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Composing a Virtual Model of Gas Turbine Engine Working Process Using the CAE System "ASTRA"

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Abstract: The study describes the computer-aided system of thermo gas dynamic calculations and analysis ("ASTRA") developed at the Aircraft Engines Theory Department of Samara State Aerospace University. The functional features of the CAE System are outlined. The features of composing a virtual model of a gas turbine engine intended for solving the tasks of the conceptual design phase of an aircraft engine.

Key words: Computer-Aided System, thermo gas dynamic calculation, analysis, gas turbine engine, aircraft

INTRODUCTION

The foundation for high efficiency of the aircraft operation is laid during the design of its power unit. The design of a new engine starts with the selection of the working process parameters values: turbine inlet temperature, total compressor pressure ratio, bypass ratio of the engine, fanpressure ratio (of the turbofan engine). The selection of these values is preceded by the determination of their optimal values. According to the systems approach, the criteria of the engine efficiency (such as overall efficiency, specific fuel consumption, specific weight of the engine) should not be used as an optimization criteria as the engine itself is an integral part of higher hierarchical level system (the plane) and the estimation of engine parameters optimality is possible only according to the performance criteria of the aircraft.

The task of optimizing and choosing the rational parameters values of the working process taking into the account the mission and characteristics of the aircraft is one of the most important and complex problems. It is practically impossible to find a solution of this problem without the use of virtual model of the gas turbine engine working process. Such a model is developed at the Aircraft Engines Theory department of Samara State Aerospace Universityon the basis of the Computer-Aided System "ASTRA" (Tkachenko, 2009; Kuz'michev, 2012a).

The computer-aided system of thermogas dynamic calculations and analysis of gas turbine engines and power plants ("ASTRA") is an integrated environment for joint solution of the initial design phase tasks suitable for any types and schemes of gas turbine engines and power-plants.

CONCEPT AND FUNCTIONS OF THE COMPUTER-AIDED SYSTEM "ASTRA"

The main purpose for the development of the "ASTRA" System is the improvement of engine efficiency, the reduction of its development time and the reduction of its life cycle cost.

The virtual model of the engine under study and the design tasksis composed using the computer-aided system "ASTRA" according to the universal principles. According to the theory of systems analysis this model is a set of interrelated elements. The elements describe the processes in the main parts of engine, the environmental conditions, perform the auxiliary functions (such as the calculation of the key performance indicators of engine). Each element contains the list of parameters and the reference to the function that implements the algorithm of calculation of the output parameters. The links between elements allow to use the parameter values calculated in one of the elements as the input data for the other element calculation.

In turn, the elements development and their inclusion into the model is performed using the library of functional modules. Modules are the prototypes for the elements, containing the information on the element parameter list and the calculation algorithm implemented in the form of a function. The Computer-Aided System "ASTRA" supports the following modules of the basic engine elements:

- Environmental conditions
- Inlet
- Compressor
- Fan
- Main combustion chamber

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- After burner
- Gas turbine
- Sub-sonic outlet
- Supersonic nozzle
- Transition duct
- Mixing chamber
- Bleed of the working medium
- Working medium input
- Power consumer
- Aircraft propeller
- Power summator
- Heat exchanger
- Steam generator
- Steam input
- Steam turbine
- Water pump
- Water condenser and others

Different versions of the modules may be used for each of the basic engine elements depending on the specificity of the thermogas dynamic designing task (e.g., variant for the designing of a projectable engine and variant for the performance calculation of a realized engine). Besides, the modules may have options depending on the type of engine element, for example, the options for uncooled and cooled turbine. There are modules that allow the additional elements modeling or the parameters calculation of the engine as a whole. Thus, the “ASTRA” System allows the composition of a virtual model of the various existing and perspective gas turbine engines and power-plants.

The implementations of calculation algorithms for the basic units included in the modules widely use the auxiliary procedures to calculate the gas-dynamic and thermodynamic functions, basic thermodynamic processes, the gas flow parameters in the air-gas channel using mathematical models of the working medium and fuels.

The working medium simulator describes the thermal characteristics dependence on temperature value and gas composition. The gas composition is characterized by a mass ratio of major air components and combustion products: oxygen, water vapor, carbon dioxide, sulfur dioxide, nitrogen, helium and argon. The fuel composition is characterized by the relative mass ratios of carbon, hydrogen and oxygen.

The engine model composed of the elements can be used only for direct sequential calculation, since it is a set of formulas from the mathematical point of view. The specialized operational modules are used to set up the engine model for solving the particular design tasks.

The “matching” module is used for solving the systems of nonlinear equation in the case when some of the input element parameters are initially unknown and the output parameters, respectively have certain restrictions (e.g., equality to specific numeric values or to the values of other parameters). The solution of systems of equations is performed using a modified Newton Method. It should be emphasized that the advantage of the Computer-Aided System “ASTRA” is that the user does not have to describe explicitly the system of discrepancies and indicatethe varying variables during the composition ofthe model. The user just indicates the type of element parameters determination (it is calculated, defined by user, equal to another parameter). If the input parameter is determined by calculation, it becomes a variable parameter automatically. If the output parameter has a specific numeric value or if it is associated with another parameter the discrepancy is generated automatically.

The “Optimization” module delivers the means for determination of optimal combination of design variables values (optimized parameters) providing the maximum or minimum value of the objective function. Depending on the problem an objective function may be determined by one or a combination of several criteria characterizing the engine efficiency (specific fuel consumption, specific thrust, engine weight, etc.) or an aircraft efficiency (flight time, fuel costs per flight cycle, the cost of transportation, etc.). The search of solution is carried out using the Nelder-Mead Method (the Flexible Polyhedron Method). Restrictions may be set on the numerical parameters to perform the conditional optimization.

The “Tabulation” module implements the analysis of the model by performing a series of calculations with a different values of the initial data. In this case, the parameter under examination is specified as tabulated and the table of values is set for it.

The “Integration” module is used to implement the numerical solution of differential equations system and allows to calculate the results of various processes such as the phase of an aircraft flight. The algorithm of this operation provides the adaptive change of an integration step (shorter step to reflect more accurately the change of values; longer stepto reduce the calculation time, if the derivative values change insignificantly). The integration may be carried out by different phase variables such as by time or by traveled distance. Besides, the algorithm provides the setting of one or more conditions to stop the execution of integration.

The “Control optimization” module implements the method of searching the optimal control function of a gas turbine engine according to the aircraft performance criteria. The optimization of control function is performed by dividing the continuous process into a set of discrete steps and the solution of the nested problems concerning parametric optimization of the control function value at each step taking into account the constraints.

A set of interrelated operation elements and modules comprises the model of task to be solved by using the engine model. The task model in turn may be combined with the models of other tasks there by possibly developing the models of complex tasks with an automatic data transfer between subtasks.

All the steps of composing the virtual model of an engine and the model of a task to be solved (adding of elements and operations; setting the relations between the elements; correctingthe initial data values, etc.) are carried out interactively using the built-in tools, implemented as (CARCAS) library.

FEATURES OF THE COMPUTER-AIDED SYSTEM "ASTRA"

The computer-aided system "ASTRA" has the following features:

- Composition of virtual models of gas turbine engines and power-plants including the complex and combined cycles
- Use of elements characteristics
- Examination of the fuel properties influence on the engine parameters
- Thermogas dynamic calculation of engines and power-plants
- Analysis of the working process parameters values impact on the specific parameters and main engine data
- Calculation and optimization of performance data
- Optimization of the engine design parameters including the optimization by the criteria of an aircraft effectiveness
- Optimization of the engine control function
- Flight cycle simulation and others

An Computer-aided System of the thermogas dynamic calculation and analysis "ASTRA" solves the whole range of tasks concerning the conceptual design phase of gas turbine engines and power plants (Kuz'michev, 2012b; Bochkarev *et al.*, 1993; Maslov *et al.*, 1976; Kuz'michev and Morozov, 1991; Zhukov *et al.*, 1985) identification of mathematical models in accordance with the test results (Korzh *et al.*, 1973a, b) and the gas-dynamic development of aircraft engines and power-plants.

VIRTUAL MODEL OF GAS TURBINE ENGINE COMPOSITION

Composition of a virtual model of a gas turbine engine usingthe computer-aidedsystem "ASTRA" includes several stages.

Problem statement for the engine model composition: The list of initial data and the types of elements are selected depending on the task. The elements are divided into four main groups (Fig. 1):

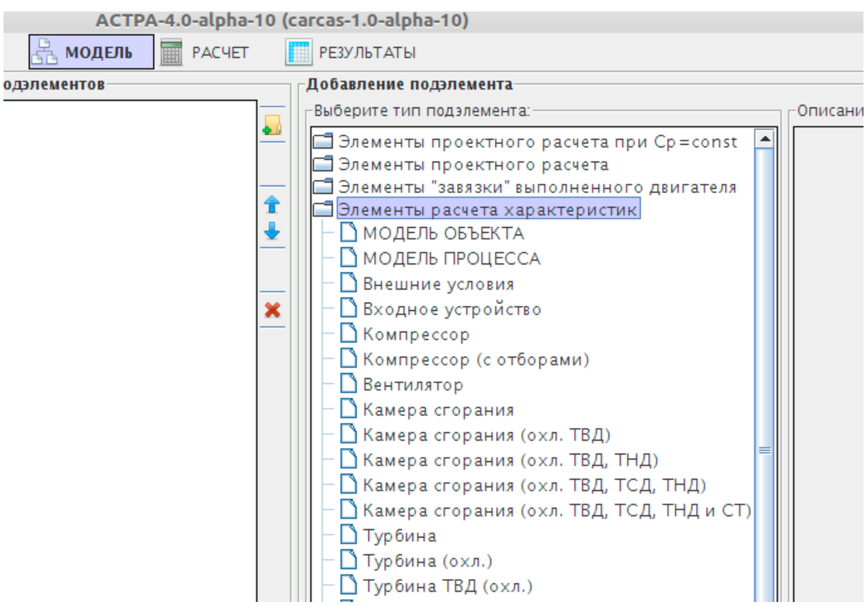


Fig. 1: Groups of elements to compose the engine model

- Elements for the simplified calculations with a constant heat capacity
- Elements for the engineering calculations with variable heat capacity
- Elements for the starting point calculations of the implemented engine (dimensioning of the section areas of engine)
- Elements for the performance data calculation

Starting the software package: The astra.jar file is started from the software package folder. The execution of the program is carried out by a virtual Java machine. So, the availability of installed Java operational Environment (JRE) on your computer is necessary.

The Windows Operating System starts the software package as well as the usual run of the executable file. The Linux operating system starts the file from a terminal window by «java-jar astra.jar» command. After the start of a software package the initial window appears, the image of which is shown by Fig. 2.

The left panel displays the list of available ready-made gas turbine engine models of different types and schemes developed for typical problems solution.

The top panel contains buttons for composing a new model and for uploading of a previously generated model from a file.

New model development: By clicking "Create a new model" the model editing window opens (Fig. 3). The top panel has the buttons to save the information about the current model into a file, as well as buttons that let you to switch between program modes: model development, calculation start and results view.

The left panel displays a model structure tree. When the item is selected a window for editing its properties appears on the right panel.

For example when the "Elements" nodeis selected, the panel for adding/removingthe elements will be displayed (Fig. 4).

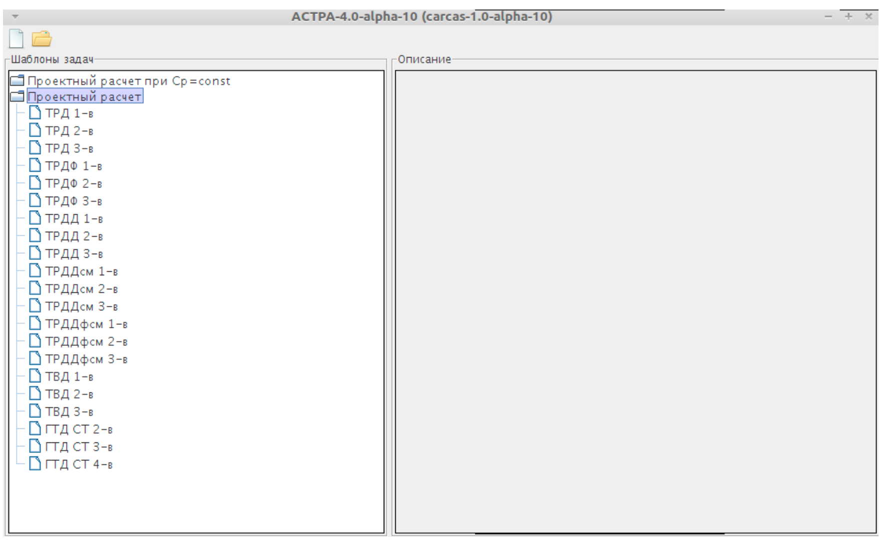


Fig. 2: Start window image of the software package

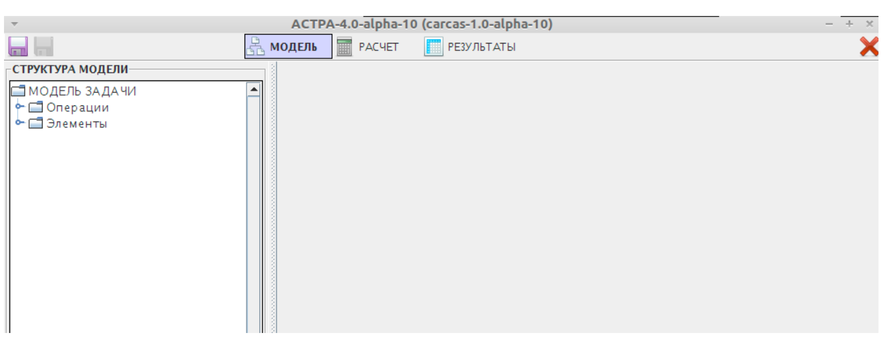


Fig. 3: Software window view with a new model

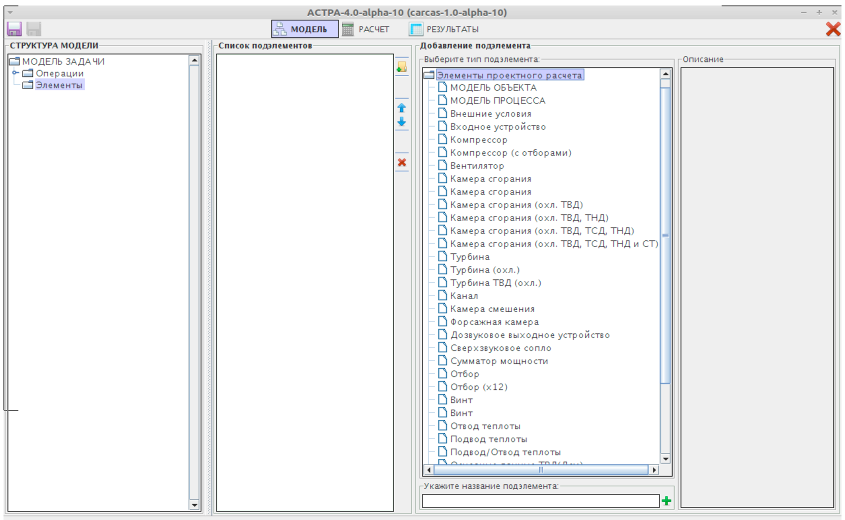


Fig. 4: List of the element types

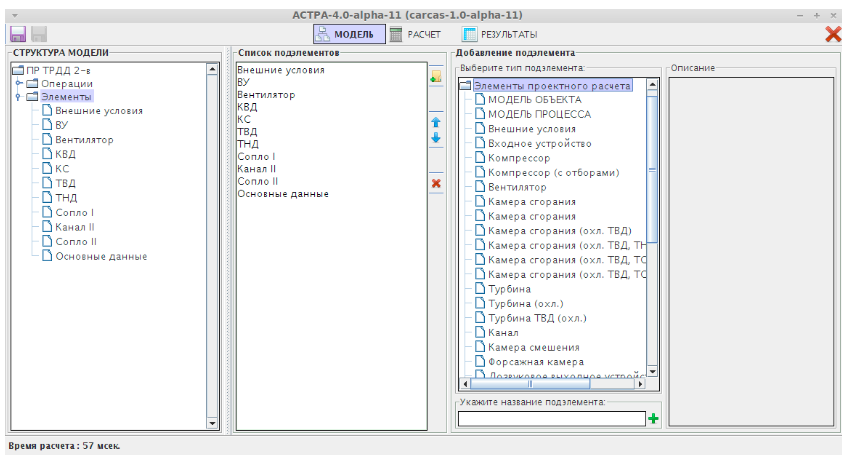


Fig. 5: Composing the element list of the Engine Virtual Model

Adding of elements into a model: To add an element one should select an element type, provide its name and press the "+" button. The new element will be represented in the model tree and the list of elements where the place of the element in the list may be changed, the selected element may be removed or uploaded from a file. In such a way the virtual model of an engine is composed (Fig. 5).

Elements linking: The right panel displays the list of the element parameters when the element in the model tree is selected. The name of each parameter may be changed, whether it will or will not be displayed in the table of results may be selected and the method of its value determination may be specified as well as the initial value of the parameter. At the bottom of this panel the description of the parameter is provided (Fig. 6).

To specify that the parameter value should be calculated in another element it is necessary to double "click" on the cell in the "Definition" column and choose the appropriate item in the pop-up menu ("Link" option) and specify the element and parameter name which would be the basis for calculating this value (Fig. 7).

Initial and resulting parameters defining: Similarly to the setting of a parameter links the parameters that belong to the initial data, the "Definition" column specifies if the parameter is "initial" or "initial (tabulation)" and alsoits value or a table of values (Fig. 8).

The parameters that are determined during the calculation should be set to the "Resulting" type even if the parameter is an input one for a given element (Fig. 9).

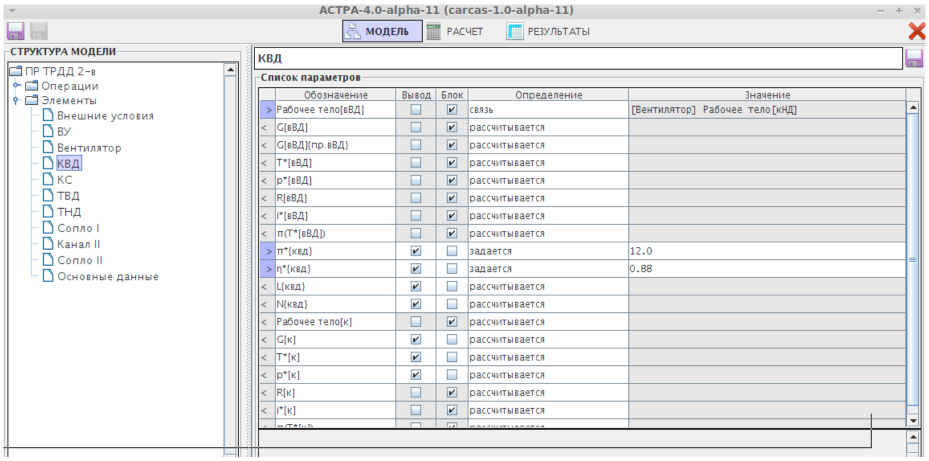


Fig. 6: Edit window of element parameter properties

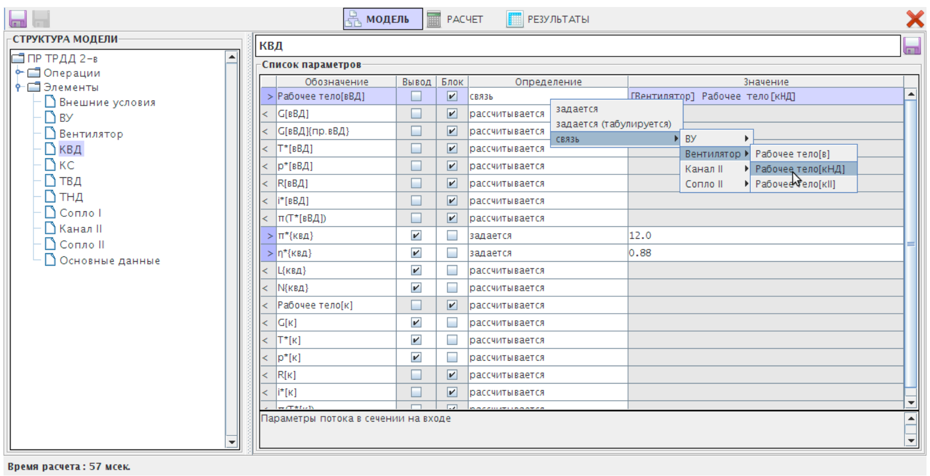


Fig. 7: Parameter link setting

Model set-up according to the particular design task: Virtual model of an engine, composed using the CAE System "ASTRA" is usually intendedfor solving a particular thermogas dynamic task. However, the model may be easily reconfigured for solving different tasks.

For example, a model configured for the start up calculation of an engine may be easily reconfigured for the engine performance data investigationas the discrepancies system remains the same. The list of source data differs only so, only the method of value determination for certain parameters needs to be changed.

To implement the optimization operation the "optimizable" option of the parameter method of value determination should be chosen. The objective function also needs to be chosen using the "Optimization" operation settings and the optimization type (minimization or maximization) should be specified (Fig. 10).

The influence of various factors on the engine parameters is investigated by means of the tabulation of the parameters characterizing these factors and the table of values needs to be specified for these parameters (Fig. 10).

Model saving, calculation, results view and work completion: The information about the composed model may be saved to a file and be loaded again. There are "Save" (to save with the current filename) and "Save As" (to save with a new filename) buttons located on the top panel for this purpose. The name of the current file is displayed in the right side of the upper panel. There is a button for model closingnext to it that returns the system to the initial screen (Fig. 11).

The calculation process is started with the "Calculation" button on the top panel (Fig. 12). Upon the calculation completion the panel with the results table is displayed automatically (Fig. 13).

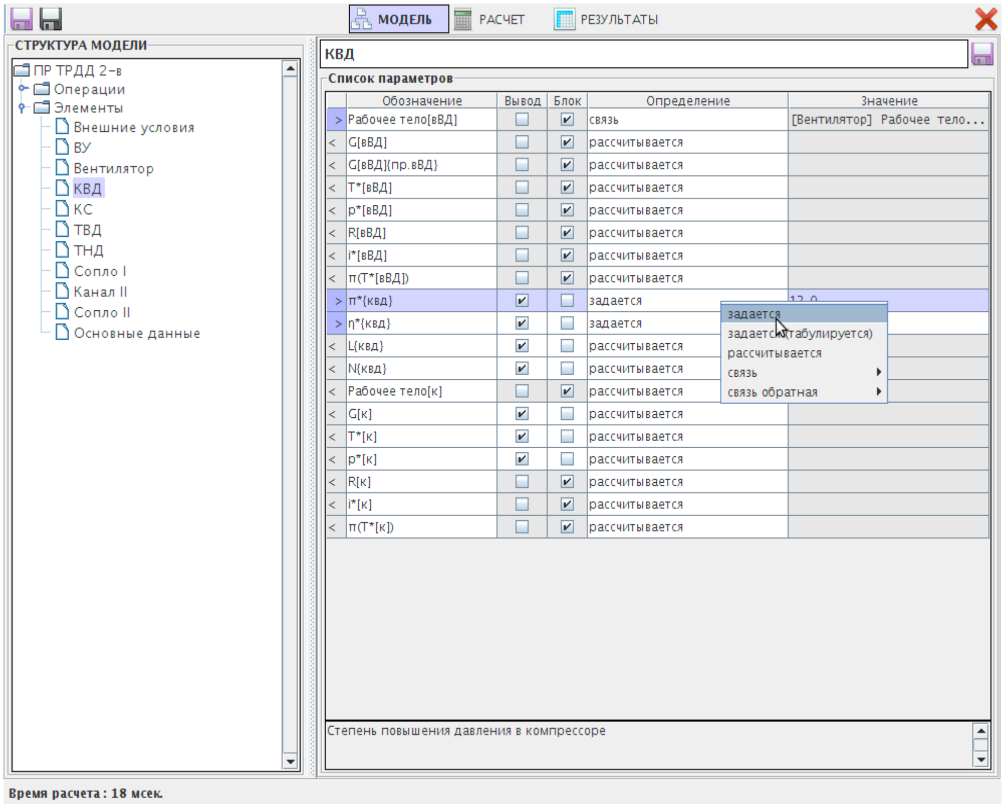


Fig. 8: Initial data set

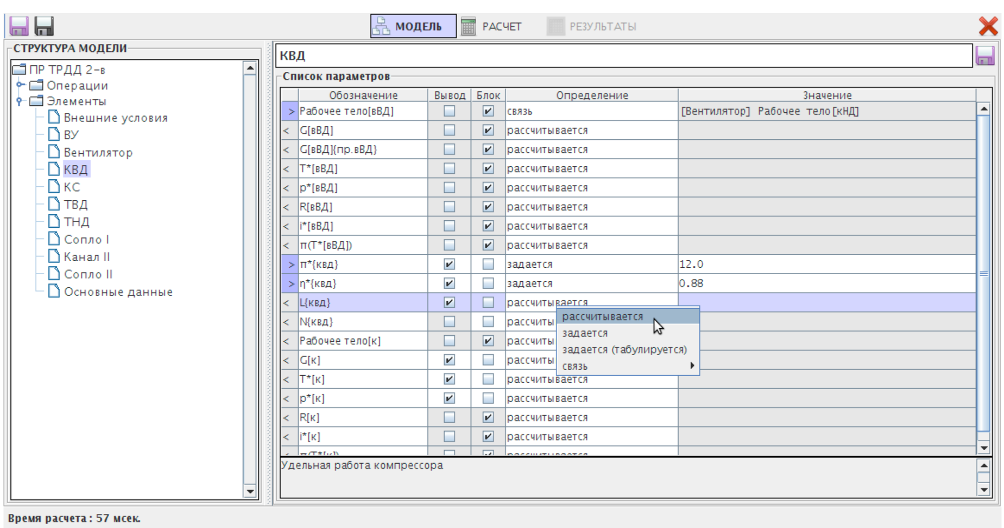


Fig. 9: Resulting parameter choice

The table may be saved using the hypertext document format and be opened in a text editor or a spreadsheet editor later. To continue editing of the model the "Model" button should be pressed.

Current results table is kept until the initial data or the operation setting are changed and may be examined by clicking the "Results" button (Fig. 13).

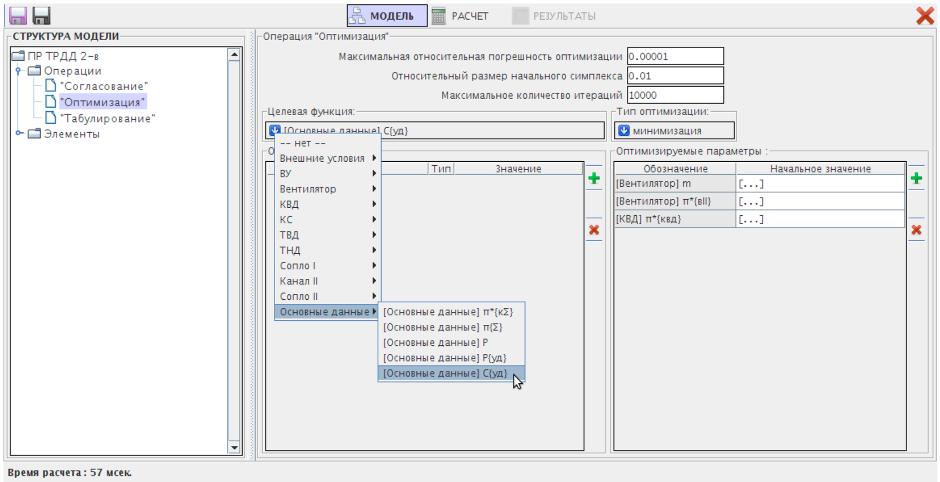


Fig. 10: “Optimization” operation properties panel

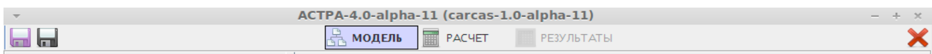


Fig. 11: Upper panel of the system

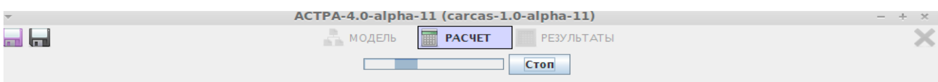
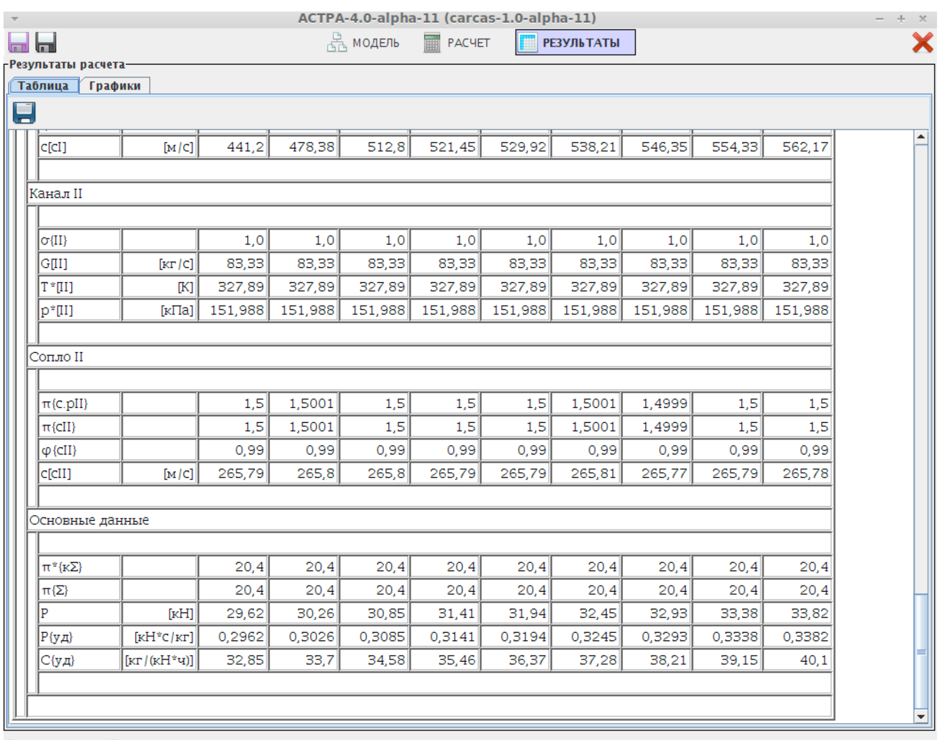


Fig. 12: Button for calculations starting



c[cI]	[м/с]	441,2	478,38	512,8	521,45	529,92	538,21	546,35	554,33	562,17
Канал II										
σ(II)		1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0
G[II]	[кг/с]	83,33	83,33	83,33	83,33	83,33	83,33	83,33	83,33	83,33
T*[II]	[K]	327,89	327,89	327,89	327,89	327,89	327,89	327,89	327,89	327,89
p*[II]	[кПа]	151,988	151,988	151,988	151,988	151,988	151,988	151,988	151,988	151,988
Сопло II										
π(c.pII)		1,5	1,5001	1,5	1,5	1,5	1,5001	1,4999	1,5	1,5
π(cII)		1,5	1,5001	1,5	1,5	1,5	1,5001	1,4999	1,5	1,5
φ(cII)		0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99
c[cII]	[м/с]	265,79	265,8	265,8	265,79	265,79	265,81	265,77	265,79	265,78
Основные данные										
π*(кΣ)		20,4	20,4	20,4	20,4	20,4	20,4	20,4	20,4	20,4
π(Σ)		20,4	20,4	20,4	20,4	20,4	20,4	20,4	20,4	20,4
P	[кН]	29,62	30,26	30,85	31,41	31,94	32,45	32,93	33,38	33,82
P(уд)	[кН*с/кг]	0,2962	0,3026	0,3085	0,3141	0,3194	0,3245	0,3293	0,3338	0,3382
C(уд)	[кг/(кН*ч)]	32,85	33,7	34,58	35,46	36,37	37,28	38,21	39,15	40,1

Fig. 13: Table of results

SYSTEM REQUIREMENTS

The Computer-Aided System “ASTRA” is implemented as a software package developed using the object-oriented programming language Java. The software package operates on personal computers running under Windows, Linux and MacOS operational environment. Hardware requirements:

- Processor with a clock frequency of at least 1500 MHz
- At least 256 MB of RAM
- A monitor and graphics card that supports the display mode with the resolution of at least 1280×800 pixels and the color rendering capacity of 16 bit
- The amount of free space on your hard drive at least 100 MB

To run the software package the Java Run time Environment (JRE) of the version no less than 6u20 is required.

CONCLUSION

The Computer-Aided System ASTRA and the virtual models of gas turbine engines and power plants developed with it have been tested during the development of the universal baseline engine core of high energy efficiency, prospective turbofanof the thrust of 300 kN, the power plant for gas turbine locomotive; numerical simulation of flight cycles for Tu-154M and An-124 aircrafts as well as during the number of other studies. The obtained results showed a high convergence with the data obtained experimentally and using the specialized mathematical models used in design offices.

Usability of the tools for virtual model of gas turbine engines composition, efficient algorithms, the implemented concept of hierarchical model development and combined models ensured the universality, high reliability, stability and performance in comparison with similar Computer-Aided Systems.

This allows more extensive and detailed studies to be performed during the initial design stage as well as data a more precise definition during the subsequent design stages and the engine development. Thus, reduction of design time and improvement of engines characteristics is achieved.

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