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Effectiveness Analysis of Water Injection into the GTD Compressor Duct in Its Various Stages

Abstract: **-** this report presents the results of the authors research using the developed CompressorWI program to assess the influence of water injection conditions into the compressor ducts of GTD and GTU on their parameters and characteristics.

Keywords: GTD compressor, liquid injection; program for calculating parameters; calculation results; tables and graphs; analysis of results

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I. INTRODUCTION

A significant number of experimental studies and tests have been devoted to the influence of water injection into axial GTD and GTU compressors, as well as examples of modeling these processes in the scientific and technical literature. Such works include, for example, research of the authors of the works [1,2,3,4,5, etc.]. The interest in this topic is given the rise to the fact that, as shown by the authors of these works, as well as the results of numerical modeling by the authors of this work on the example of GTD AL-21 14-stage axial compressor, performed using the developed program CompressorWI Visual Studio 2022, written in the C# programming language (C Sharp) [6], water injection into the compressor duct allows you to significantly increase its effective efficiency η_ef^*, compression ratio π_c, and improve some of the characteristics of the GTD as a whole.

II. EFFECTIVENESS ANALYSIS OF WATER INJECTION INTO THE GTD COMPRESSOR DUCT IN ITS VARIOUS STAGES

With complete evaporation of water in the path, working fluid parameters at compressor outlet are determined primarily by thermodynamic factors related to the heat of evaporation of water and energy exchange between the evaporating liquid and compressed air, and therefore with the flow rate of injected water G_f. To improve the characteristics of the compressor, it is advisable to supply water in such a way as to provide it with the possibility of the most efficient rapid and complete evaporation, thereby reducing hydraulic losses along the duct. And in this case, the determining factor is that the maximum degree of water evaporation in the stage is limited along the

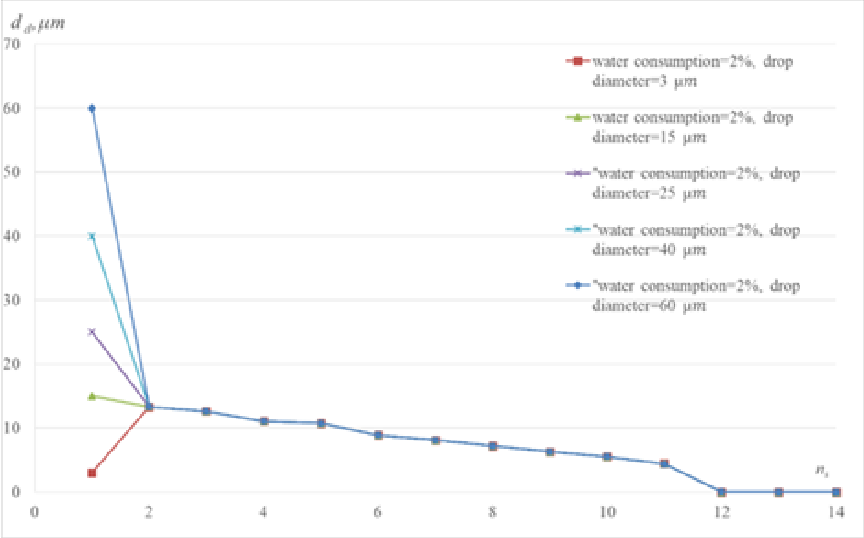

Figure 1 – Droplets diameters in stages when liquid droplets of different sizes are injected at the compressor inlet

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duct under conditions of increasing pressure and temperature by the maximum relative humidity of the mixture of air and steam, equal to $\varphi = 100\%$, that is, the saturation state with partial pressure $P_s = f(t)$. Let's consider these aspects in more detail, based on the results of numerical simulation of the GTD AL-21 compressor using the CompressorWI program. The choice of it as the base for calculations was determined by the presence in earlier publications of its detailed geometric dimensions and the results of bench tests.

The maximum moisture content in $d_{si}$the compressor stages is determined by the classical formula:

$$d_{si} = 0{,}622\frac{P_{si}(t_i)}{P_i - P_{si}(t_i)}, \frac{kg}{kg}, \qquad (1)$$

Table 1 The results of calculating the parameters of the vapor phase in a mixture with air along the compressor duct when injecting 2% water in front of the compressor. The droplet diameter is 40 µm, the relative humidity at the inlet is φ=30%, the number of revolutions of the turbocharger is 7300 rpm.

Step number	T, K	P, MPa	d, kg/kg	g_v, %	r_v, %	P_v, MPa	P_s, MPa	d_s,kg/kg
1	303,2	0,1163	0,0007	0,0679	0,1092	0,0001	0,0001	0,0007
2	318,5	0,1351	0,0009	0,0891	0,1434	0,0002	0,0003	0,0014
3	334,5	0,1572	0,0013	0,1280	0,2060	0,0003	0,0009	0,0034
4	350,9	0,1867	0,0018	0,1760	0,2831	0,0005	0,0014	0,0048
5	369,7	0,2282	0,0025	0,2477	0,3981	0,0009	0,0029	0,0079
6	393,9	0,2966	0,0038	0,3792	0,6090	0,0018	0,0064	0,0136
7	418,6	0,3871	0,0061	0,6093	0,9774	0,0038	0,0136	0,0226
8	441,8	0,4928	0,0094	0,9358	1,4982	0,0074	0,0240	0,0318
9	461,4	0,6030	0,0130	1,2862	2,0547	0,0124	0,0389	0,0429
10	481,0	0,7191	0,0173	1,6980	2,7058	0,0194	0,0573	0,0539
11	504,9	0,8308	0,0204	1,9981	3,1782	0,0264	0,0976	0,0828
12	526,0	0,9382	0,0204	1,9981	3,1782	0,0298	0,1358	0,1053
13	545,1	1,0412	0,0204	1,9981	3,1782	0,0330	0,1803	0,1303
14	562,3	1,1397	0,0204	1,9981	3,1782	0,0361	0,2320	0,1590

where P_i,t_i and $P_{si}$are pressure, temperature and the corresponding partial pressure of steam in the saturation

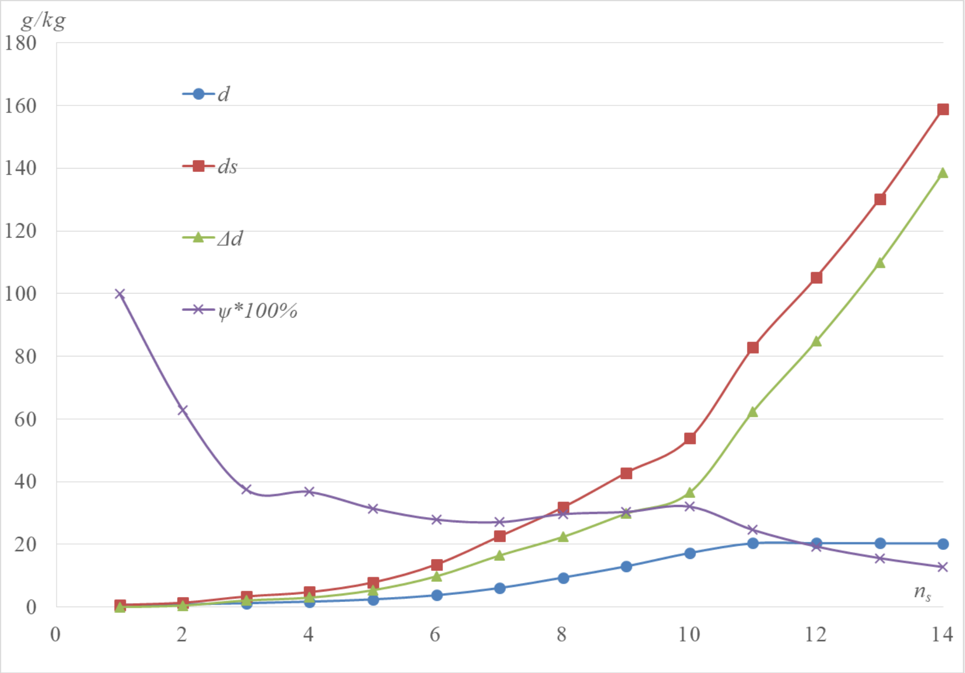

Figure 2 – Changes in the values of the mass moisture content, their differences and the degree of saturation along the compressor stages.

state for the i-th stage of the compressor.The specifics of the calculation $P_{si}(t_i)$ by stages after the liquid injection section is that due to the evaporation of water in the previous stage of the compressor, the mass of the gas phase in the next stage increases, the liquid phase acts as a source term in the equation for the total mass of the mixture of air and steam. Thus, not only $P_i$and t_i, but also the mass fraction of steam g_{vi} and the volume fraction increase step by step r_{vi}.

The real proportion of evaporated water is characterized by the degree of saturation also by steps:

$$\psi_i = \frac{d_i}{d_{si}}, \tag{2}$$

where d_i is determined by the calculation results according to the CompressorWI program, taking into account all the factors provided for in the calculation model.

Fig. 2 shows the dependences characterizing $P_s = f(t)$according to [7] data for pure water vapor and the semi-empirical equation describing it, which:

$$P_s(t) = 8 \cdot 10^{-7} T_s^3 - 8 \cdot 10^{-4} T_s^2 + 0{,}301 \cdot T - 37{,}08, \tag{3}$$

we derived. These data are used taking into account the volume fraction of steam in the composition of the working fluid for the calculation d_{si}.

The dependencies for stepwise temperature and pressure changes along the AL-21 compressor path are also presented here, calculated according to the CompressorWI program, taking into account the evaporation of part of the water and hydraulic losses in the previous stages – for $G_f = 2{,}0\% \cdot G_a$ and injection of water before the compressor. There are also calculated data for compression in a compressor without liquid injection.

Table 1 shows the calculation results for all 14 stages of the GTD AL-21 compressor, where the first 3 lines reflect the calculated data for the CompressorWI program. Subsequent calculations were aimed to determining the maximum moisture content for each stage d_{si}, degree of saturation ψ, which will allow estimating the $G_f$possible and calculated degree of evaporation of water for various injection costs, and identifying the optimal options for choosing the injection site along the compressor duct. The sequence of determining the parameters presented in Table 1 was as follows:

- the mass fraction of steam in the flow was determined by steps according to the formula:

$$g_{vi} = \frac{d_i}{1 + d_i}; \tag{4}$$

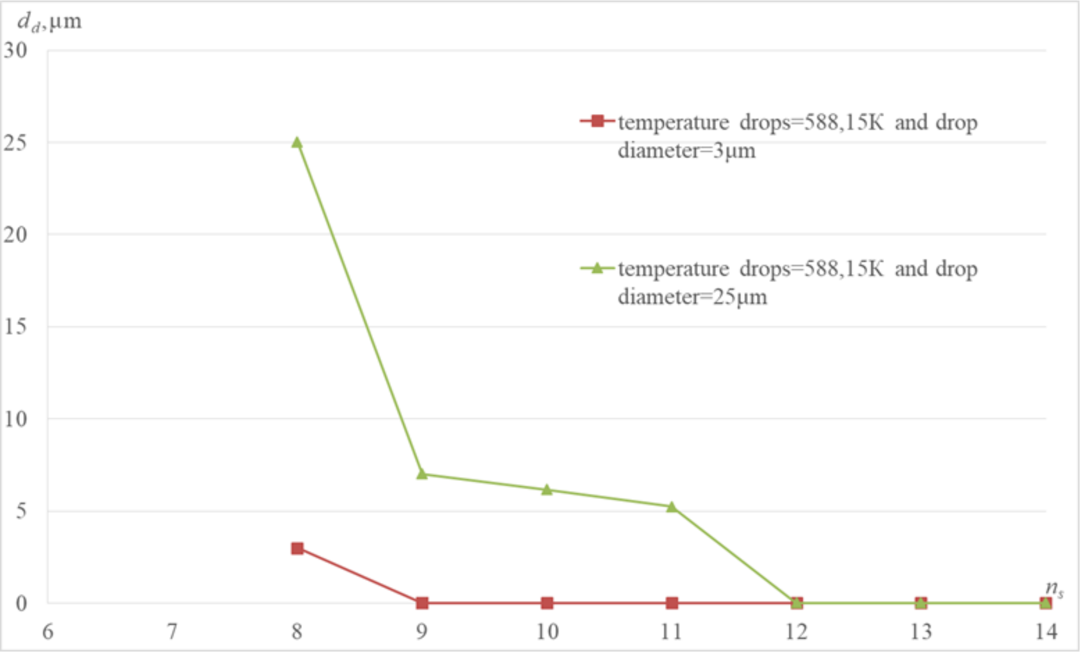

Figure 3 – Change in the diameter of droplets when water is injected before the 8th stage of the compressor.

- the volume fraction of steam was calculated r_v:

$$r_{vi} = \frac{\frac{g_{vi}}{\mu_v}}{\frac{g_{vi}}{\mu_v} + \frac{(1 - g_{vi})}{\mu_a}}; \tag{5}$$

- from this, the partial vapor pressures in the air were determined P_{vi} and $P_s = f(t)$;
- the maximum mass moisture content d_{si} in the saturation state was calculated using the above formula.

The results of Table 1 are shown in Fig.3 in the form of dependency graphs for $d_i, d_{si}, \Delta d = d_{si} - d_i$ and ψ by compressor stages. It is clearly seen that up to about stage 4, the mass moisture content is d_i very close to the limit for the saturation state and even very fine spraying of water to droplet diameters of the order of 3 μm (for example, injection of superheated liquid) will not allow for rapid evaporation (Fig. 1). Only by the 7th stage does it become possible for the $G_f = 2{,}0\% \cdot G_a$ injected water to completely evaporate without limiting the degree of saturation. In reality, complete evaporation is achieved only in stage 11, therefore, the limitation is not due to thermodynamic reasons, but to the physics of evaporation processes in the stage itself (diffusion, etc.). For 1% and 1.5%, G_f such an opportunity appears only in 5 and 6 steps, respectively.

These data make it possible to select, depending on the flow rate of the injected water, the most acceptable injection sections along the compressor duct to ensure complete evaporation of the liquid with minimal losses on hydraulic resistance in the liquid phase. As can be seen from Fig.2 and Table 1, already in the 8th stage d_{si} exceeds the value of 2% G_f of the air flow in the compressor, therefore, under certain injection conditions, evaporation can end even in one stage. For example, Figure 3 shows similar data for injection of water with a flow rate $G_f = 2{,}0\% \cdot G_a$ with droplet sizes of 3 μm and 25 μm before the 8th stage of this compressor. Genuinely, droplets with a diameter of 3 μm, despite significant water consumption, evaporate within 8 steps. For the above reasons, larger droplets of 25 μm within the 8th stage do not have time to completely evaporate, then the process switches to a predominantly film evaporation mode and ends in the 11th stage.

The considered results were obtained for a specific 14-stage GTD AL-21 compressor, but these patterns will similarly manifest themselves in other GTD and GTU compressors, including newly designed ones, the predicted data can also be obtained using the CompressorWI program.

Table 2 Check the liquid injection before the compressor for its effective efficiency.

Water injection flow rate	Without injection	0,5%	1%	1,5%	2%	2,5%	3%
T, K	617,1	604,0	588,0	574,0	562,3	545,9	533,3
$G_f, kg/s$	0	0,43	0,86	1,29	1,72	2,15	2,58
$G_a, kg/s$	86	86	86	86	86	86	86
$\pi_{c.v}$	10,8	11,07	11,22	11,32	11,36	11,48	11,53
η_{ef}^*	0,842	0,862	0,876	0,888	0,898	0,911	0,921
Increasing the effective efficiency %	-	2,34	4,84	5,48	6,58	8,17	9,34

In addition, we present the results of calculations of the effective efficiency of the compressor η_{ef}^* under "wet" compression, the increase of which was mentioned according to other authors at the beginning of the article. To determine it, the calculation method used in the Central Institute of Aviation Motors named after P. I. Baranov was used (Moscow) with the calculation data for the program for the compressor in question.

$$\eta_{ef}^* = \frac{\bar{R}_{mix}\left(\pi_{c\cdot v}^{\frac{\gamma-1}{\gamma}} - 1\right)_v}{\left(\frac{T_c}{T_1} - 1\right)_{dry}} \cdot \frac{G_a + G_f}{G_a}; \tag{6}$$

where

$$\bar{R}_{mix} = \frac{R_{mix}}{R_a} = \frac{1 + \frac{R_v}{R_a} \cdot \frac{G_f}{G_a}}{1 + \frac{G_f}{G_a}}; \tag{7}$$

$\pi_{c \cdot v}$ - the degree of pressure increase in the compressor during "wet" compression.

The calculation results are shown in the table.2 for different water injection costs. They were obtained on the basis of calculations using the CompressorWI program for "wet" compression in the GTD AL-21 compressor and this technique and confirm the thesis of a significant increase in the effective efficiency of the compressor when water is injected into its duct.

CONCLUSION

Thus, the calculation results presented in this paper demonstrate the possibility of choosing the optimal flow rates and cross sections along the compressor duct for injecting water into the duct of GTD and GTU compressors, depending on the purpose and the task being solved. At the same time, injection at the compressor inlet is the least effective due to the low evaporation rate in the initial stages and increased hydraulic resistances.

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