



Research Article

Some Results of Modeling the "Wet Compression" Process in GTD and GTU Axial Compressors with Respect to Its Multifactorial Nature

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Abstract

The article presents and analyzes the results of the development and application of the methodology for structural analysis and the CompressorWI-2S program for modeling the process of "wet compression" of air in gas turbines and axial compressors, taking into account the multifactorial characteristics of this process. This includes the selection of the location of the liquid flow path in the compressor: liquid separation on the inner walls of its housing, the presence of an internal or external bypasses (recovery) of the two-phase compressible pressure fluid section, the possibility of injecting "super-heated" liquid, incomplete wetting of the surfaces of the blades of the impellers blades (IB) and stage guide vanes (SGV) of individual stages, control of the compressor operating modes at low speeds using SGV rotary blades of some stages. The simulation results of the CompressorWI-2S were based on the 14-stage axial compressor of the AL-21F-3 gas turbine engine, for which experimental and bench test data were published in the scientific literature. We were able to determine the most significant and minor factors based on the results of the calculation, which varied a few compressor parameters and the conditions of the water injection into the flow path. The characteristics of the axial compressor under wet compression have been determined by combining it with other heat and gas dynamic calculation programs for gas turbine engines. In terms of performance and flow characteristics at the compressor outlet, the simulation results are in line with the bench test and experimental data for this axial compressor. As a result of, the research, it was established that the determining role in the process of moisture evaporation in the flow section of an axial compressor is played by thermodynamic factors, such as changing pressure and temperature of the working fluid (two-phase mixture or steam-air mixture), corresponding changes in the heat of vaporization in the flow section of the compressor, as well as the liquid injection flow rate.

Keywords

Gas Turbine Engine (GTD), Gas Turbine Unit (GTU), Axial Compressor, Water Injection, Wet Compression, Modeling, Calculation Program, Calculation Results

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1. Introduction

The process of "wet compression" in an axial blade compressor occurs in a two-phase flow in the mixture of air, water vapor and water in a rotating turbulent flow in its blade passages, complicated by evaporation of liquid on the surfaces of the impellers blades (IB), stage guide vanes (SGV) and the inner walls of the compressor housing due to the separation of liquid on it, characterized by hydraulic resistances and losses in both the gas and liquid phases. The ingress of water into the flow section of the compressor can be caused by weather conditions in transport GTD for various purposes, and by special liquid injection in ground-based GTU. As already mentioned in work [1, 13, 14], optimal injection of water into the flow section of an axial compressor according to parameters makes it possible to improve a number of its important parameters, as well as to some extent influence the operating modes. This article presents and analyzes precisely this modification of "wet compression".

Due to the great complexity of conducting experimental studies for the entire set of design and operating parameters of compressors, conditions of water injection into the compressor duct, methods of mathematical modeling of this complex process and software products developed on its basis for personal computers are of great importance. Analyzing Russian and foreign publications in this field of study, the authors of this work came to the conclusion that previously, when modeling this process, the combined effect of factors such as the injection site of liquid into the axial compressor duct, liquid separation on the inner walls of its body, the presence of an internal or external bypass (sampling) of the two-phase compressible working fluid section, the possibility of injecting "super-heated" liquid, incomplete wetting of the surfaces of the blades of IB and SGV and at individual stages, control of the compressor operating modes at low speeds using rotary blades of SGV at some stages. We have combined this generically with the "multifactoriality" term. It is also important to assess the impact of these factors on the efficiency parameters of the GTD cycle or GTU as a whole.

In accordance with this, physical and mathematical models of "wet compression" in GTD and GTU axial compressors were developed, with respect to all this multifactorial nature, implemented as a program for CompressorWI-2S PC [2] in the Visual Studio 2022 integrated environment in the C# programming language (C-Sharp), as mentioned earlier and in work [1]. The reliability of the calculation results under the program was confirmed by the example of several GTDs and GTUs, which differ significantly in its designs and basic parameters.

Next, we will consider the results of numerical modeling using the example of a 14-stage axial GTD compressor AJI-21F-3, for which there are quite informative experimental and bench test results published in the scientific literature. The initial data for the basic calculations were the inlet air tempera-

ture $T_0 = 288 \text{ K}$; pressure $P_0 = 101325 \text{ Pa}$ (760 mmHg); relative humidity $\varphi = 30\%$; air flow $G_{\text{air}} = 86 \text{ kg/s}$; turbocharger rotor speed $n = 7300 \text{ rpm}$; for the injected liquid, $T_{\text{lo}} = 288 \text{ K}$; the average median diameter of liquid droplets is $d_{\text{drop}} = 40 \text{ }\mu\text{m}$. The distribution of the flow rate of the injected liquid over the relative height of the compressor blades is shown in Figure 1 and it corresponds to an equal density of water flow in the air in the cross section of the compressor, with respect to the increase in areas along the radius with a uniform selection of control sections along the blade height.

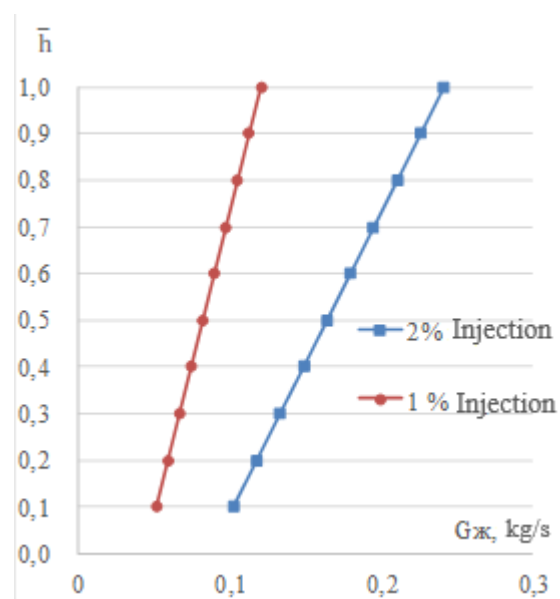


Figure 1. Distribution of water flow over the relative height of the blade in the compressor stage during liquid injection.

2. Evaluation of the Effect of Liquid Separation on the Walls of the Compressor Housing

The effect of separation of the liquid injected at the compressor inlet on the "wet compression" process is most significant in the first 3 compressor stages. As a rule, in subsequent stages, with increasing pressure, the "bearing capacity" of the flow increases and the separation of liquid onto the walls of the housing is insignificant, therefore, calculations taking into account separation were performed for the modification with water injection in front of the compressor. In the computational model of the CompressorWI-2S program, it is assumed that separation is carried out in the impeller of the stages, and film evaporation of this section of the liquid occurs on the walls of the compressor housing both in the impeller and in the guide device. The flow rate of the injected water in front of the compressor was 2% of the air flow through its flow sec-

tion. The share of expenses for ε_c liquid separation were assumed to be 0.4 for the 1st stage, 0.2 for the 2nd stage, and 0.05 for the 3rd stage of the compressor. Thus, in total, they reached 65% of the liquid consumption during injection. In general, this significantly reduces the proportion of liquid evaporating in the main stream of these stages in the form of droplet liquid in the blade passages of the impeller and guide

device and in the film mode on the surfaces of its blades. An example of the calculation is presented in Table 1 (here, π_c^* is the degree of pressure increase in the compressor according to the full flow parameters; N_c is the power consumed by the compressor; $\Delta\eta_c$ is the relative increase in compressor efficiency; n_c is the number of liquid droplets).

Table 1. The effect of separation on some compressor parameters in its outlet section during injection of different fluid flow rates at the inlet of the AJI-21F-3 GTD.

Modification	1	2	3	4	5	6	7
Separation accounting	no	no	yes	no	yes	no	yes
Water injection flow rate	Without injection	1% of air consumption	1% of air consumption	2% of air consumption	2% of air consumption	3% of air consumption	3% of air consumption
φ	0.3 (30%)	0.3 (30%)	0.3 (30%)	0.3 (30%)	0.3 (30%)	0.3 (30%)	0.3 (30%)
T_{10} , K	288.15	288.15	288.15	288.15	288.15	288.15	288.15
T_0 , K	288.15	288.15	288.15	288.15	288.15	288.15	288.15
T_c^* , K	617.1	591.7	592.3	566.7	567.9	541.7	543.6
P_c^* , Pa	1080843	1115981	1117912	1130829	1132526	1140949	1149501
π_c^*	10,519	10,858	10,880	11,058	11,113	11,198	11,295
N_c , W	28972990	29150597	29149246	29279980	29278987	29391821	29393064
$\Delta\eta_c$, %	-	2,706	2,808	5,126	5,216	7,311	7,768
n_c , 1/s	-	0	0	0	0	0	0
d_c , microns at the outlet	-	0	0	0	0	0	0

The results of these calculations for this GTD were also compared with the data of similar calculations for a significantly different design, dimensions, turbocharger speed and air consumption of the ГТЭ-160 GTU, which allowed us to draw the following conclusions:

1. Separation of liquid onto the compressor walls in the first 3 stages slows down its evaporation, in particular, for AJI-21F-3 GTD by 1.7%, and for ГТЭ-160 GTU with significantly higher air consumption by 10.8% compared to the calculation without separation. It is noted that the degree of influence of separation strongly depends on the scale factor. This is also confirmed by the fact that the complete evaporation of the injected liquid with a flow rate of 2% of the air flow rate is completed for AJI-21F-3 GTD in the 10th stage of the compressor, and for ГТЭ-160 already in the 8th stage. The more intense evaporation of liquid for GTU is determined by the large size of the blade passages in the stages, which enhances the role of drip evaporation of liquid. The very slowing down of the liquid evaporation process during its separation onto the compressor walls is explained by the fact that a smaller proportion

of the liquid evaporates in the drip mode in the blade passages.

2. The percentage effect of separation is less significant on the total pressure and temperature of the flow behind the compressor: for AJI-21F-3 GTD, 0.20% and 0.15%, respectively, for ГТЭ-160 GTU, these changes are 0.40% and 0.73%.

3. A consistent result was obtained for the total power loss for the compressor drive, taking into account the separation of N_k : for AJI-21F-3 GTD and for ГТЭ-160 GTU, it decreased by only a proportion of percent.

To confirm the adequacy of the developed methodology and calculation program, Table 2 presents the results of calculations using the CompressorWI-2S program, which are compared with data from one of the few studies [3], which presents the results of the most detailed experimental studies of the "wet compression" process obtained during tests on the stand of the modified AJI-21F-3 GTD axial compressor. Data on the temperature of the flow behind the compressor during injection of different water flow rates were compared, the discrepancies between the calculated data, with respect to water separation on inner walls of the compressor, and the experiments

did not exceed 0.5%.

Table 2. Comparative data on the flow temperature at the outlet of the AJI-21F-3 GTD compressor when injecting water at the compressor inlet according to experimental data [3] and calculations using the CompressorWI-2S program.

Operating mode: $n = 7320$ rpm; $T_0 = 279.3$ K; $G_{air} = 84$ kg/s		
Relative flow rate of liquid injection at the compressor inlet	Experimental data of the work [5]	Calculation with respect to water separation on the housing walls
G_l , %	T_c , K	T_c , K
1.6	556.2	557.3
2.2	542.5	543.3
2.5	536.4	536.3

Data on the values of effective efficiency during "wet compression" are also of interest, which were evaluated by many authors using methodology of P. I. Baranov Central Institute of Aviation Motors. Table 3 presents the results of comparing the values of η^*_{eff} calculated using this technique based on

calculations of the parameters of the axial compressor of the aviation AJI-21Φ-3 GTD according to the CompressorWI-2S program, and in [3, 7, 8] according to bench tests at different water injection rates. They demonstrate that the differences in these values do not exceed 1%.

Table 3. Comparison of the effective efficiency values for "wet compression" in the AJI-21F-3 GTD axial compressor, calculated according to the CompressorWI-2S program with stand test data.

Water injection flow rate	0.5%	1.0%	1.5%	2.0%
Work data [6] η^*_{eff}	0.8510	0.8610	0.8710	0.8770
Calculation according to the CompressorWI program η^*_{eff}	0.8521	0.8658	0.8753	0.8831
Effective efficiency difference η^*_{eff} , %	0.13	0.56	0.50	0.69

As noted, for example, in [4-6], the main ways of regulating axial compressors in variable modes are air bypass, rotation of the blades of guide devices, the use of multistage kinematic schemes, as well as its possible combination. Let's consider the first two of it in relation to "wet compression" and modeling using the CompressorWI-2S program.

2.1. Calculation of the "wet compression" Process Taking into Account the Bypass of Part of the Working Fluid Between Stages

Air bypass technologies in axial compressors are usually aimed at optimizing the flow inlet angles before the first and last compressor stages to avoid flow disruption at variable turbocharger speeds. It can be carried out by taking part of the compressed air flow outside or by passing between the stages.

Let's consider the second modification, which does not entail the loss of part of the compressed air. Since the compressor stages are calculated sequentially from its inlet, and the "internal" bypass is carried out from a high-pressure stage to a lower-pressure stage in the direction opposite to the main flow of the working fluid, another iteration cycle occurs in the calculation algorithm (flowchart). Between the selection stages and the "internal" supply, the flow rate of the working fluid will be increased by the amount of flow in the selection compared to the main two-phase flow. Compared to the calculation option without bypass, the parameters in the stage where a part of the working fluid is supplied change, and the power consumption in a number of stages changes. The calculation according to the CompressorWI-2S program can be carried out simultaneously taking into account the separation of liquid onto the compressor housing or, for simplification, without respect to this factor. An example of such a calculation for the

АЛ-21Ф-3 GTD, with respect to the separation of liquid onto the compressor housing, is given in Table 4 for the option of

bypassing 5.25% of the flow rate of a two-phase working fluid from the 9th stage of the compressor to the 4th stage.

Table 4. The effect of the internal bypass on some parameters in the compressor stages and in its outlet section when injecting 2% of the water flow at the inlet.

АЛ-21Ф-3 GTD, 2% injection at the compressor inlet, separation on the housing, bypass from stage 9 to stage 4							
Stage No.	1	2	3	4	5	6	7
G_{air} , kg/s	86,000	86,000	86,000	90,522	90,522	90,522	90,522
G_{cym} , kg/s	87,793	87,793	87,793	92,409	92,409	92,409	92,409
T_{st}^* , K	304.0	320.2	337.0	353.3	372.5	397.4	422.8
P_{st}^* , Pa	116500	135968	158834	188399	230052	298595	388875
N_{st} , W	1385844	1476484	1558746	1736899	2097250	2828323	3114301
n_{drop} , 1/s	3.08E+10	6.46E+11	7.41E+11	3.36 E+12	2.67E+12	4.50E+12	5.29E+12
d_{drop} , microns	4.00 E-05	1.26 E-05	1.14 E-05	9.88 E-06	1.05 E-05	8.67 E-06	7.89 E-06
Stage No.	8	9	10	11	12	13	14
G_{air} , kg/s	90,522	86,000	86,000	86,000	86,000	86,000	86,000
G_{cym} , kg/s	92,409	87,793	87,793	87,793	87,793	87,793	87,793
T_{st}^* , K	446.5	468.1	489.0	512.9	533.8	552.9	570.0
P_{st}^* , Pa	494196	603618	718232	828015	933389	1034264	1130730
N_{st} , W	3029326	2857337	2465681	2201833	1938666	1767607	1587776
n_{drop} , 1/s	5.90E+12	5.86E+12	3.74E+12	0	0	0	0
d_{drop} , microns	7.01 E-06	6.13 E-06	5.33 E-06	0	0	0	0
Compressor output parameters							
G_{air} , kg/s	G_{sum} , kg/s	T_c^* , K	P_c^* , Pa	N_c , W	n_{drop} , 1/s	d_{drop} , microns	π_c^*
86,000	87,793	570.0	1130730	30046073	0	0	11,159

In Table, G_{sum} is the total flow, including the flow of "dry" air, vaporized phase and liquid.

A comparison with the data in Table 1 for identical parameters in terms of liquid injection rate, size and temperature of injected droplets, and the proportion of its separation on the walls of the compressor housing in the first 3 stages shows that differences in parameters in the presence of an "internal" bypass are expressed as follows:

- the temperature T_c^* , K behind the compressor increased by 0.37%;
- pressure P_c^* , Pa and the degree of pressure increase in the compressor P_c^* decreased by 0.16%;
- power loss in the compressor increased by 2.5%;
- The complete evaporation of the injected liquid is also completed in 10 stages.

Thus, the increased flow rate of the working fluid between the 4th and 9th stages of the compressor did not significantly

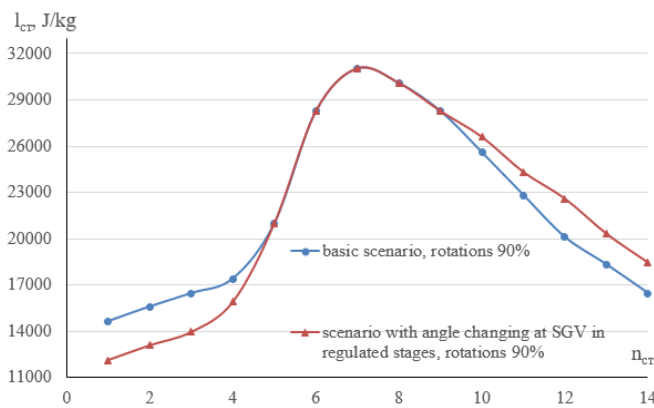
affect the parameters in the outlet section, and a slight increase in power loss for "wet compression" is compensated by optimizing the flow inlet angles before the first and last stages of the compressor to avoid flow disruption at variable turbo-charger speeds. Similar results were obtained for ГТЭ-160 GTU with the same internal bypass parameters.

2.2. Calculation of the "wet compression" Process in Gas Turbine Engine Compressors Taking into Account its Multifactorial Nature

The peculiarity of calculating an axial compressor in reduced modes is that a number of compressor parameters turn out to be interrelated and this is reflected in its characteristics. In particular, if the main variable parameter is the rotational speed of the compressor rotor n , rpm, or the reduced frequency

$\bar{n}_{rs}$, then the interrelated variables are the air flow rate G_{air} , the efficiency of the stages and the compressor as a whole, the axial component of the absolute velocity C_a , the specific operation of the stages l_{st} and the compressor as a whole. These relationships are characteristic of the operation of axial compressors in the absence of injection (or ingress of moisture from the atmosphere) of liquid into their flowing section, and they are naturally characteristic of "wet compression" in it.

The design feature of the considered AJI-21F-3 GTD is a well-developed control system for operating modes by means of rotary blades of the guide devices of individual compressor stages, in particular, 1-4 stages and 10-14 stages, to eliminate disruptive phenomena in its flow section. The control of the operating modes of the axial compressor using the rotary blades of the guide devices of the individual stages consists in lowering the angles α of the installation of these blades at the inlet and outlet for the first stages and increasing them in the last stages.



To simulate the process of "wet compression" in a compressor in reduced modes, according to the CompressorWI-2S program, the specified revolutions were selected $\bar{n}_{rs}$, equal to 90% and 70%, which corresponds to the compressor characteristics of the n1 turbocharger revolutions = 6570 rpm and $n_2 = 5110$ rpm, and G_{air} consumption, equal to 77.4 kg/s and 60.2 kg/s, the calculated compressor efficiency is 0.836 and 0.825, respectively. The previously mentioned mode c $\bar{n}_{rs} = 100\%$ or $n = 7300$ rpm, $G_{air} = 86.0$ kg/s, compressor effective efficiency 0.840 with "no injection" modifications and a water injection rate of 2% were chosen as the base mode for comparison.

The calculation results for these conditions are shown in Figure 2 and they show that when the angles of installation of the blades of the guide blades change, the specific compression work l_{st} is redistributed along the compressor stages.

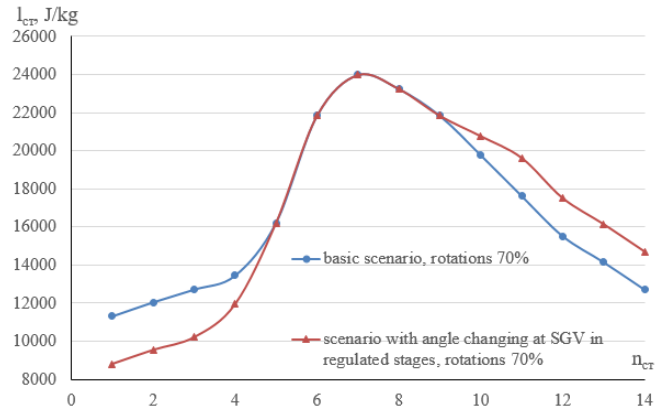


Figure 2. Specific operation of the stages of the AJI-21F-3 GT compressor during its operation with a rotor speed of 90 and 70% when changing the angles of installation of the SGV blades adjustable stages.

For revolutions $\bar{n}_{rs} = 90\%$, the angle α was assumed to be 1.6 degrees less for the first stage, 1.3 degrees more for the last stage; for $\bar{n}_{rs} = 70\%$, similar angle deviations were 2.8 degrees and 2.3 degrees. Obviously, when choosing other values of the rotation angles of the adjustable steps, we will get a slightly different distribution of specific work across the compressor stages. The required changes in these angles for adjustment, as a rule, do not exceed 5 degrees.

The simulation results of the "wet compression" process at low compressor speeds show that the rate of water evaporation slows down, although the percentage of water injection relative to air consumption remained unchanged and equal to 2%. Thus, for $\bar{n}_{rs} = 70\%$, complete evaporation of water is completed in 11 stages instead of 10 stages in the nominal mode, although its physical consumption is correspondingly 30% less.

2.3. Calculation of the "wet compression" Process in Compressors Taking into Account the Reduction in Blade Wettability

In a number of scientific papers, for example [9, 10], when modeling the process of "wet compression" in GTU axial compressors, the possibility of incomplete wetting of the surface of the blades of individual stages as a result of separation of liquid droplets from the stream on them with the formation of an evaporating film is considered. The reasons for this may be a number of factors, such as the uneven height of the liquid injection blades, the effect of centrifugal forces on the liquid film on the impeller blades, and the separation of part of the liquid onto the inner walls of the compressor housing. Insufficient flow densities and axial components of the absolute flow velocity in the steps, as well as other factors, are also significant.

Although the developed CompressorWI-2S program does

not provide complicated calculations of two-phase flows in a three-dimensional formulation, however, it provides the opportunity to perform calculations of the process of "wet compression" of air in axial compressors GTD and GTU, taking into account incomplete wetting of the blade surfaces of SGV and IB of its individual stages. This is solved by setting the relative values of the wetted surfaces of the K_{fim} and K_{fgv} blades in the table of initial data. By varying the values of these coefficients, it is possible to investigate the influence of this factor on the "wet compression" process and the compressor output parameters. Figure 3 shows an example of such a setting of the K_f coefficient (the same for the impeller and the guide device in the stage), taking into account the separation of water onto the walls of the compressor housing in the first 3 stages of the compressor at the same values of ε_c parameter by stages that were indicated above.

The results of modeling and calculating some parameters of the wet flow by stages in the flow section of the compressor and the parameters at the compressor outlet are presented in Table 5. Here, $K_f = 1$ meant that in the calculations, all surfaces of the IB and SGV of stages were considered wet. The data on the effect of incomplete wetting of the blade surface, with respect by the K_f coefficient, correspond to Figure 3. Table 5 presents the results for the 2% water flow rate during

injection at the compressor inlet, reflecting the flow parameters along the compressor stages and at its outlet based on the results of modeling the "wet compression" process without taking into account ($K_f = 1.0$) and taking into account the factor of incomplete wetting of the surface of the blades of IB and RGV ($K_f = 1.0 \dots 0.7$).

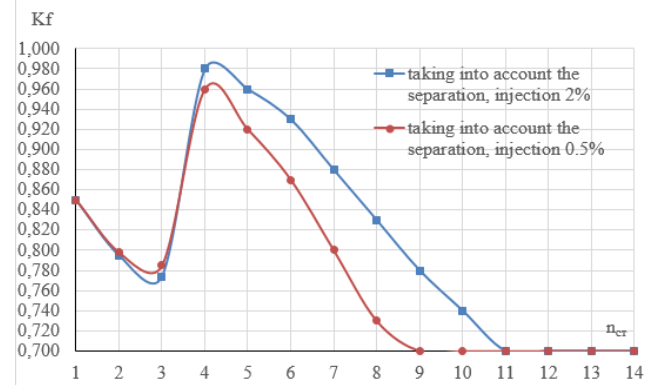


Figure 3. The values of the proportion of the wetted surface of the blades adopted when modeling the process of "wet compression" of air in the AJI-21F-3 GTD axial compressor, with respect to the separation of water on its housing during water injection before its 1st stage.

Table 5. Simulation results using the CompressorWI-2S "wet compression" program in the AJI-21F-3 GTD compressor, with respect to separation on the housing walls and the proportion of the wetted surface of the IB and SGV blades.

GTD AL-21F-3, 2.0% injection at the compressor inlet, drops of 40 microns, separation on the body, the proportion of the wetted surface of the blades of the IB and SGV $K_f = 1.0$							
Stage No.	1	2	3	4	5	6	7
T_c^* , K	304.0	320.2	337.0	352.9	371.8	396.3	421.4
P_c^* , Pa	116499.6	135968.3	158834.3	188353.2	230001.7	298632.6	389143.6
N_{st} , W	1385844	1476484	1558746	1650247	1992902	2688001	2960218
n_{drop} , 1/s	3.08E+10	8.51E+11	1.09E+12	2.57E+12	4.09E+12	4.81E+12	5.41E+12
d_{drop} , microns	4.00E-05	1.14E-05	9.88E-06	1.06E-05	8.88E-06	8.06E-06	7.16E-06
AJI-21Φ-3 GTD, 2.0% injection at the compressor inlet, drops of 40 microns, separation on the body, the proportion of the wetted surface of the blades of SGV and $K_f = 1.0$							
Stage No.	8	9	10	11	12	13	14
T_c^* , K	444.6	465.9	487.1	510.9	531.9	550.9	568.0
P_c^* , Pa	494870.3	604890.3	720262.3	830760.2	936851.4	1038437.5	1135603.7
N_{st} , W	2879941	2716908	2467813	2203596	1940218	1769022	1589047
n_{drop} , 1/s	5.43E+12	3.74E+12	9.50E+11	0	0	0	0
d_{drop} , microns	6.24E-06	5.46E-06	4.22E-06	0	0	0	0
Compressor outlet parameters for $K_f = 1.0$							
T_c^* , K	P_c^* , Pa	N_c , W	n_c , 1/s	d_c , microns	π_c^*		
568.0	1135603.7	29278987	0	0	11.207		

GTD AL-21F-3, 2.0% injection at the compressor inlet, drops of 40 microns, separation on the body, the proportion of the wetted surface of the blades of the IB and SGV Kf = 1.0

Stage No.	1	2	3	4	5	6	7
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AJL-21F-3 GTD, 2% injection at the compressor inlet, drops of 40 microns, separation on the body, the proportion of the wetted surface of the blades of SGV and Kf = 1.0 ... 0.7

Stage No.	1	2	3	4	5	6	7
T_c^* , K	304.0	320.2	337.0	352.9	371.9	396.5	421.8
P_c^* , Pa	116499.6	135968.3	158834.2	188352.3	229997.2	298610.6	389064.2
N_{st} , W	1385841	1476466	1558682	1650145	1992762	2687739	2959733
n_{drop} , 1/s	3.08E+10	8.51E+11	1.09E+12	2.57E+12	4.09E+12	4.81E+12	5.41E+12
d_{drop} , microns	4.00E-05	1.14E-05	9.88E-06	1.06E-05	8.88E-06	8.06E-06	7.16E-06

AJL-21Φ-3 GTD, 2% injection at the compressor inlet, drops of 40 microns, separation on the body, the proportion of the wetted surface of the blades of SGV and Kf = 1.0 ... 0.7

Stage No.	8	9	10	11	12	13	14
T_c^* , K	445.3	466.8	487.9	511.0	532.0	551.0	568.1
P_c^* , Pa	494642.0	604403.2	719404.6	829579.4	935496.9	1036915.1	1133919.6
N_{st} , W	2879164	2715879	2466807	2203170	1940218	1769022	1589047
n_{drop} , 1/s	5.43E+12	3.74E+12	9.50E+11	0	0	0	0
d_{drop} , microns	6.24E-06	5.46E-06	4.22E-06	0	0	0	0

Compressor outlet parameters for Kf = 1.0... 0.7

T_c^* , K	P_c^* , Pa	N_c , W	n_{drop} , 1/s	d_{drop} , microns	π_c^*
568.1	1133919.6	29274676	0	0	11.191

A comparison of the calculation results of the "wet compression" process in the AJL-21Φ-3 GTD compressor according to the parameters of the working fluid at the compressor outlet, taking into account and without taking into account the factor of incomplete wetting of the surface of the blades of the I and RGV shows that the differences in them are very small and amount to fractions of a percent. Thus, we conclude that thermodynamic factors such as changing pressure and temperature of the working fluid (two-phase mixture or vapor-air mixture), corresponding changes in the heat of vaporization along the flow part of the compressor, and the flow rate of liquid injection play a decisive role in the evaporation of moisture in the flow part of the axial compressor.

2.4. The Effect of Water Injection into the Flow Section of the Compressor on Its Characteristics

Next, we will consider examples and results of modeling the compression process in GTD and GTU axial compressors, based on the combined combination of the program Compres-

sorWI-2S with other software packages actively used for thermogasodynamic calculations of processes and cycles of GTD and GTU, but without detailed modeling of the "wet compression" process. In this case, the DVIGwT simulation system was used [11, 12]. Using this method, the characteristics of the AJL-21F-3 GTD axial compressor were calculated when water was injected into its flow section, which significantly reduces the input procedures required for multivariate calculations with various combinations of parameters using the CompressorWI-2S program alone. The results of such combined calculations, in particular, the characteristics of the AJL-21F-3 GTD axial compressor for both "wet compression" and "dry compression", are presented below in comparison with the previously published experimental data of the authors [3, 8].

The initial data for the basic calculations were the inlet air temperature $T_0 = 288$ K; pressure $P_0 = 101325$ Pa (760 mmHg); relative humidity $\varphi = 30\%$; air flow $G_{air} = 86.0$ kg/s; turbo-charger rotor speed $n = 7300$ rpm; for the injected liquid, $T_{g0} = 288$ K; the average median diameter of liquid droplets is $d_{drop} = 40$ μm. A comparison of the calculated and experimental data presented in Figure 4 and Figure 5 shows that for

all values of n_{rs} greater than 0.8, their high degree of coincidence is noted for both "wet compression" and "dry compression", which refers to both the characteristic for π_c^* , degree of

pressure increase in the compressor, so is the η_{eff}^* effective efficiency. Significant differences are noted only at low n_{rs} , mainly for "wet compression".

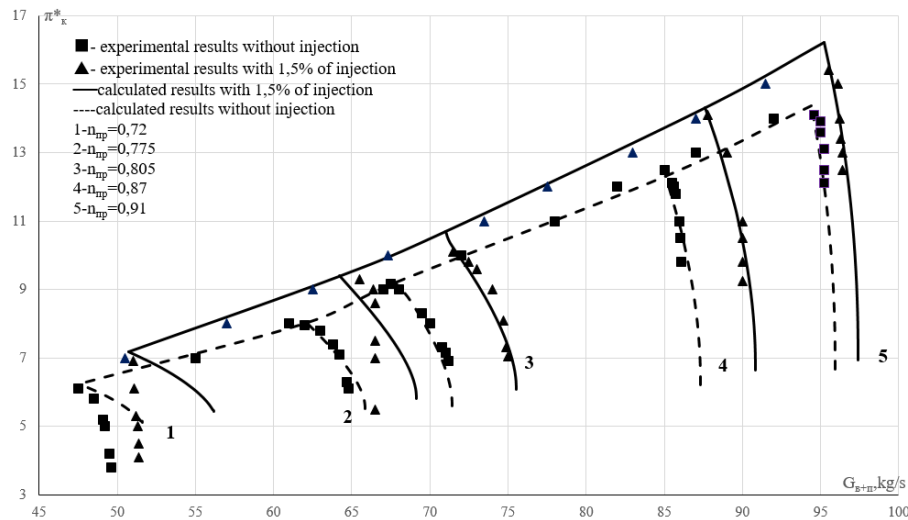


Figure 4. Comparison of the characteristics of the AJI-21F-3 GTD compressor in terms of the degree of pressure increase during injection and without injection of water into the flow section, calculated according to the methodology of this work and according to the results of bench tests by the authors [3, 8].

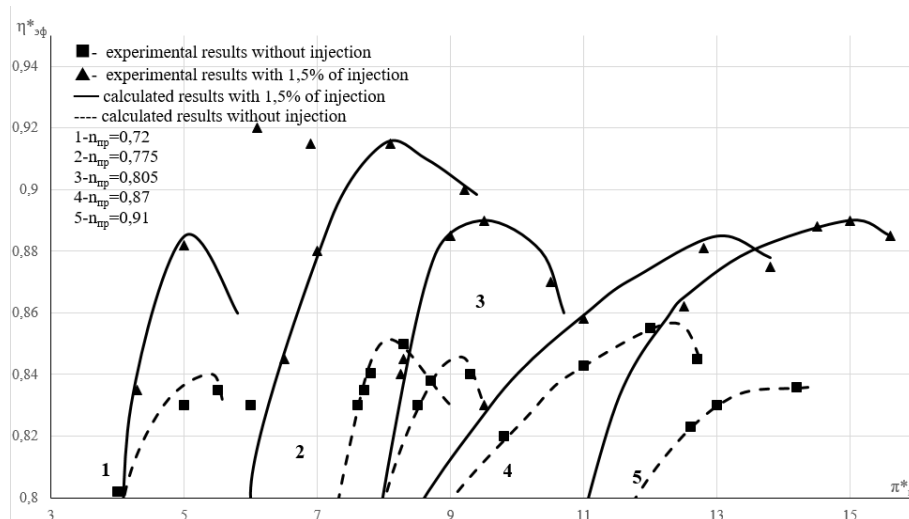


Figure 5. Comparison of the characteristics of the AJI-21F-3 GTD compressor in terms of effective efficiency with and without injection of water into the flow section, calculated according to the methodology of this work and based on the results of bench tests by the authors [3, 8].

2.5. Calculations of the "wet compression" Process in a Compressor Using the CompressorWI-2S Program

Water injection in GTD or GTU compressors leads not only to a change in the flow parameters in the flow section of the compressor and in its outlet section, affecting the characteristics, but obviously has an impact on the parameters of the power plant as a whole. Further, in the combustion chamber

and other elements of the engine or power plant, due to the injection of liquid and its complete evaporation in the compressor, the flow rate of the working fluid (moist air) increases compared with the air flow rate in front of the compressor, its pressure in front of the combustion chamber, its thermo-physical properties change, and these changes contribute to improving the characteristics of the gas turbine or gas turbine engine. At the same time, water injection in the compressor can, as a rule, reduce the total temperature T_c^* behind the compressor, which of course will also affect the parameters of power plants.

To assess the impact of the totality of these factors on their effective efficiency, the AJI-21F-3 GTD was modeled in 2 modifications: while maintaining the gas temperature T_g^* in front of the compressor turbine constant, which requires an increase in fuel consumption G_T in the cycle, as well as while maintaining the flow rate G_T unchanged when water is injected into the compressor, which leads to a decrease in T_{gas}^* . Calculations were also performed by combining the Compressor

WI-2S program and the DVIGwT simulation system for afterburning thrust operation of the gas turbine engine. The main simulation results are presented in Table 6. The specifics of these calculations also consisted in the fact that the injection of "super-heated" liquid was carried out at appropriate pressure levels, and this, when injected before the 8th and 12th stages of the compressor, made it possible to ensure almost "instantaneous" boiling of the liquid.

Table 6. The results of calculations of the gas turbine engine parameters during injection of "super-heated" water into the AL-21F-3 compressor in the amount of 2% of the air flow rate.

Calculation results for AJI-21F-3 GTD in afterburner mode							
Water consumption in shares of G_B	without injection	2%	2%	2%	2%	2%	2%
Injection site	-	before compressor	before compressor	before 8 stages	Before 8 stages	before 12 stages	before 12 stages
Condition	-	$T_r^* = \text{const}$	$G_t = \text{const}$	$T_r^* = \text{const}$	$G_t = \text{const}$	$T_r^* = \text{const}$	$G_t = \text{const}$
T_g , K	-	388	388	488	488	588	588
d_{dro} , microns	-	3	3	3	3	3	3
G_{air} , kg/s	86	87.72	87.72	87.72	87.72	87.72	87.72
T_{gas}^* , K	1373.1	1373.1	1301.5	1373.1	1339	1373.1	1346.9
G_{tur} , kg/s	1.9154	2.126	1.9155	2.0166	1.9155	1.9933	1.9155
G_{gas} , kg/s	87.9154	89.846	89.6355	89.7366	89.6355	89.7133	89.7133
T_{tur}^* , K	1111.3	1123.05	1047.1	1122.2	1086.03	1122.0	1094.23
l_{spe} , kJ/kg	321.7	314.79	315.53	315.17	315.53	315.25	315.53
p_{tur}^* , kPa	367.2	401.87	376.33	384.4	372.92	380.3	371.68
N_{tur} , kW	28282.8	28282.8	28282.8	28282.8	28282.8	28282.8	28282.8
T_{aft}^* , K	1102.1	1123.05	1047.1	1122.2	1086.03	1122.02	1094.24
P_{aft}^* , kPa	346.0	393.84	368.80	376.72	365.46	372.77	364.24
η_{noz}	0.99	0.99	0.99	0.99	0.99	0.99	0.99
R_{noz} , kN	71.4	77.39	72.90	76.17	74.06	75.88	74.27
T_{noz}^* , K	815	807.77	761.49	815.6	793.38	817.55	800.41
W_{noz} , m/s	812	861.40	813.40	848.8	826.32	845.88	828.6
η_{eff}	0.3518	0.364	0.3600	0.3727	0.3715	0.3744	0.3739

As the data in Table 6 presents, the injection of water into the flow section of the GTD compressor led to an increase in the cycle effective efficiency by 6.40%. $\eta_{noz}=0.99$ A comparison of the calculation results for the 2 above-mentioned calculation approaches when choosing the options $T_g^* = \text{const}$ or $G_{fuel} = \text{const}$ did not reveal a significant difference in effective efficiency of the η_{eff} cycle for both GTD and GTU modeled on the basis of the gas generator AJI-21F-3 GTD. This is explained

by the fact that as fuel consumption increases to ensure that $T_g^* = \text{const}$, the engine thrust increases equivalently in the case of GTD, and for GTU, the power of the free turbine increases accordingly. Similar results were obtained with respect to two-roller (two-stage) GTD designs.

The calculation results are consistent with the stand test data published in the scientific literature. The combined use of the programs CompressorWI-2S and DVIGwT allows you to perform multivariate calculations in order to select the optimal

conditions and parameters for liquid injection into the flow section of the compressor at the stage of preliminary design of power plants.

3. Conclusions

A methodology has been developed for calculating the "wet compression" process in GTD axial compressors and the CompressorWI-2S program, which allows considering a complex of diverse factors at the design stage of compressors and their modification during the development of various types of transport and energy GTU based on them, including:

- 1) type (single shaft or double roller), geometric and operating parameters of the compressor;
- 2) selection of the injection point of water into the flow section of the axial compressor;
- 3) selection of parameters of the injected liquid;
- 4) changing the parameters of the compressible working fluid in steps, taking into account the dependence of the thermodynamic and thermal and physical properties of air and water vapor on temperature and pressure;
- 5) the degree of separation of liquid on the inner walls of the compressor housing;
- 6) the presence of a bypass of a part of a two-phase compressible working fluid (both external – selection and between stages);
- 7) possibility of injection of "super-heated" liquid;
- 8) incomplete wetting of the surfaces of the IB and SGV blades,
- 9) adjustment by means of rotary blades of separate stages.

The influence of these factors can be assessed separately and together in the required combination.

The results of calculations based on the developed program are confirmed with a fairly high degree of reliability by known data from bench tests and experiments performed for the AJI-21F-3 GTD.

Abbreviations

IB	Impellers Blades
SGV	Stage Guide Vanes
GTD	Gas Turbine Engine
GTU	Gas Turbine Unit
ε_c	Separation Coefficient
Tl0	Compressor Inlet Temperature
st	Stage
g0	The Injected Liquid
rs	Reduced Speed
eff	Effective
l	Liquid
Kfim	Impeller Wettability Coefficient
Kfgv	Wettability Coefficient of the Guide Vane
tur	Turbine
spe	Specific

noz Nozzle

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Conflicts of Interest

The authors declare no conflicts of interest.

References

- [1] Ma Jiarui., Bakirov Fedor Gayfullovich. Effectiveness Analysis of Water Injection into the GTD Compressor Duct in Its Various Stages. Journal of Electrical Systems. Vol. 20 № 5s (2024). - Page 1281 - 1285. ISSN 1112-5209. Jes is indexed by Scopus and ISI Thomson Reuters.
<https://doi.org/10.52783/jes.2455>
- [2] Certificate of state registration of computer program No. 2024668838 "Program for calculating a compressor with water injection, taking into account separation and bypass between stages Compressor WI-2S". F. G. Bakirov, Ma Jiarui, R. F. Bakirov, O. F. Akhtyamova. Date of registration: 12.08.2024. Moscow: ROSPATENT, 2024. Sereda S. O., Gel'medov F. S., Muntyanov I. G. Experimental study of the effect of water injection into the inlet channel of a multistage axial compressor on its characteristics. Thermal Engineering. 2004. T. 51. № 5. C. 409-414.
- [3] Berkovich, A. L. Water injection into a gas turbine compressor: monograph. A. L. Berkovich, V. G. Polischuk, V. A. Rassokhin: - St. Petersburg: Polytechnic University. 2010. - 154 p.
- [4] Kistoichev, A. V. Design of blading apparatus for axial compressors of gas turbines: a tutorial. A. V. Kistoichev. - Ekaterinburg: Ural. University, 2014. - 120 p.
- [5] Pismenny, V. L. Russian Patent No. RU 2535186C1 Method for regulating an axial compressor in a gas turbine engine system. V. L. Pismenny. Published: 10.12.2014.
- [6] Sereda, S. O. Increasing the efficiency of stationary gas turbines based on aircraft gas generators by injecting water into the flow path of the axial compressor: Abstract of Cand. Sci. (Eng.): 05.07.05. Sereda Svetlana Oganovna. - M., 2006. - 42 p.
- [7] Sereda S. O., Belyaev V. E., Gelmedov F. Sh., Muntyanov I. G., Muntyanov G. L. Results of tests of the compressor of the MES-60 unit with water injection into the flow part. Gas turbine technologies. - 2005. - No. 4 (39). - P. 16-20.

- [8] Skvortsov A. V. Increasing the parameters of gas turbine units by injecting water into the flow path and optimizing the working process in the compressor: dissertation Cand. of Technical Sciences: 05.04.12. Skvortsov Aleksandr Vsevolodovich. - St. Petersburg, 2010. - 173 p.
- [9] Anurov Yu. M., Peganov A. Yu., Skvortsov A. V., Berkovich A. L., Polishchuk V. G Calculation study of water injection on compressor characteristics of a gt-009 gas-turbine installation. Thermal Engineering. 2006. T. 53. № 12. C. 964-969.
- [10] Goryunov I. M. Thermogasdynamic calculations in the DVIGwT software package: a tutorial. I. M. Goryunov. - Ufa: Ufa State Aviation Technical University, 2022. - 162 p.
- [11] Certificate of state registration of computer program No. 2004610623. I. M. Goryunov, "System of mathematical modeling of thermal, energy and combined units (DVIGwT)" dated 04.03.2004. Moscow: ROSPATENT, 2004.
- [12] Ma Jiarui., Bakirov Fedor Gayfullovich. Methodology for Determining the Completeness of Liquid Evaporation when Injected into the Path of Gas Turbine Engine and Gas Turbine Compressors. Proceedings of the International Conference «Scientific research of the SCO countries: synergy and integration». Part 1 - Reports in English. March 13, 2024. Beijing, China, PRC. Page 190 - 194. Scientific publishing house Infinity. 2024 <https://doi.org/10.34660/INF.2024.91.42.361>
- [13] Ma Jiarui. CompressorWI-2S program for calculating "wet compression" in an axial compressor of a gas turbine engine with water injection into its tract, taking into account water separation, bypass or selection of the working fluid. Ma Jiarui, F. G. Bakirov. Bulletin of Ufa State Aviation Technical University. - 2024. - Vol. 28. - No. 3 (105). - P. 100 - 115. https://doi.org/10.54708/19926502_2024_283105100
- [14] Ma Jiarui. On the influence of liquid injection into the flow path of axial compressors of gas turbine engines on the process of "wet compression". Ma Jiarui, F. G. Bakirov, I. M. Goryunov. Bulletin of Ufa State Aviation Technical University. - 2025. - Vol. 29. - No. 3 (109). - P. 96 - 109. https://doi.org/10.54708/19926502_2025_29310996

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