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IMPROVING THE EFFICIENCY OF GAS TURBINE BY USING AEROTHERMOPRESSOR FOR INTERCOOLING CYCLIC AIR

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ABSTRACT

The most common direction of increasing power and reducing fuel consumption is contact cooling of the air flow by water injection. The methods of cooling cyclic air include technology of thermogasdynamic compression – an increase in pressure as a result of the instantaneous evaporation of injected liquid into the airflow accelerated to the speed of sound in a two-phase jet device – aerothermopressor. An analysis of a number of models was carried out using computer CFD-modeling to determine the main characteristics of the aerothermopressor. As a result of thermogasdynamic compression, the increase in the air pressure of the aerothermopressor has been 1.5–10.0% at incomplete evaporation. It was found that provides efficient fine atomization of a liquid with an average droplet diameter of 15 μm. This contributed to an isothermal process in the compressor. It allowed to increase efficiency and to reduce specific fuel consumption by 1.5-2.0%.

Keywords: Gas Turbine, Instantaneous Evaporation, Inject of Water, Aerothermopressor, Intercooling Cyclic Air, Thermogasdynamic Compression, Dispersion Flow.

1. INTRODUCTION

There are several directions for the development of energy-saving technologies that ensure the utilization of low-grade heat of secondary energy resources and contribute to increasing the efficiency of combustion engines and plants (Kumar, et al., 2013; Radchenko A. et. al., 2018, 2020; Trushliakov E. et al., 2018, 2020),. Complex gas-turbine circuits with cyclic air cooling are mainly used to approximate the process of compressing the working fluid in gas turbine compressors to isothermal, which leads to an increase in the thermal efficiency of the cycle (Kumar et. al., 2013; Trushliakov E. et. al., 2020; Radchenko A. et. al., 2020; Forduy S. et. al., 2020).

Today, the most promising is contact cooling of cyclic air, for the implementation of which you can use a two-phase jet device - an aerothermopressor (Eidan A. and Alwan K., 2017; Konovalov D. and Kobalava H., 2020). This device provides efficient evaporative cooling of gas turbine without loss of total pressure. And with the rational organization of work processes and the corresponding development of the design of the flow part of the aerothermopressor, the probability of increasing air pressure at the outlet of the apparatus by 5-30% (Konovalov D. and Kobalava H., 2020; Stepanov I. and Chudinov V., 1977; Alekseev, A., 1961; Konovalov D. et al., 2020).

2. THE RESULTS

2.1. General approaches and original ideas

One of the promising ways to increase the efficiency of the GTP is to use air intercooling at the compression process in the compressor, that is, increase the compressor work efficiency by isotherming the process of air compression (to come of the final compression temperature near to the initial) (Jonsson, M. and Yan, J., 2005). Hence, without loss of power, the temperature of the gases at the inlet of the turbine is reduced, which favorably affects the GTP's resource or the opportunity to increase the GTP's power without reducing the life of its operation (Khaliq A. et al., 2010; Mahmoudi S. et al., 2009).

Supply of water to the compressor channel of the GTP is one of the effective ways to increase the capacity and efficiency of the GTP (Jonsson, M. and Yan, J., 2005). High pressure water is injected into the unsaturated air flow in which it evaporates, because of the difference of the partial pressures of water vapor on the surface of the water droplets and in the air flow, heat is removed from the cyclic air. Water injection carries out two functions: it removes heat from the air flow and returns it to the GTP cycle. This method has long been used in the wide range of GTP (Yang, Ch. et. al., 2009).

A promising method of water spraying is to use the thermodynamic compression, which allows combining two physical processes, such as contact air cooling and pressure increase (Konovalov D. and Kobalava H., 2020). To implement these functions an aerothermopressor is used (Stepanov I. and Chudinov V., 1977; Fowle A., 1972). It should be noted that to use the thermodynamic compression, as a means of efficient spraying of water and increasing the mass flow rate of workflow in gas turbine plants, is one of the topical trends in improving the efficiency of power plants based on gas turbine engines (GTE) and internal combustion engines (ICE) (Günnur, Şen G. et al., 2018; Popli S. 2013; Konovalov D. et al., 2020).

The difference of the proposed technology lies in the fact that it provides the intensive heat and mass transfer processes and high flow speed in the air cooler, an effective fine atomization of water. Thus, when more water is injected than is necessary for complete evaporation, there is a more efficient evaporation of the remaining droplets in the air flow when compressed in the high pressure compressor of the GTE (Konovalov D. and Kobalava H., 2020).

The use of the aerothermopressor for cooling cyclic air has several advantages, namely:
1) to accelerate the air flow to close to the sound speed and water evaporation with minimal aerodynamic resistance, the thermal potential of the power plant cyclic air is used;
2) the air pressure increase in the aerothermopressor allows to compensate for the aerodynamic losses along the GTP path and to reduce the compression work in the compressor stages;
3) at the contact cooling, the working flow is increased, and as a result, the power of the GTP increases;
4) the aerothermopressor is more compact and structurally and technologically simple apparatus in comparison with traditional surface air coolers.

The main problem in the development of the aerothermopressor is to determine the geometric characteristics of the flowing part of the apparatus and the system of fluid injection, which would allow its effective use (Butrymowicz D. et. al., 2018; Elbel S., 2016; Elbel S., 2011; Smierciew et al., 2014). Due to this, it is appropriate to carry out numerical simulations of the aerothermopressor to determine its basic characteristics (Lawrence N. and Elbel S., 2015; Zhu J. and Elbel S., 2016; Lawrence N. and Elbel S., 2012).

2.2. Research methodology

To determine the main characteristics of the aerothermopressor of the GTP cyclic air cooling system, a series of typical models were analyzed by using CFD modeling in the ANSYS Fluent software complex. On this basis, the design of the aerothermopressor for the GTP brand WR-21 Rolls Royce was developed. The aerothermopressor was installed between the stages of the compressor GTP.

The aerothermopressor construction is designed to study work processes in the event of thermogasdynamic compression in order to determine the optimal geometric and operational parameters. A working fluid is considered as the moist air with initial parameters of pressure, temperature and relative humidity of air corresponding of the gas turbine cycle parameters after the first stage of the compressor (Table. 1).

3D model of the aerothermopressor is shown in Fig. 2. The following basic geometric characteristics of the aerothermopressor model flow part were adopted: aerothermopressor length (at (L/D) = 5) Latp = 1324 mm; confuser inlet diameter D_{c1} = 188 mm; confuser convergent angle α = 35 °; working chamber diameter D_{ch} = 68 mm; working chamber length L_{ch} = 340 mm; diffuser outlet diameter D_{d2} = 190 mm; diffuser divergent angle β = 5 °; droplets diameter 1-10 μm.

Table 1. Technical characteristics of the aerothermopressor operation for the GTP WR-21 from Rolls Royce

Parameter	Value
Inlet air pressure P_{atp1}, kPa	301,3
Inlet air temperature T_{atp1}, K	650
Mach number at the inlet working chamber M	0,5-0,55
Relative velocity of injected fluid (w_w/w_{air1})	0,55
Temperature of injected water T_{w1}, K	300
Air mass flow G_{air}, kg/s	1,56
Relative mass flow rate of injected water g_w, %	5–15

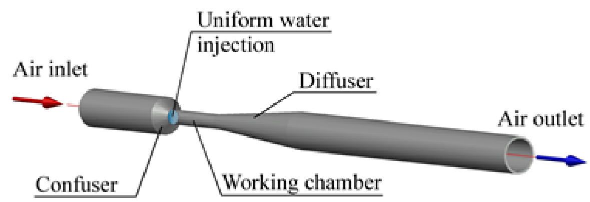

Figure 1: 3D model of the aerothermopressor

Numerical simulation of the airflow process in the aerothermopressor was carried out using the finite volume method in the ANSYS Fluent software package (ANSYS, 2016; Nijdam J. et. al., 2006; Montazeri H., 2015). A calculation method was defined based on the Pressure-Based solvers, a turbulence model was selected, a calculation was made taking into account the convergence of results, and the output data were processed and visualized in Post Processing in the form of graphs and fields for the main parameters of the workflow.

The operating parameters of gas turbine compressors were calculated according to well-known methods (ANSYS, 2016; Nijdam J. et. al., 2006; Montazeri H., 2015), taking into account the peculiarities of moist air compression.

The initial parameters for numerical computer simulation are the main parameters of a two-phase flow (air-water) at the exit of the aerothermopressor (at the entrance to the next degree of a gas turbine compressor): total air pressure P_{atp}, air velocity w_{air} and water velocity w_w, temperature T_{atp}, water droplet diameter in the air flow δ, air density ρ_{atp}, mass concentration of water m_{H2O}.

2.3. Analysis of the research results

The cycle air flow rate of the WR-21 gas turbine plant is quite high and amounts to about 50 kg/s. Therefore, the length of the aerothermopressor will exceed 10 m, which makes it impossible to constructively develop the aerothermopressor model. It is advisable to use several devices arranged in a circle. For example, it is proposed to use 30 aerothermopressors with an evaporation chamber diameter by D_{ch} = 68 mm and the air mass flow by G_{air} = 1.56 kg/s. The use of such a low-cost aerothermopressor will ensure its length up to 1.5 m, which allows constructively installing it into the gas turbine.

Special attention should be paid to the injection system at the aerothermopressor modeling, since the average water droplet diameter at the outlet of the nozzle and their distribution over the cross section of the flow part determines, ultimately, the length of the evaporation section. Hence the friction loss will be determined and, as a result, a complete increase in pressure in the result of thermogasdynamic compression. For application in the composition of the modeling aerothermopressor, a thin atomization nozzle (FMT-120) was used. For this nozzle type the dispersion of sprayed water at the pressure above 3.5 MPa is δ = 10-15 microns. Water injection was carried out at the inlet of the evaporation chamber.

To ensure maximum pressure increase as a result of thermogasdynamic compression, water injection was carried out with excess. At the inlet to the diffuser (the evaporation chamber outlet), the amount of liquid was at least 15% of the total water flow.

At the first stage of the study, a simulation of a "dry" aerothermopressor was carried out (without water injection into the evaporation chamber). It was found that the decrease in the air flow pressure (Fig. 2, a, b) due to friction losses is ΔP_{dry} = 15 kPa (5%). The air velocity w_{dry} (Fig. 2, c) at the inlet to the evaporation chamber is 280 m/s (0.55 M). The diffuser divergent angle ensures the absence of flow separation and the presence of reverse currents at the walls of the diffuser, which reduces local pressure losses in the diffuser (Fig. 2d).

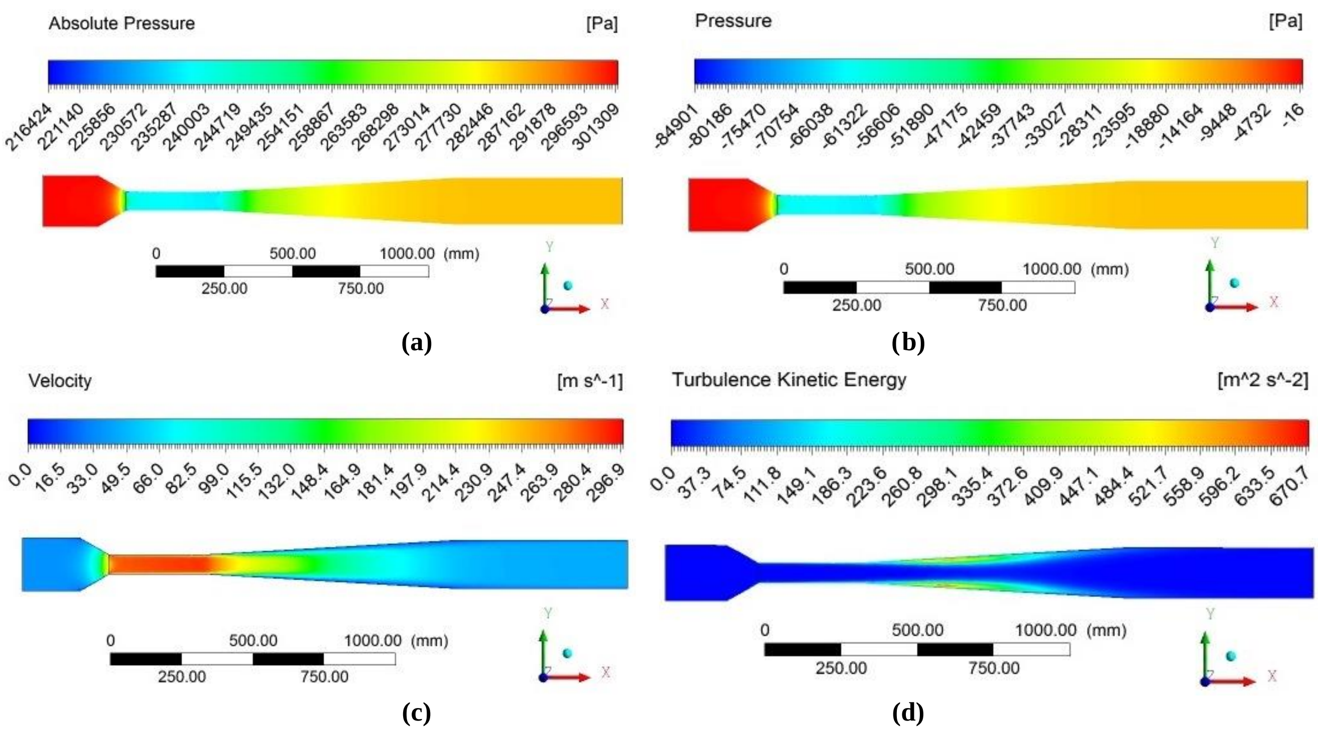

Figure 2: The fields distribution of the total pressure P_{dry} (a), difference in static pressure $\Delta P_{st.dry}$ (b), flow velocity w_{dry} (c) and turbulent kinetic energy k (d) in the flow part of the "dry" aerothermopressor (without water injection)

At the second stage of the study, an aerothermopressor was simulated with water injection into the flow part (at the evaporation chamber inlet).

The increase in total pressure as a result of thermogasdynamic compression (Fig. 3, a) is ΔP_{atp} = 4.5 kPa (3.1 %) relative to the inlet pressure. It should be noted that the velocity (Fig. 3b) in the evaporation chamber increases and amounts to w_{atp} = 285 m/s (0.56 M), which is explained by an increase in the mass flow rate of the working fluid with a constant cross-sectional diameter. then the velocity decreases approximately by 4-6% due to an increase in density during evaporation of liquid droplets and cooling of the flow. Also, there is no separation of the flow and the presence of reverse currents at the walls of the diffuser, which positively affects the reduction of local pressure losses in the diffuser.

The cooling of the cyclic air in the aerothermopressor is ΔT_{atp} = 280 K (Fig. 3, c), from the initial temperature T_{atp1} = 650 K (377 °C) to the outlet temperature T_{atp2} = 370 K (97 °C). The increase in pressure as a result of thermogasdynamic compression is also caused by an increase in the flux density ρ_{atp} due to liquid evaporation from 1.6 kg/m^3 to 2.5 kg/m^3 (Fig. 3d).

The mass concentration of water that does not evaporate at the aerothermopressor outlet (at the diffuser outlet) is

m_{H2O} = 0.11 kg/m^3 (Fig. 3, f), while the specific mass amount of water (Fig. 3, e) that evaporated μ_{H2O} = 0.085 (8.5% of the total flow rate of the working fluid). Excess water should evaporate already in the flow part of the gas turbine compressor. This amount is almost μ_{H2O} = 0.02 (2%), which in terms of the absolute mass flow rate of water is G_w = 0.031 kg/s for one aerothermopressor, and for the whole complex of the cooling system by aerothermopressors are up to $G_{w.GTU}$ = 0.93 kg/s.

The dispersion of water droplets at the evaporation chamber inlet was in accordance with the characteristics of the nozzle δ_1 = 10 µm. As a result of contact evaporation, the diameter of the droplets decreased and, at the diffuser outlet water did not evaporate, the dispersion averaged δ_2 = 2.5 µm (Fig. 4, 5). In this case, the concentration of water droplets (dispersed two-phase flow) at the outlet is observed closer to the axis of the diffuser and has a diameter of about 50 mm.

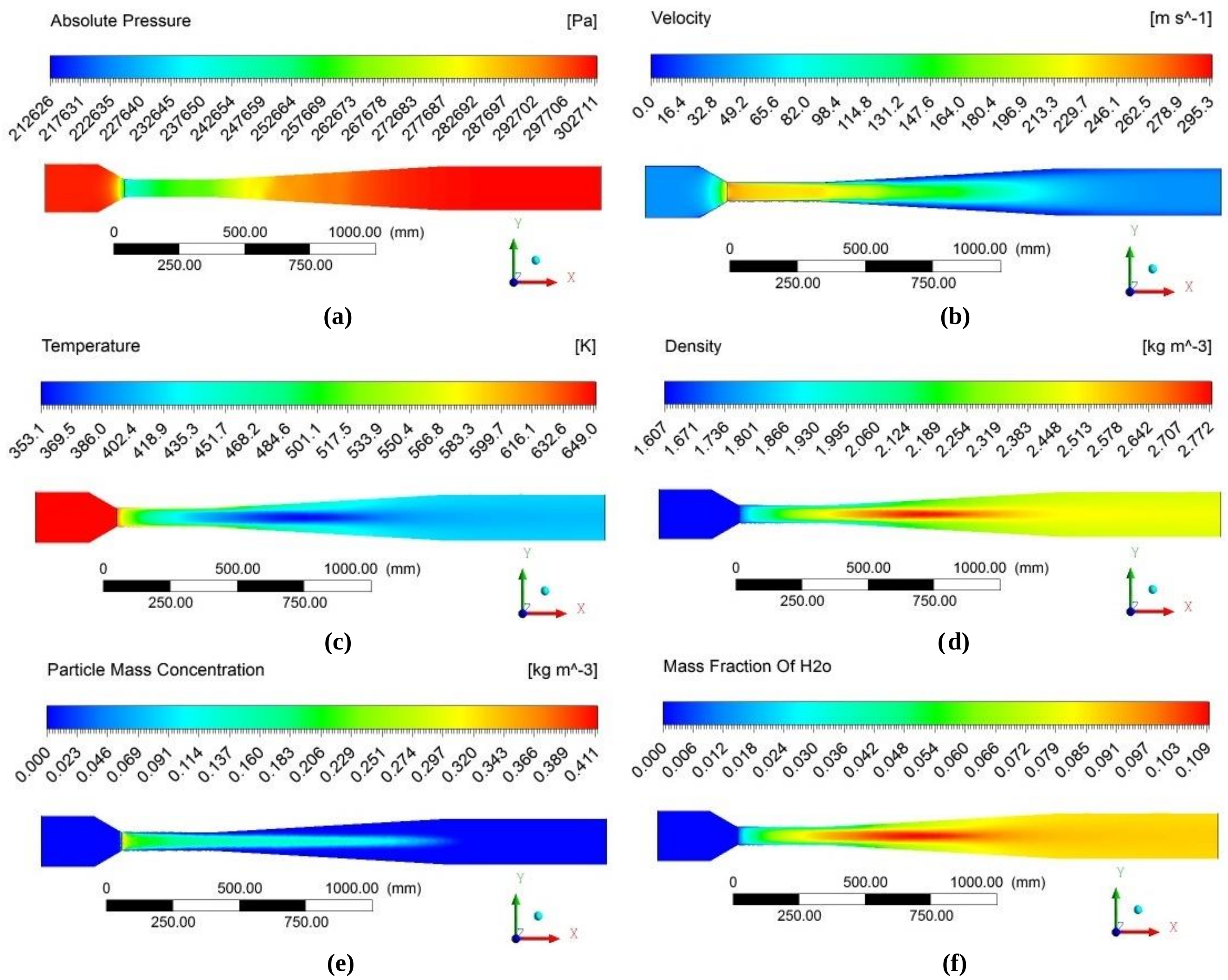

Figure 3: The fields distribution of the total pressure P_{atp} (a), flow velocity w_{atp} (b), flow temperature T_{atp} (c), flow density ρ_{atp} (d), mass water concentration m_{H2O} (e) and specific mass amount of evaporated water μ_{H2O} (f) in the aerothermopressor flow part

Comparison of the change in pressure P_{atp} along the length of the flow in the aerothermopressor with and without injection (Fig. 5) shows that the pressure in the evaporation chamber decreases from 240 kPa to 235 kPa due to losses, that is, the pressure loss is P_{ter1} = 5 kPa (1.7 %). However, the presence of thermogasdynamic compression increases the pressure and compensates for these losses. In this case, the total pressure in the evaporation chamber increases by ΔP_{atp1} = 15 kPa (5 %).

In the diffuser, the flow velocity decreases to 30-40 m/s with a simultaneous increase in pressure. In the absence of a dispersed flow in the diffuser (a "dry" aerothermopressor), the pressure increase is $\Delta P_{dry.atp2}$ = 50 kPa (16.6%), and in the presence of a dispersed flow ΔP_{atp2} = 54.5 kPa (18.1 %). The increase in pressure in the aerothermopressor flow part with water injection compared to the "dry" aerothermopressor will be $\Delta P_{dry.atp}$ = 20.5 kPa (6.8 %). Thus, the total increase in pressure (compared with the initial inlet pressure) in the aerothermopressor will be ΔP_{atp} = 9.5 kPa (3.1 %), which suggests the advisability of using this method for contact cooling of cyclic air between the stages of gas turbine compressors.

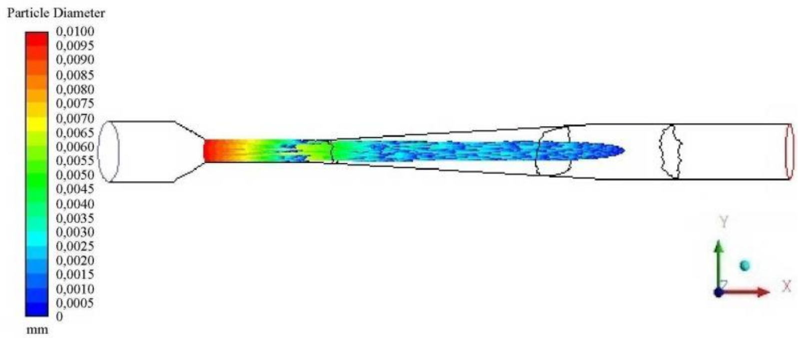

Figure 4: Dispersion distribution δ of injected water in the aerothermopressor flow part

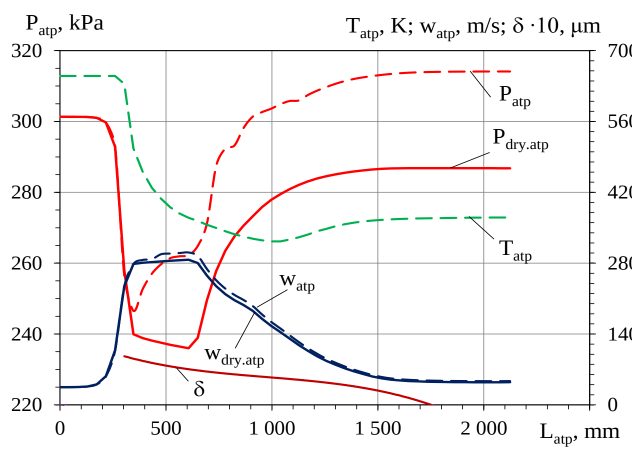

Figure 5: Dependences of the main characteristics of the flow: total pressure P_{atp}, flow velocity w_{atp}, flow temperature T_{atp} and average droplet diameter injected water δ along the length of the aerothermopressor flow part L_{atp}:
__________ - for a "dry" aerothermopressor;
_ _ _ _ _ - for an aerothermopressor with water injection into the evaporation chamber

3. CONCLUSIONS

Computer numerical simulation of the aerothermopressor for intercooling of cyclic air of GTP WR-21 Rolls Royce was carried out, its basic characteristics were determined.

The results of modeling the aerothermopressor operation showed that the increase in the total pressure of the cyclic air between the compressor stages is ΔP_{atp} = 4.5 kPa (3.1 %), the air flow is cooled by ΔT_{atp} = 280 K.

To ensure effective air compression in the gas turbine compressor, incomplete water evaporation in the aerothermopressor is considered, which makes it possible to obtain a dispersion of the flow at the outlet of the diffuser δ_2 = 2.5 μm with a relative amount of water about 2 % (0.93 kg/s).

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