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EFFICIENCY ANALYSIS OF THE AEROTHERMOPRESSOR APPLICATION FOR INTERCOOLING BETWEEN COMPRESSOR STAGES BY USING CFD MODEL

Abstract: *A study of the aerothermopressor operation for air intercooling between the stages of a multistage compressor as part of a modern gas turbine (LMS100 brand from General Electric) was carried out in the article. A calculation method has been developed using numerical modeling for the evaporation of fine water droplets in the air flow. The main characteristics of the two-phase flow at the aerothermopressor outlet have been determined. It has been found that jet apparatus provides efficient atomization of the liquid, and hence, more efficient isothermal compression process in a high-pressure compressor. The aerothermopressor applying allowed to reduce the temperature of the compressed air between the compressor stages to 50-70℃. Such a decrease in temperature under the thermo-gas-dynamic compression conditions allowed to increase the pressure at the aerothermopressor outlet up to 12-28 kPa (4-9%).*

Keywords: *Pressure Increase, Two-Phase Flow, Gas Turbine.*

Introduction

General Electric has brought into commercial operation the first modern LMS100 gas turbine with a nominal capacity of almost 100 MW using air intercooling technology in 2005. This gas turbine provides the highest efficiency in an open circuit to date. A special feature of the LMS100 is the use of intercooling within the air compression section of the compressor. Today it is the only mass-produced unit of this type in the world. The use of intercooling in the LMS100 made it possible to increase the air pressure degree up to π_c = 40, while the efficiency was η_e = 45.5% [1].

An increase in the ambient temperature (inlet air temperature) irreversibly leads to an increase in the specific air volume, a decrease in density and an increase in the mass air flow, which leads to an increase in the compressive work in the compressor and, accordingly, an increase in power consumption, and this in turn leads to a decrease in the output turbine power and a drop in the efficiency of the plant as a whole.

Brief analysis of recent publications

It is known that an increase in the external temperature for each 1°C leads to a decrease in the output power of the gas turbine plant by 0.5% [2, 3]. There are a number of technologies available to improve the efficiency of the air compression process in multistage compressors. Particular attention is paid to cycles with water or steam injection along the path of the compressor section of gas turbine engines to humidify the working fluid [4, 5] and reduce the temperature.

An alternative way to inject water into the air flow between the compressors is to use an aerothermopressor (Fig. 1a). The apparatus belongs to the type of jet devices and consists of the following main elements [6]:

1) a confuser (designed to accelerate the air flow to a speed close to the sound speed);
2) a nozzle (designed to inject water into the flow);
3) an evaporation chamber (the process of thermo-gas-dynamic compression is taken place);
4) a diffuser (designed to equalize the flow, reduce the velocity and increase the pressure of the flow).

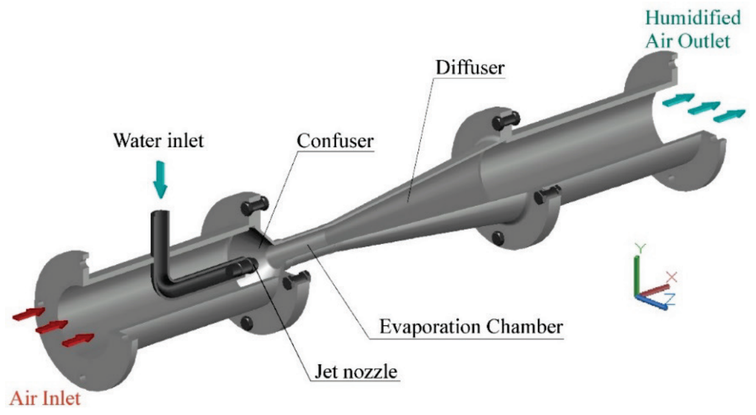
The advantages of using the aerothermopressor include the following:

– increasing the pressure and cooling of the working fluid will reduce the compression work in the compressor;
– ensuring effective atomization and humidification of liquid (water) between compressor stages;
– reduction of the additional work of the compressor during the evaporation of water droplets in the flow path during compression;
– an increase in the amount of the working fluid in the cycle.

If the optimal geometric parameters were selected, the rational organization of thermophysical processes in the flow path of the aerothermopressor could be possible. These parameters include: evaporation chamber diameter, relative length of the evaporation chamber, confuser convergent angle, diffuser divergent angle, distance between the water injection point and the evaporation chamber inlet. The correct selection of these parameters will ensure the evaporation of the water amount (80-85%) in the aerothermopressor and the additional evaporation of remaining water (15-20%) in the flow path of the high-pressure compressor. In this case, the water droplets diameter entering the compressor will not exceed 20 µm [7].

The choice of such optimal geometric parameters of the aerothermopressor, as well as the determination of the characteristics and injection mode (flow velocity; average, maximum and minimum droplet diameters; inlet air temperature; relative water flow rate, air pressure and air flow rate) (Fig. 1b) should be carried out according to the results of an experimental study of working processes and in numerical modeling [6, 7].

a)



b)

Parameter	Value
Continuous phase (air flow)	
Inlet air pressure P_1, Pa	301325
Inlet air temperature T_{air1}, K	473
Inlet air velocity w_{air1}, m/s	55
Air mass flow G_{air}, kg/s	1.56
Mach number at the inlet evaporation chamber M	0.55
Discrete phase (water drops)	
Diameter of drop δ, µm	3-30
Water temperature T_w, K	300
Water velocity w_w, m/s	100
Water mass flow G_w, kg/s	0.031; 0.062; 0.156

FIGURE 1. *3D model of the aerothermopressor (a) and the main inlet parameters of the airflow and water injection (b)*

Object, subject, and methods of research

To carry out numerical modeling, the finite volume method was applied, which is implemented in the ANSYS Fluent software package. The Eulerian-Lagrangian approach was used to simulate the interaction of injected water droplets and air flow. A two-parameter *k-ε* Realizable turbulence model from the RANS group of models was used to investigate the behavior of the air flow [8, 9]. Discrete Phase Model was used to simulate the movement of water droplets.

To analyze the gas turbine cycle, the well-known calculation methods were used [10-12]. The calculation of the gas turbine cycles was carried out for the degrees of pressure increase π_c = 12-40, while in the circuits, instead of an air cooler (surface or contact with nozzle injection), it was proposed to install the aerothermopressor.

Study results and their discussion

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) due to friction losses was ΔP_{dry} = 15 kPa (5%).

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. 2) was ΔP_{atp} = 2.8 kPa (2.1%) relative to the inlet pressure. It should be noted that the cyclic air cooling in the aerothermopressor is ΔT_{atp} = 135 K (Fig. 2), from the initial temperature T_{atp1} = 473 K (200°C) to the outlet temperature T_{atp2} = 340 K (67°C).

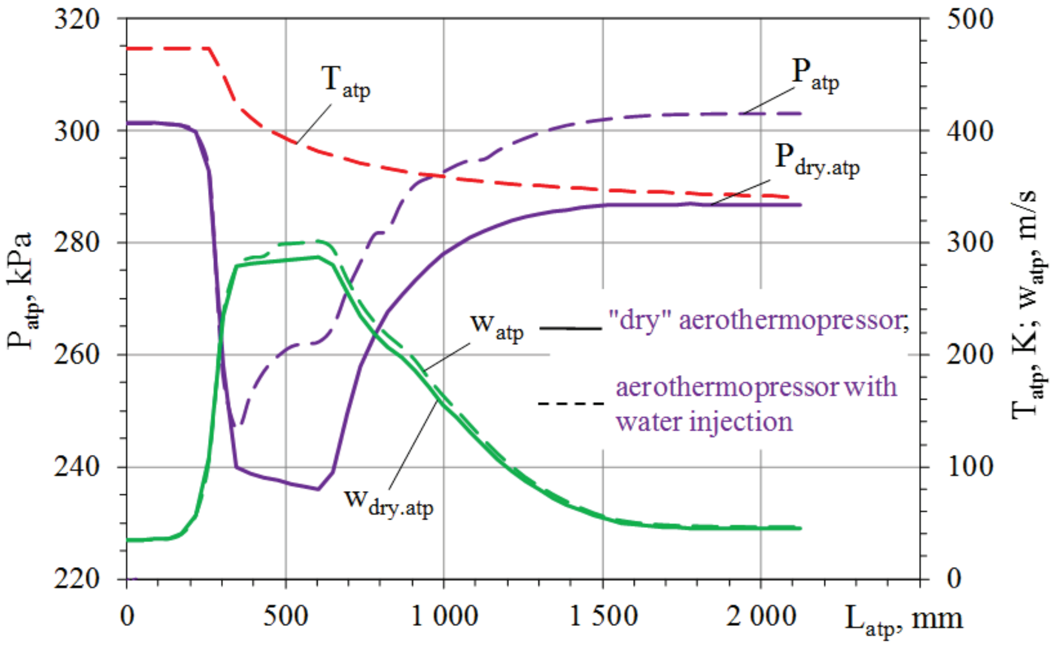


FIGURE 2. *Dependences of the flow main characteristics: total pressure P_{atp}, flow velocity w_{atp}, flow temperature T_{atp} on the length of the aerothermopressor flow part L_{atp}*

The dispersion of water droplets at the evaporation chamber inlet was δ_p = 3-30 μm. The distribution of sprayed water droplets in the flowing part of the aerothermopressor has been given: for incomplete evaporation, with obtaining smaller droplets at the outlet of the diffuser part of the aerothermopressor (G_w = 0.156 kg/s) (Fig. 3).

As this chart illustrates (Fig. 4) the use of the aerothermopressor made it possible to reduce the air temperature between the compressor stages by t_{2atp} = 50-70°C, that is, up to 50-110°C.

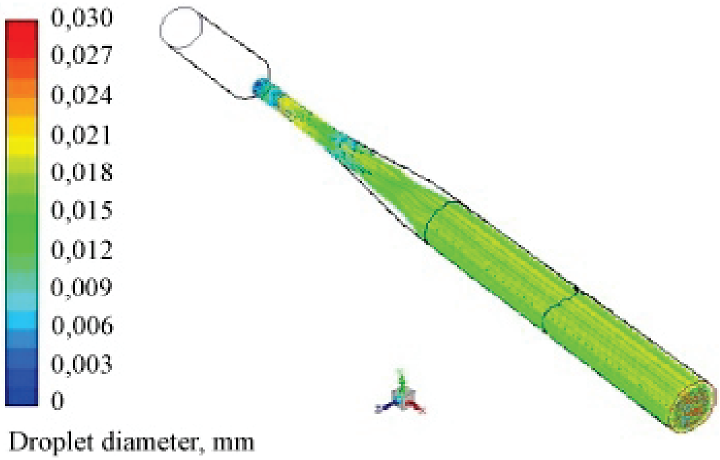


FIGURE 3. *Dispersion distribution of sprayed water δ_p in the flow path of the aerothermopressor for incomplete evaporation, with obtaining smaller droplets at the outlet of the diffuser part of the apparatus (g_w = 10%)*

Such a decrease in temperature under thermo-gas-dynamic compression conditions made it possible to increase the pressure by ΔP_{atp} = 12-28 kPa, that is, up to 4-9% (Fig. 4). Contact air cooling by using the aerothermopressor allowed to reduce the compressor compression work by 2.5-3.0%.

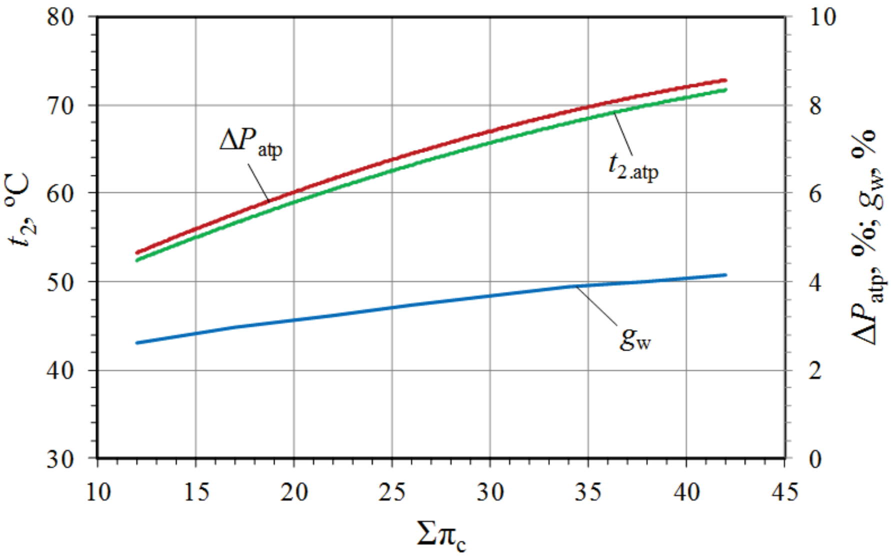


FIGURE 4. *Dependences of the outlet air temperature (t_{2atp}), the relative water flow rate (g_w) and the relative pressure increase at the aerothermopressor outlet (ΔP_{atp}) on the total compressor pressure increase $\Sigma\pi_c$*

The amount of water injected into the aerothermopressor can exceed the value required for evaporation in the evaporation chamber (up to 10% relative to the amount of air). This solution will allow to obtain evaporation during compression in a high-pressure compressor and, as a consequence, bring the compression process closer to isothermal with the lowest value of the work in compression. Thus, the use of the aerothermopressor can be an alternative to the traditional contact cooling of compressed air when injected by nozzles.

The simulation of gas turbine plant operation by using the developed software package to calculate of gas turbine cycles showed the following efficiency from the aerothermopressor using to provide intercooling of cyclic air. Injected water after evaporation is an additional working fluid, the increase of which, in turn, makes it possible to increase the gas turbine specific power. A decrease in the compressor operation and a simultaneous increase in the amount of the working fluid in the cycle makes it possible to increase the efficiency GTP by $\Delta\eta_c$ = 0.01-0.02 (1-2%). In this case, the specific fuel consumption will decrease by Δg_e = 5-10 g/(kW·h). At the same time, the gas turbine specific power is increased by ΔN_s = 5-30 kW/(kg/s), which is 3-10% (Fig. 5). The simulation of the gas turbine operation was carried out for the range of degrees of pressure increase in compressor stages of the gas turbine π_c = 12-42, which are typical for the operation mode according to the classical cycle.

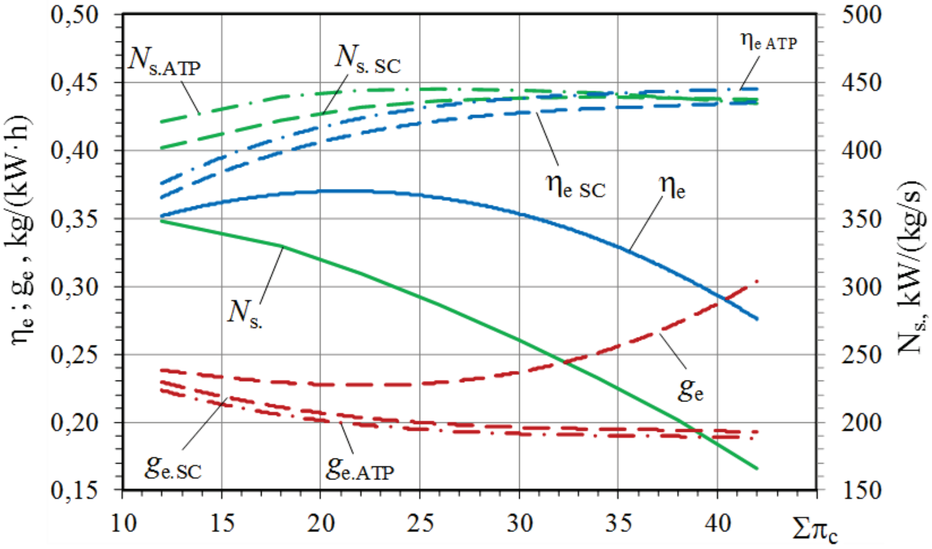


FIGURE 5. Dependences of specific power output (N_s), specific fuel consumption (g_e) and efficiency (η_e) on the total compression ratio ($\Sigma\pi_c$) in compressors for the simple cycle, the complex cycle with a surface air cooler (SC) and the complex cycle with an aerothermopressor (ATP)

Conclusion

The paper analyzes the efficiency of using an aerothermopressor for contact cooling of compressed air in the LMS100 gas turbine circuits. Aerothermopressor provides effective fine atomization of water, and hence, a more efficient compression process in the high-pressure compressor.

It has been determined that the aerothermopressor allows to increase the air pressure between the compressor stages by 4-9%, as a result of which the compression work in the compressor stages decreases; increase the amount of the working fluid in the cycle by g_w = 2-4%, and, as a consequence, increase the specific power of the gas turbine by 3-10%.

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