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To investigation of performance of the gas turbine plant, which operates with the working medium humidification in the inlet and overexpansion in the outlet

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Abstract. The possibilities of increasing the specific power and efficiency of the gas turbine plant are considered by the working medium overexpansion behind the power turbine and the water injection into the engine inlet. The paper demonstrates that such a means can be used not only for a newly designed GTP, but also implemented in already operating power plants.

1. Introduction

It is known that the combustion chamber temperature and the compressor pressure ratio should be increased in order to achieve relatively high efficiency of a gas turbine plant (GTP). Higher temperatures negatively affect the engine service life and the design of high pressure ratio compressors remains a task of high complexity, especially for relatively small engines.

Researchers in Russia, Germany, and Great Britain at various times considered solutions to increase the GTP efficiency by lowering the pressure behind the power turbine. For this purpose, a heat exchanger was proposed to be installed at the engine exhaust for cooling the working medium and then compressing it in a gas compressor [1–3]. In all these designs, the gas (boosting) compressor was driven by a power turbine. Difficulties in matching the power turbine rotational speed, which, for example, drives simultaneously an electric generator with rotational speed of 3000 rpm and a booster compressor of 12000 rpm, ultimately defined this approach as unworkable.

The idea of producing the reduced pressure behind the power turbine was implemented by the invention of a vacuum unit (VU), a completely autonomous member that consists of an over-expansion turbine, a heat exchanger and a booster compressor [4]. Gas turbine engine with the VU is shown in Figure 1. Here the VU itself is demonstrated with sequentially located over-expansion turbine 1, heat exchanger 2, and booster compressor 3. The work obtained on it due to expansion of the hot gas and compression of the cold gas is transmitted by the gas duct to the power turbine of the main engine, behind of which the reduced pressure is set of $P = \sim 0.09$ MPa and below.



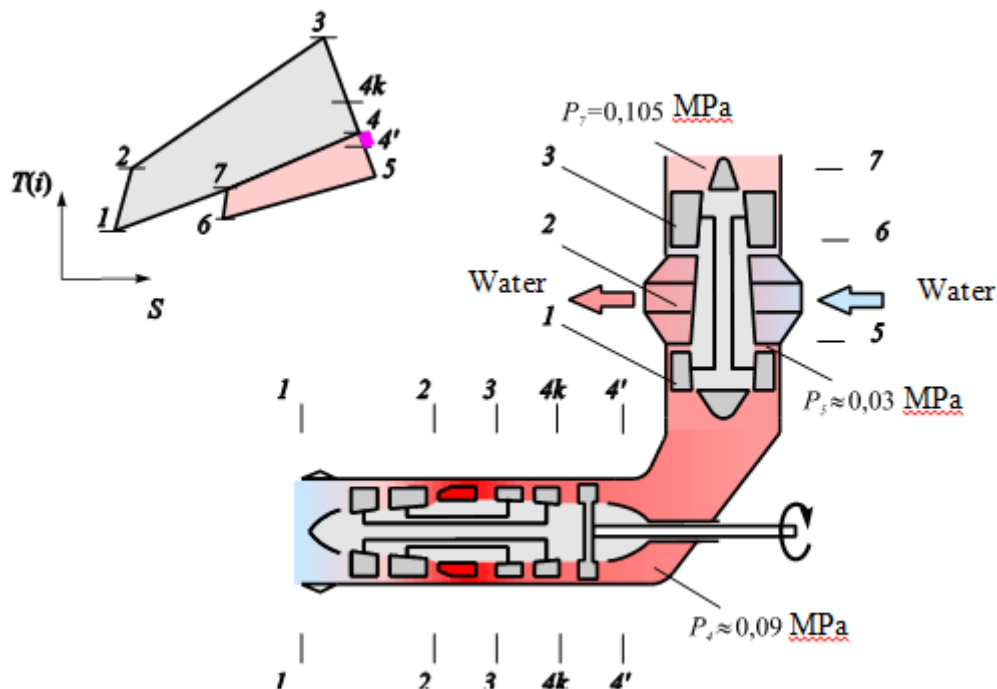


Figure 1. GTP with overexpansion of the working medium behind the power turbine on the basis of a vacuum unit.

The work gain of the pressure lowering behind the power turbine is shown in T-S diagram (it is equivalent to an area of 4-5-6-7). A number of studies of a similar power plant was carried out in Russia in the Kazan Aviation Institute [5] and experimentally tested in the Sevastopol State University [6].

This paper is devoted to further exploring the possibilities of the cycle with overexpansion. The authors pay attention to the effective way of increasing the power plant efficiency and specific power by water injection in the inlet and in the flow passage of the main compressor of the GTP.

The subject of this work study is to identify the possible combinations of the GTP parameters, namely, water injection in the engine inlet in the booster compressor inlet. This problem statement is relevant in view of further improving the efficiency and had not been previously studied in such a combination according to the scientific publications.

To understand the defining relationships of the problem under study, at the first stage of the analysis we consider the following:

- parameters of the GTP of a simple scheme;
- GTP with a simple vacuum unit (VU);
- an engine according to item b) with the water injection in front of the booster compressor of the VU.
- an engine with the water injection in the GTP inlet only;
- an engine with the water injection both in the GTP inlet and in the inlet of the booster compressor of the VU.

Let us refer to Figure 2. As we can see, in a simple cycle, the maximal efficiency $\eta_{\max} = 0,405$ is attained at $\pi_{\max} = 46.6$. In this case, $L_{\max} = 345$ kW/kg/s. For stationary gas turbine plants, such high rates of pressure ratio are not achievable yet. The maximum specific power $L_{\max} = 415$ kW/kg/s is attained at $\pi_{\text{KL}} = 15.5$. Here, the efficiency $\eta_{\text{GTP}} = 0.356$. Let us consider a certain promising gas turbine plant with $\pi_{\text{K}} = 24.6$ and $\eta_{\text{GTU}} = 0.386$. We carry out a numerical analysis of parameters for it with different levels of complications in order to obtain high values of efficiency and specific power.

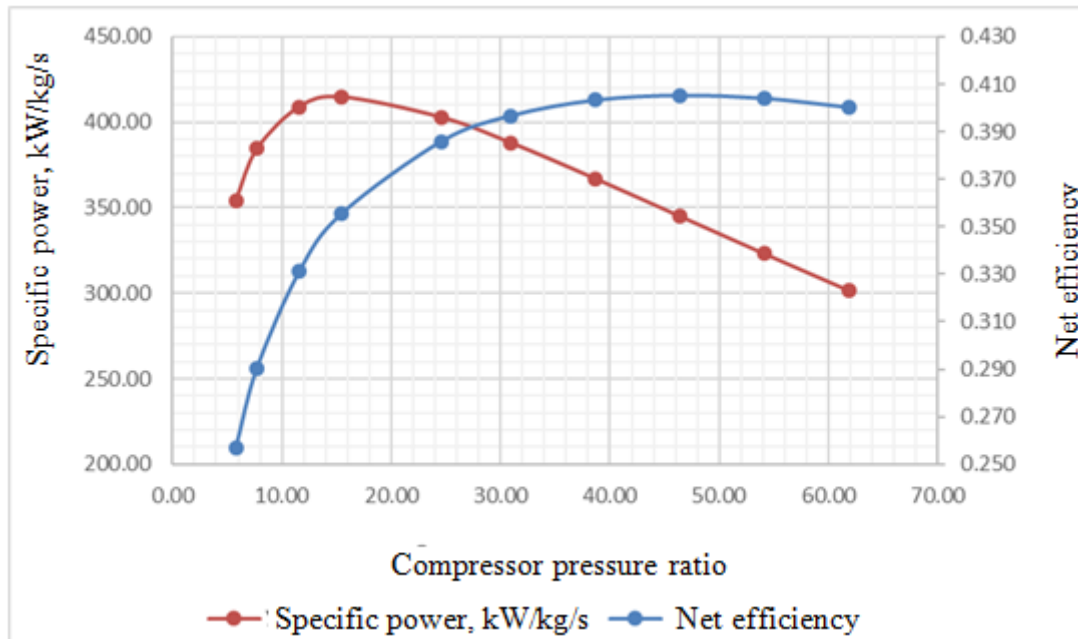


Figure 2. GTP of the simple scheme.

Next, we calculate the scheme of the gas turbine plant shown in Figure 1. Here we assume that a simple VU is installed behind the main engine. The working medium is cooled to $T_5 = 320\text{K}$ in front of the booster compressor. The efficiency reaches $\eta_{\text{VU}} = 0.448$ at the pressure ratio in the vacuum compressor $\pi_{\text{kv}} = 3.5$. Comparing the obtained result with the simple engine, we can see that the excess in efficiency occurred $\delta\eta = 0.448 / 0.386 = 1.1606$ times. In power, $\delta Ne = 18575/16000 = \sim 1.16$ times (which is natural).

Here we should note the following. The highest efficiency of a power plant with a VU is achieved when the engine being complicated operates around its maximum power (in Fig. 1, this mode is corresponded of the pressure $\pi_L = 15.5$). But at the same time, optimal pressure ratio in the VU compressor reach values of the order of $\pi_{\text{kvopt}} = 7-8$, which leads to the unacceptable heat exchanger dimensions. Based on the design reasons, let us use the best of achieved pressure ratio values $\pi_k = 24 - 25$. For the last one, at $\pi_{\text{kv}} = 3.5$, according to the preliminary calculations, the efficiency does not reach the maximum on less than about 1%.

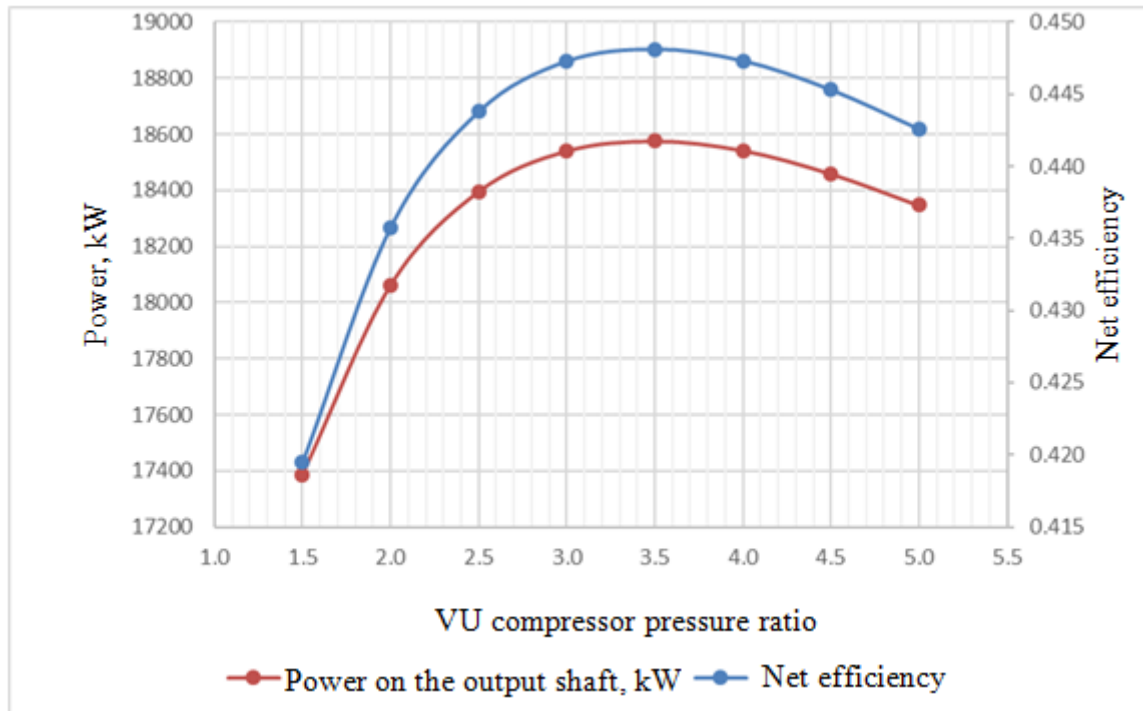


Figure 3. GTP with the simple VU.

Further, we consider a gas turbine plant with a VU, which is injected in the inlet approximately of 0.6% of the total water flow. The results are presented in Figure 4. As can be seen from the graph, there is a further increase in the specific work and in efficiency. The excess in efficiency is $\delta\eta = 0.459 / 0.386 = 1.189$, the excess in the specific power is $\delta N_{sp} = 479.27 / 402.85 = 1.189$.

Great efforts to further increase the gas turbines efficiency by the method of injecting water into a low-pressure compressor began around 1995. The main studies in this direction are carried out by Hitachi and Siemens. There are reports of such works being carried out by General Electric, Chinese, Russian companies, etc. [7, 8].

In modern developments, a number of researchers experimentally showed that the injection of water in the inlet to the main compressor makes it possible to increase the GTP absolute efficiency on 2–3%.

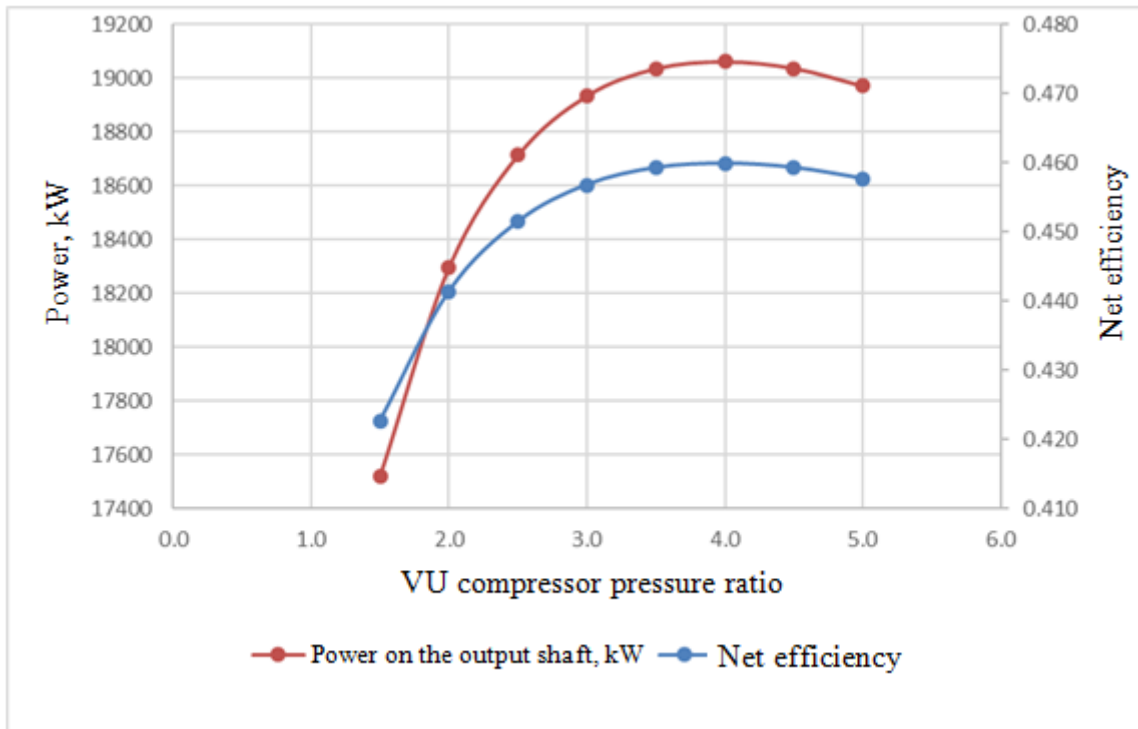


Figure 4. GTP with the VA under the water injection in VU.

Experiments with hot water injection are known also. It should be noted that earlier and at present, the injection of cold water to the engine inlet is widely used in military aviation when taking off from high-altitude airfields in the summer time.

Let us address to Figure 5. Here the calculation results of parameters with water injection in front of the GTP inlet are presented. As before, the pressure ratio in the booster compressor here is $\pi_{kv} = 3.5$. As calculations shown, with injection of 0.54 kg/s water, the efficiency $\eta_{GTP} = \sim 0.5$ can be obtained in this case. Other parameters are significantly improved also.

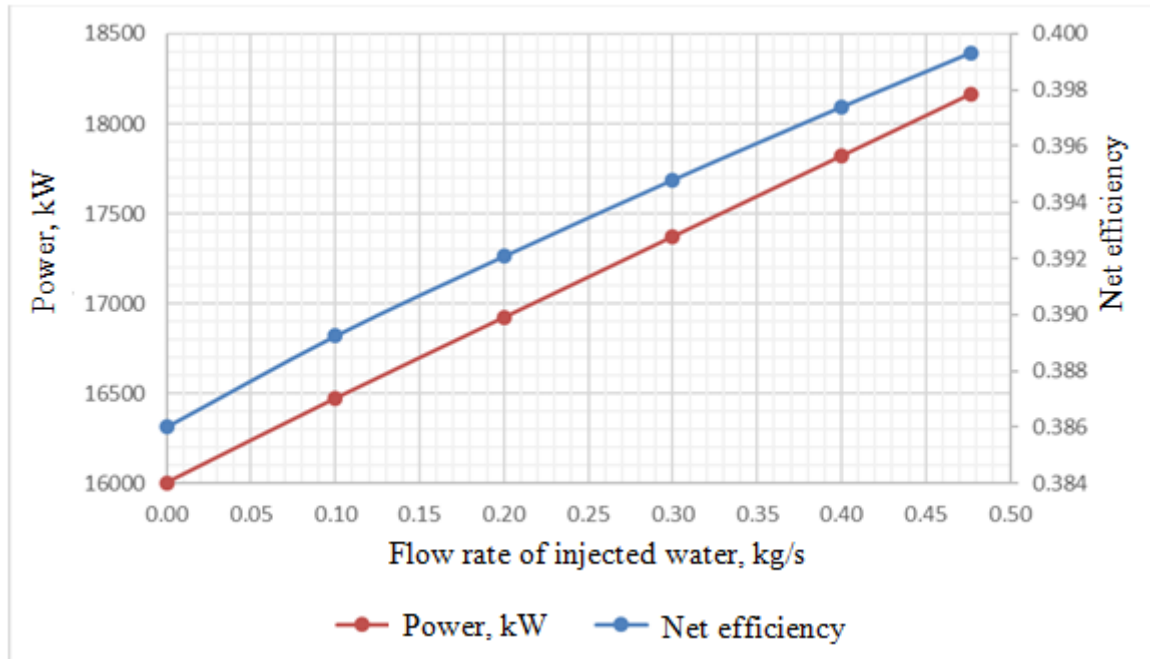


Figure 5. GTP parameters in the case of water injection in the GTP inlet.

In conclusion, we consider to the plant, in which water is injected both in the inlet of the main GTP and in the inlet of the VU. Here, the GTP efficiency reaches $\eta_{\text{GTP}} = 0,4815$. The remaining calculation results for this plant are shown in Table 1.

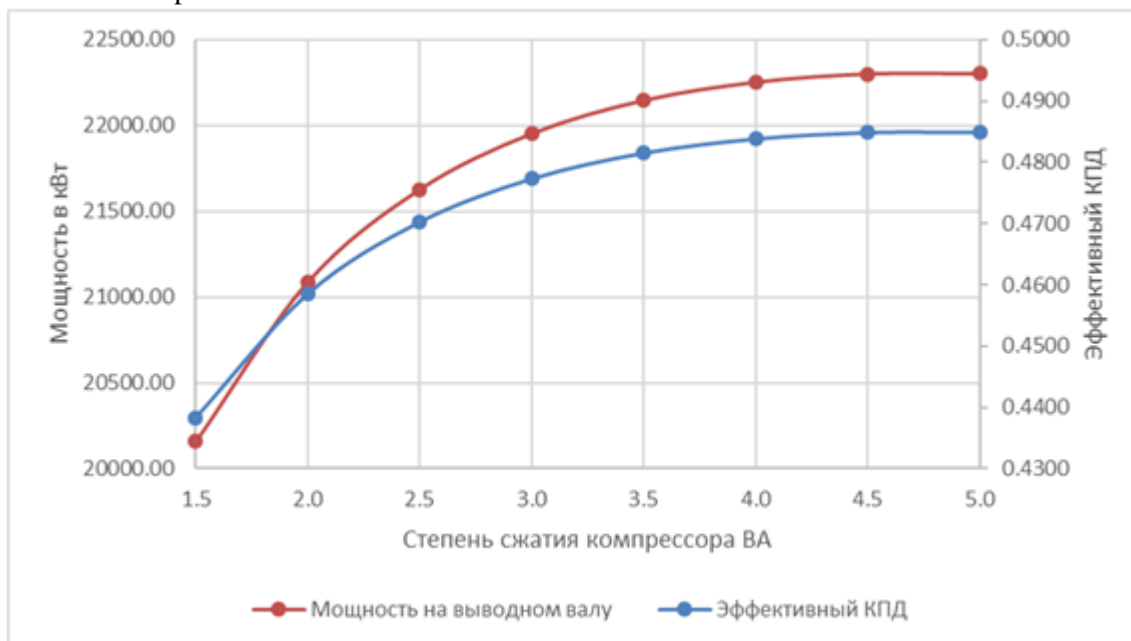


Figure 6. GTP parameters in the case of water injection in the GTP inlet.

Table 1. Calculation results for the plant, in which water is injected both in the inlet of the main GTP and in the inlet of the VU.

No.	Name of parameter	Notation	Unit	Initial GTP	GTP+VU	GTP+VU+H ₂ O	GTP+VU+H ₂ O inlet	GTP+VU+H ₂ O inlet
				GTE-1	GTE-2	GTE-3	GTE-4	GTE-5
	Scheme number							
1	Engine power	N_e	kW	16000	18575.7	19036.6	18164	22146.9
2	Specific power of engine	$N_{e_{sp}}$	kW/kg	402.851	467.666	479.27	457.3	557.575
3	Air flow rate in the inlet	G_g	kg/s	39.72	39.72	39.72	39.72	39.72
4	Pressure ratio of the main compressor	π_k		24,61	24.61	24.61	24.61	24.61
5	Gas temperature in front of the turbine	T_3	K	1500	1500	1500	1500	1500
6	Pressure ratio of the vacuum unit	π_{kv}		–	3,5	3,5	-	3,5
7	Specific fuel rate	C_e	kg/kW□h	0.179	0.154	0.150	0.173	0.144
8	Relative increment of specific power			1	1.1606	1.189	1.135	1.384
9	Total fuel flow rate per hour	G_f	kg/h	2867,06	2866.34	2866.34	3145.34	3180.55
10	Net efficiency	□		0.386	0.448	0.459	0.399	0.4815
11	Relative decrement of the fuel flow rate			1	1.162	1.193	1.035	1.243
12	Relative increment of efficiency			1	1.1606	1.189	1.0336	1.248
13	Temperature of exhausted gases	T_{exh}	K	776	478.24	437.135	777.13	389.513
14	Cooling degree	τ		1	0.616	0.563	1	0.502
15	Flow rate of injected liquid in front of the VU compressor %%	G_{cool}	kg/s			0.539	-	1.073
16	Flow rate of injected liquid in the inlet of engine	G_{inj}	kg/s			-	0.477	0.477
17	Total flow rate of injected water		kg/s				0.477	1.493
18	Flow rate of water in the heat exchanger		kg/s		80	80	-	80

The analysis shows that it is quite possible (in continuation of this work) to consider the issue of upgrading some GTPs in operation in view of a substantial increase both the power and economical efficiency, or the efficiency only.

In conclusion, we consider the main parameters of GTP with all the improvements designed for a capacity of 16 MW. The data obtained are given in Table 2.

Table 2. The main parameters of the GTP.

	Name	Notation	Unit	Mode No. 0
1	Engine power	Net	kW	16000.0
2	Specific engine power	Ne_sp	kW/kg/s	586.294
3	Air flow rate in the engine inlet	G	kg/s	27.290
4	Pressure ratio of the main compressor	C2	-	24.628
5	Gas temperature in front of the turbine	T*_2	K	1500
6	Pressure ratio of the vacuum unit	Pi*_k	-	3.5
7	Specific fuel rate	C_sp	kg/h·kW	0.143
8	Total fuel flow rate per hour	S_TSum	kg/h	2283.210
9	Net efficiency	h	-	0.4815
10	Gas temperature at the exit of the heat exchanger	T*_2	K	319.984
11	Flow rate of injected liquid in the inlet of engine	G_z1	kg/s	0.305
12	Flow rate of injected liquid in front of the VU compressor	G_z2	kg/s	0.368
13	Flow rate of water in the heat exchanger		kg/s	54

As can be seen from Tables 1 and 2, in the second case (with water injection and VU installed), the engine of the power of 16 MW can be designed not for the flow rate of 39.72 kg/s, but for the flow rate of 27.3 kg/s, with the efficiency not equal to $\eta = \sim 0.386$, but to $\eta = \sim 0.4815$, which exceeds the original version in terms of economy by $\sim 25\%$.

All numerical studies were performed on a specially designed mathematical model.

2. Conclusions

A comparative analysis of various schemes with over-expansion of the working medium behind the power turbine showed that it is possible to modernize existing GTPs, as well as to create new power plants using the stated methodology.

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