upwards on hierarchy – the information that was received as a result of the solution of local optimization tasks for slave nodes of the turbine flow path. Therefore, created at each higher level FMM of criterion function includes the best solutions of all below laying levels.

The layer 1 at 1st level of the solution of the general optimal design task (Fig. 1) allows determining optimal values of "base" design parameters of a flow path, and a layer 2 is used for definition of optimal schedules of "regime" design parameters change in their presence. So called "regime" design parameters of flow path are the parameters which values changes from mode to mode while in service, for example, angles α_1 in the presence of rotary nozzle blades of all stages along the flow path.

Level 3 (Fig. 1) is available during using two-dimensional mathematical model, it is intended for design of profiles of the optimal aerodynamic form along the blade height. For the purpose of increase of computing efficiency in a task of multimode optimization according to Boiko et al., 2002, the geometrical quality criterion of a profile smoothness of (as alternative aerodynamic) is used. Profiling is carried out with the account of strength and technological restrictions.

Ranges of change of design parameters are defined relative to values received as a result of preliminary designing or relative to geometrical parameters of a prototype (if the problem of modernization of the existing unit is posed).



Level	VPL	OPL
Cylinder	$d_{1,2}$; $l_{1,2}$; α_1; α_{0g}; β_2; β_{1g}; p_0; i_0; p_2; G_0; u/C_0	$d_{1,2}$; $l_{1,2}$; α_1; α_{0g}; β_2; β_{1g}
Stage	$d_{1,2}$; $l_{1,2}$; α_1; α_{0g}; β_2; β_{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	α_1; α_{0g}; β_2; β_{1g}; $Z_{1,2}$; $b_{1,2}$; $m_{1,2}$; r_1; $\omega_{1,2}$	r_1; $\omega_{1,2}$

Fig. 1: The structure of optimal design technique

Algorithms of search optimization

In the developed technique of turbines optimal design taking into consideration variability of operation modes during solution local and global optimization tasks the points of Sobol sequences (Sobol, 1985) are used. So, for each of set of these points calculation of FMM of functional restrictions of a form (3) is carried out. For points that satisfy to these restrictions calculation of FMM of quality criteria of a form (5) is carried out. The obtained values of quality criteria are ranged. In tasks of below laying levels the solution is point of Sobol sequences, corresponding to the maximum value of quality criterion. In a task of level "Cylinder" five best (first) variants of design, which are calculated by OMM, are used and the received results are given to the user for the further analysis in other subsystems of CAD "Turboaggregate". If necessary, parameters of one of these points can be specified by new iteration in which process created in narrower range new FMM of quality criterion and functional restrictions are used in optimization algorithm.

Used mathematical models

As original mathematical models (OMM) in optimization technique the designer can use procedures of direct one-dimensional (1D) and two-dimensional (2D) axial-symmetric calculation of the turbine flow path developed by Boiko and Govorushchenko, 1989. Indicated OMM take into account a wide spectrum of various kinds of energy dissipations, including: losses in cascades; the losses connected with the phenomena of an unsteady flow; energy losses connected with disk friction, ventilation, tapping, humidity, presence of fastening wires; the losses called by presence of leakages (diaphragm, hub, tip, in unloading apertures) (Boiko and Govorushchenko, 1989, Craig and Cox, 1971, Stepanov, 1962).

During development and improvement of these models the special place was given to questions of their verification and identification. At present the given models reliably enough and authentically estimate levels of energy dissipation in flow path and correctly reflect character of influence on its efficiency, both design, and regime parameters. Particularly, the comparative analysis of efficiency of various by geometrical parameters of turbine cascades has yielded absolutely valid results by:

- dependences of cascade losses from incidence angle.
- degrees of influence on losses of Reynolds and Mach numbers.
- character and level of influence on cascades efficiency of cascade pitch, blade height, chord, etc.

All mathematical models of turbine flow path calculation are integrated in the CIS of CAD "Turboaggregate" that provides their effective use in computing processes during solution of a various kind of tasks of the analysis and optimal synthesis.

Thus, developed optimal design technique allows solving problems of optimal design in three basic statements:

- optimal design of the flow path working on one – nominal mode (a special case of multimode optimization);
- optimization of "base" parameters of the flow path taking into consideration the specified schedule of loading change;
- optimization of "base" and "regime" design parameters of the flow path working in conditions of variable loading with the known schedule of its change.

RESULTS OF OPTIMAL DESIGN

By means of the developed technique of optimal design two variants of the axial 4-stage RTEU have been designed. A working fluid of the turbine expander is natural gas (gas from the main pipeline is passed through the flow path of the unit for the pressure decreasing before its supplying to the consumer). Feature of given RTEU is very wide range of working loadings, which is caused by seasonal non-uniformity in consumption of natural gas.

Variant 1: Optimal design of turbine expander taking into consideration the mode of operation

The mass flow of working fluid through the flow path of the unit, subject to operating mode, changed in limits from 10,18 to 20,66 kg/s (the mass flow at nominal mode G_{nom}=16,66 kg/s). Flow path geometry of initial variant of unit and modes of its operation are resulted in Tables 1, 2 (the prototype geometry was taken from the flow path of the existing unit). The stage number is fixed (it is equal to the stage number of prototype). During optimal design, as regime parameter the mass flow of natural gas through the flow path acted at fixed heat drop (p_0=1,2 MPa, T_0=383,15 K, p_2=0,19 MPa). Regulation of the mass flow of working fluid through the flow path is provided with change of outlet effective angle of nozzle cascade (α_1) of 1st stage, i.e. the nozzle cascade of 1st stage is carried out with rotary blades.

The procedure of direct one-dimensional calculation of flow path with adjustment of mass flow by angle α_1 of 1st stage with specified geometry, mass flow and heat drop of the flow path has been chosen as original mathematical model (OMM) for solution of the given task. In connection with use of one-dimensional mathematical model two-level problem statement has been chosen. According to the developed technique of optimization for creation formal macromodel (FMM) of quality criteria and functional restrictions of flow path and its stages at corresponding design levels numerical experiments are carried out according to DOE.

At top level "Cylinder" the vector of varied parameters of created FMM has been generated from 16 parameters, one of which is regime (the mass flow at the cylinder inlet – G_0), and the others 15 are design parameters. In their number are included α_1, β_2, d_2, l_2 (d_1, l_1 were defined through d_2 and l_2 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, α_1, β_2, u/C_0, $Z_{1,2}$, $b_{1,2}$). For 1st stage the dimension of FMM vector is equal 8 (angle α_1 isn't a member of FMM of 1st stage).

The sequence of the general optimization task solution looks as follows. According to a matrix of experimental design from top level "Cylinder" to level "Stage" parametrical restrictions in the form of values d_2, l_2, α_1, β_2, u/C_0 arrive. Concrete level of these parameters is defined by a current point of the plan of numerical experiment of level "Cylinder". 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 for calculation of all flow path of the cylinder.

Except the adduced parameters, in the end of optimization process inlet metal angles for of nozzle and of blade wheel cascades of each stage are specified. Their values are defined taking into account a weight part of quality criterion of each operational mode.

In total in the process of optimal design 58 parameters varied, 20 of them were the phase parameters (internal), and the others 38 were design parameters.

As quality criterion for an estimation of flow path efficiency the value equal to total work of the cylinder for one year, defined according to the developed technique by (5) was used. It is necessary to notice, that special research of criterion function on a unimodality was not developed. At the same time, the rated researches passed by authors during the solution of considered variants of problems show, that in the area limited to the chosen ranges of design and regime parameters change the criterion function is smooth and has one extremum, and in a zone closed to an optimum it has flat enough character.

The solution of assigned task of optimal design has required 4 iterations by more precise definition of an optimal design of the flow path. The range and the regime parameters curve corresponded to the performance specification and remained constants in the process of iterations by more precise definition of an optimal solutions. Results of optimal design are shown in Tables 1, 2 and illustrated in Fig. 2.

Apparently from Table 1, an optimal flow path has greater mean diameters of stages and the greater blades heights of 2-4 stages that indicate of increase of passage areas of nozzle and blade wheel cascades.

Values of powers, internal efficiencies and angles α_1 of 1st stages received from thermal calculation by OMM of two variants of flow paths designs for specified operation modes of the unit are resulted in Table 2. Apparently from Fig. 2, optimal variant of the flow path design essentially surpasses an initial variant of design in efficiency on modes with mass flow greater than nominal and yields a little to an initial variant on two modes with low mass flow. One of major causes of efficiency deterioration of the flowing part on modes with low level of the mass flow is reaction of optimal design subsystem on physical nature of the chosen quality criterion (total work of the cylinder during the year). In this case the choice of total work of the cylinder in a role of quality criterion has appeared effective and justified by following reasons:

1. Apparently from Table 2, the number of modes with mass flows above the nominal surpasses the number of modes with low mass flows.
2. Efficiency increase by 1% on a mode with large mass flow by level of the gain of produced power is equivalent to efficiency increase approximately by 2% for mode with low mass flow.

Parameter	Stage number				Stage number			
	Prototype				Optimal design			
	1	2	3	4	1	2	3	4
d_1, [m]	0,480	0,480	0,480	0,480	0,499	0,490	0,491	0,507
d_2, [m]	0,480	0,480	0,480	0,480	0,500	0,489	0,496	0,513
l_1, [m]	0,0305	0,0350	0,0425	0,0510	0,0300	0,0380	0,0440	0,0550
l_2, [m]	0,0310	0,0375	0,0465	0,0560	0,0330	0,0390	0,0500	0,0640
α_1, [degree]		16,00	19,60	24,50		15,27	18,94	24,57
β_2, [degree]	22,00	25,70	29,10	34,00	21,23	25,53	27,65	30,38
Z_1	54	54	46	46	62	47	51	46
Z_2	69	69	53	53	74	74	55	57
b_1, [mm]	35,099	35,099	42,118	42,118	32,000	41,000	39,000	45,000
b_2, [mm]	30,809	30,809	40,150	40,150	33,000	32,000	43,000	42,000
α_{0g}, [degree]		95,250	92,540	90,410		99,737	93,692	88,992
β_{1g}, [degree]	30,75	35,68	44,03	53,72	48,68	33,73	39,46	65,14

Table 1: Results of optimal design along stages of the turbine expander

Mode number	G_0, [kg/s]	Prototype			Optimal design				
		Angle α_1 of 1st stage, [degree]	Efficiency	P, [MW]	Angle α_1 of 1st stage, [degree]	Efficiency	Efficiency difference %	P, [MW]	Power gain, %
1	18,71	16,91	0,8689	4,727	14,73	0,8910	2,543	4,848	2,560
2	20,66	34,93	0,8295	4,983	20,05	0,8831	6,462	5,306	6,482
3	18,71	16,91	0,8689	4,727	14,73	0,8910	2,543	4,848	2,560
4	10,18	9,66	0,8215	2,432	9,21	0,7880	-4,078	2,333	-4,071
5	10,55	9,62	0,8286	2,542	9,22	0,7973	-3,777	2,446	-3,777
6	17,57	14,02	0,8779	4,485	13,19	0,8874	1,082	4,534	1,093
7	20,35	31,02	0,8329	4,929	18,77	0,8856	6,327	5,241	6,330

Table 2: Results of thermal calculation by OMM for specified operation modes of the turbine expander

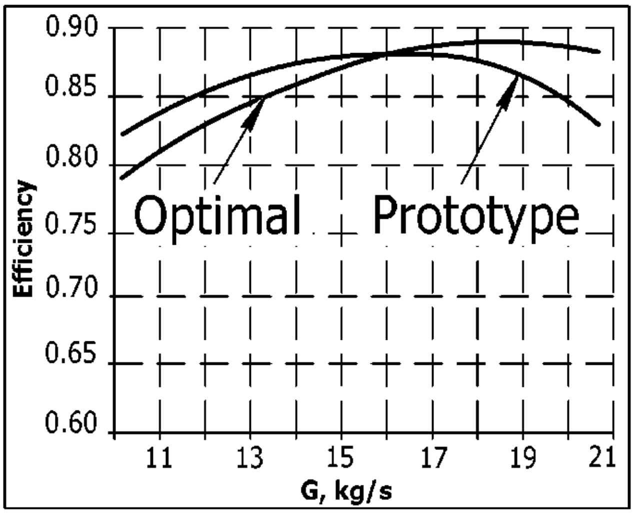


Fig. 2: Efficiencies of turbine expanders

Variant 2: Optimal design of turbine expander with rotary nozzle blades of all stages taking into consideration the mode of operation

Difference of the given task from the previous consists in presence of rotary nozzle blades at all stages of design flow path. The performed calculation researches have shown that performance of rotary nozzle blades allows to expand a range of working loadings of a turbine unit and to raise efficiency of flow path, but here in addition it is required to solve a problem of "correct" selection of outlet effective angles of nozzle cascades of each stage for each operation mode. Usually, during definition of angles α_1 depending on change of the mass flow of the working fluid through the flow path of turbine unit linear laws of their change from stage to stage are accepted. However such way of angles α_1 control cannot provide the highest efficiency of the cylinder. It is obvious, that to reception of additional efficiency increase, the rotation angle of nozzle blades of each stage should be defined by means of corresponding optimization algorithms, and their turn to be carried out independently from each other.

According to design conditions the mass flow of natural gas through flow path of RTEU, depending on an operation mode, changed within the limits from 4,94 to 20,66 kg/s. Regulation of the mass flow of working fluid is carried out by turn of nozzle blades (change of output angles α_1) all steps. Optimization was performed taking into account 12 modes (months) of turbine expander operation. Quality criterion, OMM and regime parameter for the given task is the same, as in the previous case. In addition in the optimization process the layer 2 at 1st level of design (Fig. 1) has been involved that has provided definition of optimal schedules of change of turn angles of nozzles depending on operation mode of the turbine unit.

At the first level of optimal design optimal values of "base" ($d_{1,2}$, $l_{1,2}$, β_2) and "regime" design data (angles α_1) were defined. At the second level the search of the best combinations of chords and blades numbers ($Z_{1,2}$, $b_{1,2}$) was carried out.

As the given task solved for flow path with standard nozzle profiles (H-2-35), during variation of angle α_1 corresponding alteration of the inlet metal angle of nozzle cascade (α_{0g}) was considered also. During calculation of the shock losses at cascade inlet, angles of profiles insensitivity to blow according to atlas data were taken into account.

Inlet metal angles of blade wheel cascade for each stage were defined by averaging of their values by modes taking into account a weight part of quality criterion values of each mode.

The "base" design parameters received as result of the solution of the general task of optimal design are resulted in Table 3. The received distributions of angles α_1 for each stage of the flow path as functions of mass flow change are presented in Fig. 3. Apparently from Fig. 3 optimal curves of angles differ greatly from the linear curve received at uniform simultaneous turn of nozzles.

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. 4.

The efficiency of the received flow path essentially surpasses efficiency of initial flow path on all operation modes (Fig. 4).

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. 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. On operation modes with the mass flow close to nominal or surpassing nominal, increase of efficiency of the flow path became possible due to selection of an optimal combination of "base" design parameters ($d_{1,2}$, $l_{1,2}$, β_2, $Z_{1,2}$, $b_{1,2}$) for each stage.

Parameter	Stage number				Stage number			
	Prototype				Optimal design			
	1	2	3	4	1	2	3	4
d_1, [m]	0,480	0,480	0,480	0,480	0,481	0,483	0,489	0,498
d_2, [m]	0,480	0,480	0,480	0,480	0,482	0,484	0,490	0,499
l_1, [m]	0,0305	0,0350	0,0425	0,0510	0,0290	0,0360	0,0450	0,0560
l_2, [m]	0,0310	0,0375	0,0465	0,0560	0,0320	0,0390	0,0490	0,0600
β_2, [degree]	22,00	25,70	29,10	34,00	21,70	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	40,150	40,150	33,250	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

Table 3: Results of optimal design along stages of the turbine expander

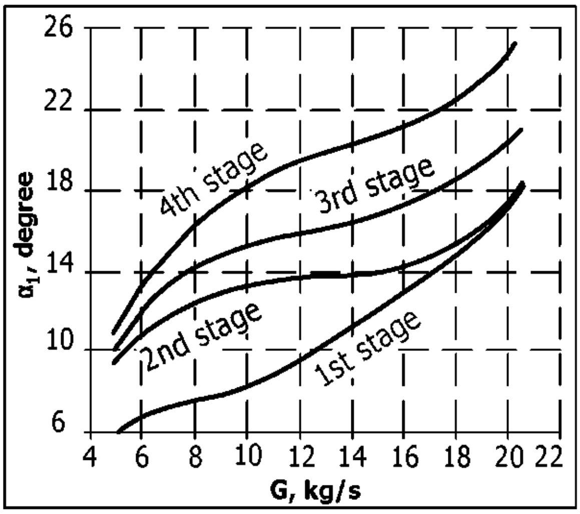


Fig. 3: Optimal distribution of angles α_1 along the flow path subject to mass flow

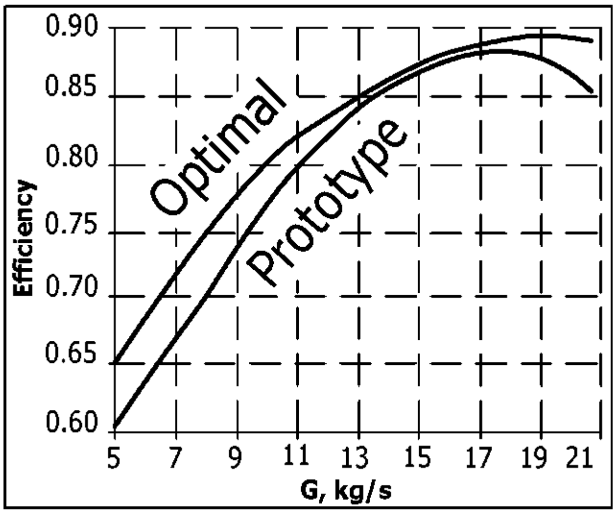


Fig. 4: Efficiencies of turbine expanders

CONCLUSIONS

1. The offered recursive algorithm of multilevel optimization of the turbines flow paths, working on a variable mode, allows to present optimal design task as a united complex of system-hierarchically coordinated subsystems of optimization which provides the solution of "own" problems in various statements and with necessary sets of quality criteria and restrictions at each level of hierarchy, providing thus effective achievement of an overall purpose – reception of the optimal solution for the flow path in whole.

2. Advantage of the described above approach to the solution of optimal design problems consists in possibility of consideration of huge number of various combinations of the turbine design parameters and allows providing a choice of the best, optimal variant, under the given regime parameters curve.

3. Introduction of the described optimization technique in common information space (CIS) of CAD "Turboaggregate", essentially expands its possibilities in respect of an exchange of optimal design results with other subject components of CIS and software products out of CIS, that allows to carry out more detailed and comprehensive analysis of the received flow path design and to make a choice more justified and reliable.

4. Results of the performed researches have confirmed:

- efficiency and reliability of the developed technique of multilevel recursive optimization for flow paths of the axial turbine units which operate on a variable mode;
- necessity and appropriateness of the account of the factor of operation loadings variability during flow path designing;
- adequacy of the chosen quality criterion defined as total work of the cylinder for one year in tasks of optimization of flow paths of axial turbines which operate with a variable load curve.

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