ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

UDC 621.452.3.038.26 **doi: 10.32620/aktt.2024.3.01**

Ruslan TSUKANOV, Sergii YEPIFANOV

National Aerospace University «Kharkiv Aviation Institute», Kharkiv, Ukraine

ANALYSIS OF SYSTEMS FOR COOLING LIQUID INJECTION IN TURBINE ENGINE GAS FLOW DUCT

*The **subject of this** article is a system for cooling liquid injection in gas flow duct of aviation gas-turbine engine (GTE). The **goal** is to soften the acuteness of contradictions between economic and ecological requirements; ecological requirements and technological limitations; marketing and service life requirements, due to the application of a system for cooling liquid injection in gas flow duct of GTE. The **tasks** to be solved are: development of a classification, revealing the advantages and drawbacks of various technologies of systems for cooling liquid injection in the gas flow duct of GTE, analysis of the investigation methods used for cooling liquid injection systems, and analysis of the system application experience in various aircraft (A/C) and A/C projects. The **methods** used are: search of corresponding information sources on the Internet and analysis based on operational experience in the aviation branch. The following **results** were obtained: in terms of found information sources, classification of systems for cooling liquid injection in the gas flow duct of GTE has been developed; advantages and drawbacks of various cooling liquid injection technologies have been formulated; it was revealed that, three types of methods (experimental, computational fluid dynamic, and analytical) are used for cooling liquid injection system investigation; results of available research are briefly presented; application of cooling liquid injection systems in A/C with the purpose of extending the airplane flight envelop, increasing of aviation GTE thrust/power, and decreasing emissions of nitrogen oxides during takeoff have been analyzed. **Conclusions**. The scientific novelty of the results obtained is as follows: 1) information from numerous sources of literature that clarifies classification, advantages and drawbacks of various technologies of cooling liquid injection in the gas flow duct, development of these system investigations by various methods, and experience of these systems application both in real A/C, and in A/C projects were collected in the review article; 2) necessity in development of transport category A/C design methodology taking into account installation of the system for cooling liquid injection in the gas flow duct of GTE has been revealed. The goal and challenges of the following research in this field are outlined.*

Keywords: *gas-turbine engine; cooling liquid; cooling liquid injection system; fogging; wet compression; emissions of nitrogen oxides.*

Introduction

Such problems as: aviation engine thrust/power increase, their specific fuel consumption decrease, their service life increase, and decrease in greenhouse gas emissions (first of all CO_2 and NO_x [1]) to the atmosphere are ones of the most actual. Unfortunately, efforts directed to solve these problems are clashed with some contradictions.

On the one hand, economic reasonability continuously forces to improve fuel efficiency of transport category aircraft (TCA), which leads to increase in compressor pressure ratio (which results in higher combustor inlet temperature) and turbine inlet temperature. Nevertheless, this higher temperature promotes nitrogen oxides formation during combustion, thus ICAO even introduced limitation for overall pressure ratio [2]. On the other hand, care about environment preservation leads to permanent rise in requirements as for decreasing in greenhouse gas emissions to the atmosphere [3, 4]. As far as other branches of industry show real progress in decreasing of these emissions, but air transportations grow approximately by 3.2...3.6 % annularly [5, 6], airports are sustained considerable pressure to decrease the harmful emissions. Herewith, airports introduce fines, based on levels of these emissions, to push aviation industry for development, but airlines for adoption of TCA having low levels of greenhouse gas emissions [7]. **Thus, economic requirements come in contradiction with ecological requirements**.

Nowadays, huge quantity of scientific researches directed to improve the environment ecological state are underway. Various ways to decrease greenhouse gas emissions to the atmosphere are considered, which are usually subdivided as follows [8]:

1) continued evolution (methods that partially reduce greenhouse gas emissions: gas-turbine engine (GTE) efficiency increase, improvement of A/C design and structure, air traffic control system, cooling liquid injection systems (CLIS), etc.);

2) «Net zero» (methods that reduce net emissions: offsets – funding tree planting, renewable energy projects, etc. to mitigate CO_2 emissions at the expense of ecological fines; sustainable aviation fuels – biofuels, waste-to-fuel, synthetic fuels);

3) hybrid electric power plants (methods that reduce greenhouse gas gross emissions by 10...50 %);

4) «Zero carbon» (methods that reduce carbon gross emissions to zero: replacing kerosene combustion with hydrogen combustion in modified jet engines);

5) «True zero» (methods that reduce all gross emissions to zero: transition to electric cruise motors with hydrogen fuel cells or with electric batteries (which are charged at ground from renewable sources)).

But, the first way only allows reduction in quantity of CO_2 and NO_x emissions, which is assumed insufficient, accounting pace of world industry development. The second way allows only reduction in quantity of net CO_2 emissions, but these emissions during GTE operation at cruising altitude remains as is, and it also requires big investments in these fuel manufacturing. The third way requires considerable increase in specific energy and specific power of electric devises, development of complicated cooling systems for their cooling, protection against thermal runaway and development of reliable models for estimation of aerodynamic performance of novel aircraft configurations (especially with distributed propulsion), and also cost price of electric and hybrid aircraft, which together requires lots of time and money. The fourth way also requires solving of a great deal of complicated problems: arrangement of hydrogen tanks of required volume onboard aircraft, provision of high gravimetric efficiency of the tanks, tank's heat insulation, provision of tank materials and fuel system components operability under cryogenic temperatures, GTE combustors modification, explosion safety provision under conditions of hydrogen considerable permeation, production and transportation of sufficient quantity of «green» hydrogen at ground, provision of competitiveness price of hydrogen airplanes and hydrogen itself, and also ecological results of huge (2.6 times greater comparing to kerosene) water vapor emissions at high altitudes. The fifth way requires development of light and powerful electric motors, reaching required properties of batteries, reliable and safe operation of high voltage electric system at considerable flight altitudes, integration of propulsor, power plant (PP), and A/C systems, considerable improvement and cost cutting of fuel cells, so huge time and expenses [9].

Taking into account the fact that, global economy is now in powerful financial crisis, we could not expect considerable investments in essentially new methods of fuel production, structures of engines and TCA.

Thus, ecological requirements come in contradiction with technological limitations (absence or imperfection of technologies) **and economic requirements** (all ecological technologies considerably increase operating cost of transportation).

Desire to extend airport network, where this TCA model can operate, forces to improve its takeoff and landing performance (especially ensuring as short as possible required length of runway), that requires rather high takeoff thrust/power of engines. It also leads to considerable increase in compressor pressure ratio and turbine inlet temperature (especially at takeoff mode). In supersonic airplanes, for short-term thrust increase (including takeoff modes), thrust augmentation is widely used, but it results in substantial growth in engine sizes (which complicates their arrangement in airplanes), and fuel consumption; moreover it is impossible in turboprops and turboshafts. On the other hand, approximately a third of service life of engine hot-section parts (in particular high pressure turbine blades) is spent just at this mode (which makes about 3 % of total operation time). **Thus, marketing requirements come in contradiction with service life requirements**.

Basing on existing technologies, it is possible to conclude that, acuteness of all these contradictions can be considerably soften due to application of a system for cooling liquid injection (CLIS) in the gas flow duct of gas-turbine engine (GTE). This method allows decrease in nitrogen oxides (NO_x) emissions to the atmosphere, increase in service life of engine hot-section parts, and short-term increase in engine thrust/power [7]. It can be used not only for turbojets and turbofans, but also for turboprops and turboshafts.

It is necessary to note, that among existing methods of mitigation of greenhouse gas emissions to the atmosphere, the only CLIS gives substantial NO_x emission reduction [10].

1. CLIS: Appearance of Idea, Advantages and Drawbacks

CLIS have been proposed by M. Rowe & G. Ladd [11] to improve aircraft engine performance as early as 1946. They concluded that, water offers the best rate of cooling at high power output, but water-methanol mixtures will afford the most increase in power output normally limited by destructive detonation.

In 1950, E. Wilcox et al. [12], and later M. Trout [13] in NACA reports theoretically consider turbojet engine thrust augmentation by water injection at the compressor inlet using Mollier diagrams. The evaporation of this water cools the air and results in a lower mixture temperature and a higher compressor pressure ratio than for the same engine operation mode without evaporation. An increase in compressor pressure ratio increases the jet velocity and the mass flow of gases through the engine, which results in increased thrust.

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

The authors stress that, the effect is greater at low altitude, high temperature and low humidity, which mainly corresponds to take-off conditions.

In 1963, P. Hill in publication [14] considered effects of inlet coolant injection upon axial-flow compressor performance, using results of turboshaft engine tests. The author showed, that evaporation of the coolant changes the stage work distribution as well as the ideal compression work and that these effects may be estimated by elementary thermodynamic methods. Simplified prediction procedures are suggested and compared with experimental results.

This technology offers a number of **advantages**. Firstly, reduction of NO_x emissions (up to 85…90 % [15, 16]) due to decrease in combustor temperature. Secondly, decrease in turbine inlet gas temperature allows service life increase of GTE hot-section parts (by 29 % [16]). Thirdly, short-term thrust/power increase (during takeoff and climb) of existing engines, which parameters have been optimized for cruising mode. Fourthly, this technology can be applied with minimal modifications for GTE of any scheme (including turboprops and turboshafts). Fifthly, many years of experience of this technology utilization in ground gas turbines decreases technical risk of its implementation. Sixthly, it may allow combustors to be optimized for cruise NO_x reduction instead of compromising on a balance of cruise and takeoff reduction [2]. Seventhly, it may promote compressor cleaning to prolong engine performance which could help to reduce fuel use [2].

The **negative aspects** of cooling liquid injection technology are considered as reduction in payload or flight range due to extra mass of CLIS and the liquid, reduction in compressor surge margin, possible increase in specific fuel consumption (SFC), airport infrastructure issues of supplying the conditioned liquid, possible unforeseen affects of liquid injection [2], and possible corrosion of aluminum parts due to higher corrosion activity of demineralized water, that requires heavier material application (steel or titanium) [16].

2. CLIS Classification

CLIS can be classified by several features. Firstly, by cooling fluid injection place (Fig. 1): 1) inlet fluid injection; 2) low-pressure compressor (LPC) or high-pressure compressor (HPC) fluid injection; 3) inter-stage fluid injection; 4) combustor fluid injection.

Secondly, CLIS can be classified by type of injected fluid: a) water; b) water steam; 3) water-alcohol mixture.

Thirdly, by purpose: A) CLIS for extending of airplane flight envelope; B) CLIS for increasing of GTE thrust/power on/near ground; C) CLIS for decreasing NO_x emissions on/near ground.

Inlet fluid injection (version 1a) (or inlet air cooling with water injection or inlet fogging/misting) involves the addition of sufficient amount of water at the engine intake, so as to cool and saturate the inlet air (or achieve 100 % relative humidity) [10]. It gives increase in power and efficiency especially under high ambient temperature conditions, but reduces compressor surge margin [17, 18]. There are a lot of publications concerning this technology for ground gas turbines both to increase power (version 1aB), and to reduce NO_x emissions (version 1aC). But this method is not considered to be feasible for aviation turbofans, because largest part of water would exit though fan duct and not affect engine core; in addition, fan icing is possible here [17, 2].

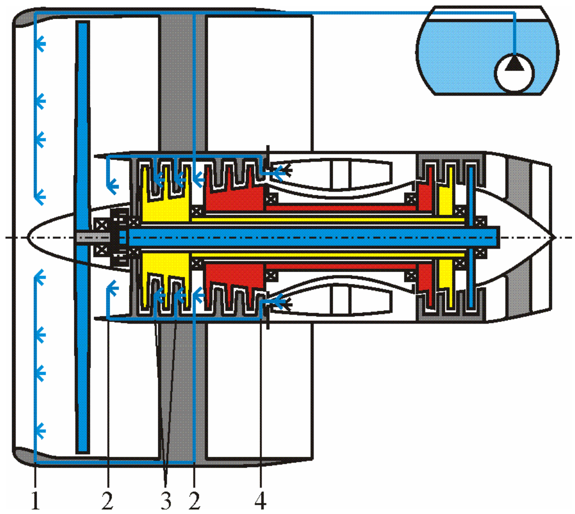

Fig. 1. Possible places of cooling liquid injection:
1 – Inlet injection; 2 – LPC or HPC injection;
3 – Inter-stage injection; 4 – Combustor injection

LPC or HPC water injection (version 2a) (or water misting intercooler technology or wet compression, or overspray fogging, or high fogging, or inlet fog boost, or AlFog) means continuous evaporation of water droplets through the compressor [10]. **Advantages of compressor water injection are**:

1. Substantial drop in the compressor outlet temperature (thus increase in its density and air flow) due to the intercooling effect, thereby tending towards isothermal compression [19, 20]. The p-V and T-S diagrams for different types of compression are shown in Fig. 2 [21, 22]. The points i, w, s, and n correspond to isothermal, water injection, isentropic and polytropic process respectively. Vertical hatching area in the p-V diagram means difference (reduction) in required compressor work between dry polytrophic compression (1-2n-b-a-1) (yellow area) and wet compression (1-2w-b-a-1) (inclined hatching area) [10].

2. Significant reduction in the work required by the turbine to drive the compressor [10]. Utamura [20] concludes that this reduction in required compressor work contributes to a rise in cycle thermal efficiency. This increase in thermal efficiency could be achieved at constant power output operation, as well as augmented power operation, when maintaining unchanged firing temperature at additional heat input. Cumpsty [23] notes that cycle efficiency depends on the ratio of TIT to Compressor Inlet Temperature (CIT), and that reducing CIT has the same effect of increased efficiency as rising TIT, especially for high pressure ratio engines [10].

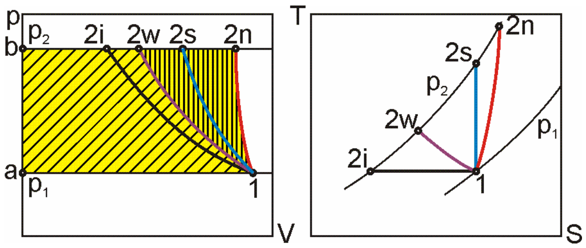

Fig. 2. p-V and T-S diagrams for different types of compression

3. Increase in engine overall thrust/power and efficiency (even for relatively low ambient temperatures) (due to required compressor work decrease) [10].

4. Suitable (about 50 %) NO_x emission reduction (due to lower flame temperature) [2, 16].

5. Extension in the creep life of the turbine, which translates into potential maintenance costs savings (due to TIT decrease) [24]. Reduction in TIT (around 220 K) could double the life of the engine hot parts [10]. Askeland et al. [25] show the impact of temperature on rupture life due to creep, also showing that a very small change in temperature can have a significant effect on hot component life. Daggett [16] estimates, that a gas turbine life could increase by 46 %, in case of water injection is implemented. Cumpsty [23] suggests, that turbine blade creep life could be doubled for every 10 K drop in temperature.

6. Insensitiveness to ambient conditions and ease of control, comparing with inlet water injection [10].

7. When water injection is applied to maintain specified thrust, at reduced throttle setting, the fuel flow is reduced. Burning less fuel reduces CO_2 emissions proportionally to the specific fuel consumption decrease (near 4 %) [2, 16].

The most important variables influencing evaporation time are diameter of water droplets and their residence time within the compressor [26]. Reducing the droplet residence time in the compressor by injecting the water as early as possible is of great importance as this ensures that the water is completely evaporated at the end of the compression process, and will reduce the possibilities for blade impact and blade erosion [10]. White [27] suggests the use of droplet diameters below 5 μm to ensure that they follow the flow path, as well as avoid them being centrifuged towards the compressor casing, or impacting on the blades [10].

This technology is widely used in industrial gas turbine applications in predominantly hot and dry climates when the demand for energy increases partly due to increased use of air-conditioning [10].

As the effectiveness is less pronounced when water is injected into the HPC as compared to LPC [10], a lot of authors [20, 18, 28] think that, the most effective location for water injection is at the inlet of the LPC.

Sometimes, they distinguish **inter-stage injection (version 3)** (or interstage fogging), which is water mist injection directly between the compressor stator blades at suitable locations around the perimeter through the casing at one stage or simultaneously at different stages [29].

Drawbacks of water injection in compressor are:

1. Increase in A/C empty equipped mass due to mass of CLIS and water, which can lead to flight range or payload decrease [16]. But airlines can take the advantage of the increased earnings/competitiveness from the cabin space, which remains free [10].

2. Significant compressor stage rematching (unloading of the initial ones and uploading of the later ones [29]), which leads to surge margin reduction [18] (by 3...9 % [16]). Thus water-to-air ratio is limited by 3 % due to possible compressor surge [30, 31, 24].

3. Possible compressor blade erosion [16].

4. Reduction of the combustor flame temperature (due to the energy required to evaporate the water) reduces thermal efficiency and leads to decrease in fuel efficiency. However, these thermal losses are overcome by improvements to the compressor, which is now operating closer to the peak efficiency line (which results in engine efficiency increasing) [30, 31, 24].

Two versions of cooling fluid injected in combustor are considered: water and water steam. The **advantages of combustor water injection (version 4a) are**:

1. Almost twice lower amount of water required to achieve specified NO_x emission reduction comparing to water injection in the compressor [2].

2. Better water distribution could be maintained, because fuel and water were atomized together [7].

3. This technology is considered capable up to 85...90 % NO_x reduction (in case of water injection with 1:1 water-to-fuel ratio) [32, 16].

4. Possibility of significant increase in engine power [18].

Drawbacks of water injection in combustor are:

1. Necessity of additional fuel consumption to evaporate the water, which results in lowering the thermal efficiency [18, 16, 33].

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

2. Inconsiderable (but permissible) reduction in compressor surge margin [18] (by 0.4…1.6 % [16]).

3. Non-uniform distribution of water resulted in uneven temperature distribution in high pressure turbine [24].

4. Thermal stressing in high pressure turbine parts due to sudden introduction-termination of cool water that impinged on hot metal surfaces [16, 34].

This technology has been used since 1970-th for ground gas turbines [30, 31] both for power increase (version 4aB) (especially under high temperatures), and for NO_x emissions reduction (version 4aC). Publications are known [35] concerning this technology application in shipboard gas turbines to reduce NO_x emission to the atmosphere. Similar scheme was used in Boeing-747-100/200 airplanes, where water was injected directly in front of the combustor [2].

Combustor water steam injection (version 4b) gives emission reduction and significant increase in both engine efficiency and power, but also reduces surge margin [18]. This technology application is considered for ground gas turbines, but additional power losses and complication of the CLIS itself makes this technology unattractive for aviation GTE [10].

Water-alcohol mixture injection in the compressor (version 2c) or in the combustor (version 4b) can give effective thrust increase (from 25...40 %) and moderated increase in specific fuel consumption (from 8 % to 15 %), depending on, which injection method was used [36]; but requires addressing two issues: prevention of toxic fumes getting to A/C environmental control system via engine air bleed ports; and modernization of the turbine cooling system (working fluid with methanol content bled for cooling behind the compressor would ignite when flowing around the turbine blades) [37].

3. Analysis of CLIS Investigation Methods

Three types of methods are used for CLIS analysis: experimental methods, method of computational fluid dynamics (CFD), and analytical methods.

3.1. Experimental Investigations

As far back as 1997, M. Utamura et al. [20] experimentally proved reduction in required compressor work at 15 MW axial-flow compressor, they also got power increase at 130 MW gas turbine due to water injection.

In 1998, H. Urbach et al. [35] described experimental investigation of combustor water injection system for shipboard gas turbine to reduce NO_x emission to the atmosphere (version 4aC). The authors denote that, to reduce NO_x emissions, water-to-air ratio should be proportional to the combustor temperature (so to the engine power settings), to ambient temperature, and also inversely proportional to relative humidity.

In 2002, M. Chaker et al. [38] provided the results of extensive experimental and theoretical studies conducted over several years coupled with practical aspects learned in the implementation of nearly 500 inlet fogging systems on gas turbines ranging in power from 5 to 250 MW (version 1aB). Part A of the paper provides some practical pointers relating to the implementation and application of inlet fogging to gas turbine engines.

The authors stress that, droplet of 5…15 μm in diameter do not cause erosion of compressor blading or blade coating; they more likely follow the airflow around obstructions in the duct and less likely to fall out; and they provide more evaporation surface area.

The authors note problems related with water injection: nozzle possible damage by foreign object; compressor icing; excessive water drainage; compressor surge; compressor intake temperature uniformity; corrosion; compressor erosion.

In the Part B [39] of the publication, the authors stress that, the most important factors for inlet air fogging are the surface area of water exposed for evaporation (affects the evaporative cooling efficiency of the spray) and the size of the largest droplet (affects the potential for compressor blade distress). Sauter Mean Diameter (SMD) is used for the first problem; and Dv90 (the diameter where 90 % of the total volume of the liquid sprayed is made up of droplets with diameters smaller than or equal to it) is used for the second one.

In 2004, I. Petukhov et al. [40] present results of experimental investigation of water injection to D-336 ground GTU. The authors note that, water injection increases GTU output power by 15…40 %, depending on the quantity (1.0...2.5 %) and the place of water supply. Inlet water injection (version 1aB) increases both power and effective efficiency. This effect is more considerable under high temperatures of incoming air. Water injection in front of HPC (version 2aB) gives more notable power increase, but has less influence to efficiency.

In 2007, I. Roumeliotis et al. [41] presented results of wet compressor experimental investigation (version 1aB). The authors note that, the pressure rise coefficient and the stage flowfield presented no measurable deviation with water injection up to 2 %. The point where initial stall occurs presented no change with droplet laden flow. Water injection result to an increase of power consumption. The decrease of stage efficiency is a strong function of the water quantity entering the engine and droplet size (12…20 μm) seems to have no effect.

In 2011, F. Sorohin et al. [42] considered spray-type air cooling system for D-336-2 ground GTU (version 1aB). The authors compare hydraulic and pneumatic nozzles. The first of them requires a powerful pump, very high precision of manufacturing and big number of nozzles (due to low water flow), which increases hydraulic pressure losses in GTU flow duct. The second of them provides inconsiderable hydraulic air pressure losses (due to small number of nozzles having enough water flow and their arrangement on the duct walls), and also work on air, which is bled from GTU. As a result, the authors give preference to the latter.

In 2011, R. Bettocchi et al. [43] presented development and set up of a specific test facility for evaluation of possible long-term negative paybacks of wet compression practice (version 1aB). Among other, the authors presented experimental graphs of deformation variation in compressor casing caused by water injectors on/off.

In 2012, F. Sorohin et al. [44] estimated influence of air bleeding for spray-type cooling system on power and efficiency of D-336-2 GTU (version 1aB). The authors note that, it is enough to evaporate 1 % of water to cool an air mass unit down by 25 K. The authors denote factors influencing the scattering dispersion (nozzle structure, specific consumption and initial pressure of air).

In 2014, O. Favorskii et al. [45] presented results of experimental study of TV3-117 gas-turbine unit (GTU) characteristics at injection of cold and superheated (metastable) water to the GTU compressor inlet (variant 1aB). The authors stress that, the intensity of evaporation process is proportional to the temperature difference between the cooled medium (air) and evaporating droplet and approximately inversely proportional to the square of the mean droplet diameter. Hence, the evaporation of the injected droplets can be efficient and will be completed within the compressor flow path only if the droplet size is sufficiently small. In the same time, commonly used jet and centrifugal mechanical and pneumatic atomizers do not allow obtaining droplets with a diameter less than 15…20 μm.

The authors note that, injecting small-size droplets reduces the intensity of liquid film formation at the compressor surfaces, thus decreasing mechanical losses due to droplet acceleration and secondary fragmentation, increasing compressor internal efficiency, and diminishing the potential danger of the blades erosion.

The authors stress that, superheated water allows finer atomization, and the water injection allows considerable increasing of the unit power. Water injection in an amount of 1.0…1.3 % of the air flow rate allows to maintain a constant temperature of the working fluid downstream of the turbine, when additional fuel is added, that provides an increase in the turbine power by approximately 8…12 % and expands GTU controlling potentialities.

In 2015, F. Sorohin et al. [46] described experimental investigation of spray-type air cooling system (water injection is performed in front of the compressor) of AI-336-8 ground GTU with a goal to increase its efficiency in conditions of high temperature of ambient air (version 1aB). Experiment were performed under constant engine power settings.

In 2017, H. Burtsev et al. [47] presented results of experimental investigation of water injection behind the compressor in single-spool micro-GTE (version 4aB) (this arrangement was selected because it is very difficult to provide water evaporation in front of single-stage centrifugal compressor). The authors denote that, water injection decreases turbine inlet temperature by 1.5...2.0 %, increases specific fuel consumption by 1.5... 2.0 % and increases power by 5.0...5.8 % (per cent of injected water). The authors have not detected water injection influence on vibration characteristics and quantity of harmful emissions to the atmosphere.

In 2017, I. Petukhov et al. [48] showed results of experimental investigations of AI-336-1-8 stationary GTU with inlet water injection (versions 1aB/C). Two sets of experiments were conducted: under constant GTU power, and under constant gas temperature behind low pressure turbine (LPT). In the first case, water injection (0.8 %) results in gas temperature decrease along all GTU duct, and also in NO_x emission reduction (by 18 %). Until the water flow does not exceed one, which provides inlet air saturation, all droplets were evaporated in front of GTU inlet. Under the following increase in water flow, «wet» compression mode takes place in the compressor. In the experiments under constant gas temperature behind LPT, water injection (0.8 %) (due to fuel flow increase) leaded to GTU power increase (by 17 %), and also to NO_x emission decrease (by 8 %).

In 2021, P. Balajti et al. [49] presented results of experimental investigation of TKT-1 GTE (modification of jet turbine starter TS-21) inlet water injection (versions 1aB/C). NO_x emissions decrease by 32 % was detected.

In 2023, E. Barakat at el. [50] described results of experimental investigation of inlet fogging and overspray for ground micro gas turbines (versions 1/2aB). The authors report about output power augmentation by 9…5 % for a load 30…70 %, the maximum output power and specific fuel consumption improvement were achieved at a 2 % overspray ratio. The authors also confirm NO_x emissions reduction due to inlet fogging and overspray.

In 2023, H. Hashim et al. [51] presented results of experimental investigation of inlet fogging to decrease GTU inlet temperature (with a goal to increase output power and efficiency of ground GTU) (version 1aB) in high temperature conditions. The temperature drop makes 19…25 % depending on ambient temperature with droplet diameters of about 100 μm.

 ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

3.2. CFD Investigations

In 2011, E. Benini et al. [52] described numerical and experimental investigation of water and steam injection (0 %, 100 %, and 200 % of the mass fuel flow) in the combustor of 200 N static thrust turbojet (versions 4a/bC). They use 3D CFD model of the combustion process for pollutant emissions (NO and CO) calculations. Results show that, although water injection gives lower turbine inlet temperature (by 1.0…1.8 %), but it gives less effective NO reduction (8 % in terms of mass fraction), compared to steam injection (16 %). Moreover, a substantial increase in the CO production can be appreciated at water injection (21.4 ppmv) comparing to steam injection (8.8 ppmv). This is due to the inadequate burning rated in the primary zone of combustor, where the water tends to withstand fuel/air mixing. As a consequence the authors conclude that, steam injection is preferred to water injection when a reduction in the NO emissions is to be pursued while maintaining relatively low CO emissions (although these gases are not greenhouse ones [1]).

In 2012, L. Sun et al. [22] presented a steady-state numerical simulation of the entire gas turbine with wet compression in order to evaluate the effects on the gas turbine performance (version 1aB/C). Compared with the dry case, the results of wet cases show increased values of compressor compression ratios, turbine expansion ratios, intake mass flow rates and engine thrusts, and also decrease in specific fuel consumption. The wet compression reduces NO_x production in the combustor. The study also indicates that, the water mass flow rate and droplet diameter are key factors impacting the engine performance.

In 2012, J. Wang et al. [53] investigated the effective positions where to inject water and how to utilize the droplets' kinetic energy. Four different injecting positions, which located on the suction surface and endwall, are chosen (version 1aB). The changes of vortexes in the compressor cascade are discussed carefully. In addition, the influences of water injection on temperature, total pressure losses and Mach number are analyzed. Numerical simulations are performed for a highly loaded compressor cascade with ANSYS CFX software.

In 2014, I. Roumeliotis at el. [54] considered mixed-fidelity (0D, 1D, 2D, 3D) model of rain ingestion effects on turbofan performance (version 1aB). The authors stress that, rain ingestion leads to compressor surge margin is halved and fuel flow required to keep thrust is doubled.

In 2017, C. Liu et al. [55] considered wet compression in GTE compressor (versions 1/2aB). They stress that, wet compression technology is an economic and effective approach to improve the performance of gas turbine. Water droplet injection effect on the heat and mass transfer characteristics was investigated, especially on the aerodynamic and thermodynamic effects of two-phase flow in an axial compressor stage by unsteady CFD method (using CFX models). The movement characteristics of water droplets (slip velocity, Weber number, Reynolds number) are analyzed.

In 2017, D. G. Kofar-bai et al. [17] considered the influence of injected water droplets diameter and surface temperature on the behavior of axial flow transonic compressor and gas turbine performance using CFD (versions 1/2aB). Water injection in the compressor is a little perturbation to the flow field due to the formation of flow separation, evaporation rate, increasing Weber number, reduction in the inlet temperature, and velocity vortex pattern relatively different from that of the dry case. The effects of water droplets on the rotor region at injection rate of 1 %, shows decrease in the inlet temperature of 11 %, outlet temperature 5 % and uplift the efficiency to 1.5 %. The authors give formulas for droplet aerodynamic breakup and droplet interaction with blades.

3.3. Investigations by Analytical Methods

In 1998, M. Utamura et al. in [20] propose application of Moisture Air Turbine (MAT) cycle for improving the characteristics of land-based gas turbine by injecting atomized water at the compressor inlet (version 1aB), among the compressor stages (version 3aB), and in front of the combustor (versions 4aB).

In 1998, M. R. Sexton et al. [56] proposed a new concept, in naval propulsion plants, to decrease NO_x production and increase power with a water fog (droplet spray) injected directly into the inlet of the engine compressor (version 1aC). The paper describes the computer model (diffusion-controlled evaporation model was used; all radiation heat transfer effects were neglected) developed to predict compressor performance resulting from the evaporation of water passing through the stages of axial-flow compressor.

In 2002, M. Chaker et al. in part A of their work [38] presented mathematical model of water droplet evaporation (versions 1/2aB). The authors stress that, the model gives quite different relation of relative humidity, droplet size and air temperature from time depending on specified active radius (radius of droplet interaction with air). But in reality, droplets of various diameters evaporate simultaneously; so small droplets evaporate quickly increasing the air relative humidity and making big droplet evaporation more difficult. As a result the latter do not manage to evaporate within 1…2 s in front of compressor. In Part C of the work [57], the authors note that, shattering of droplets occurs, when the inertial forces overcome the surface tension forces, which happens when the Webber number is less than 13.

In 2003, Q. Zheng et al. [58] presented thermodynamic model of ideal and actual wet compression processes, water droplet evaporation rate, wet compression work, inlet evaporative cooling, wet compression efficiency, and aerodynamic breaking of water droplets.

In 2004, A. J. White et al. [27] considered effect of water droplets injection into compressor inlet on its performance (versions 1/2aB). The authors present simple numerical method for the computation of wet compression process, based on a combination of droplet evaporation and mean-line calculations.

In 2006, S. Sanaye et al. [59] presented analytical mathematical model of water droplet evaporation (inlet fogging) and wet compression effect on gas turbine operation parameters and also results of the models application for gas turbine GE9171E (versions 1/2aB).

In 2006, A. Minyachikhin et al. [60] considered application of evaporative panels for inlet air cooling system of D-336-2 GTU (version 1aB). The authors note that, the more relative humidity of incoming air is, the lower useful effect from evaporative cooling is. The air temperature at LPC inlet and required flow of cooling liquid grow almost linearly with increase in the incoming air temperature.

In 2009, R. Bhargava et al. [29] studied the impact of the polydisperse spray on compressor characteristics improving the math model described in [61] (version 2aB). The authors discussed stage-by-stage parameters distribution and reached the following conclusions:

– a polydisperse spray having smaller value of SMD results in an increased evaporation rate mainly due to larger surface area of droplets;

– for a given ambient condition and with the same amount of injected water to air ratio, the use of droplets distribution having smaller SMD value allows the achievement of higher overall compressor performance due to increased evaporation rate;

– for a given droplets distribution and ambient conditions, later stages of a compressor are prone to reduced surge margin under wet compression process, but for smaller SMD value, compressor surge is reached with lower values of injected water to air ratios.

In 2009, Yu. Basov et al. [62] considered spray-type air cooling system for D-336-2 ground GUT (version 1aB); the authors briefly present mathematical model of a droplet motion and heat-mass exchange.

In 2010, K. H. Kim et al. [26] proposed mathematical model of wet-compression process using approximate analytical solutions (version 2aB). It includes a thermodynamic analysis of the simultaneous heat and mass transfer processes that occur during evaporation.

In 2010, T. Wang et al. [63, 64] focused on developing a stage-by-stage wet compression theory for overspray and interstage fogging that includes the analysis and effect of preheating and precooling at each small stage of the overall compressor performance (version 2aB). An algorithm has been developed to calculate the local velocity diagram and allow a stage-by-stage analysis of the fogging effect on airfoil aerodynamics and loading with known 2D mean-line rotor and stator geometries.

In 2014, A. Kudynov et al. [65] analyzed operation of aviaderivative ground gas turbine GTU-25 basing on NK-25 aviation engine at water vapor injection in the combustor with a goal to increase efficiency. The publication contains calculation methodology for GTE combustor.

In 2014, A. Tudosie [66, 67] analytically investigated cooling fluid injection in combustor rear section of an aircraft engine meant to temporarily increase its thrust (versions 2/4a/cB). To provide GTE stable operation (with margin from surge limit) in conditions of additional fluid injection, the author proposes by-passing of the extra air flow rate behind the compressor into supplementary combustor (which also requires GTE control system modification).

In 2014, A. Lysytsia et al. [68] considered indirect evaporative cooling, its mathematical simulation and calculation of the air temperature and pressure losses in heat-exchanger ducts, typical for D-336-2 GTU. The authors reach a conclusion that, application of indirect evaporative heat-exchanger to cool GTU air down is problematic.

In 2015, A. Berkovych et al. [69] provided brief description of program set for parameter calculation for a stationary gas turbine power plant performance with compressor-inlet water injection (versions 2/3aB/C). The authors presented certain results of the computational study of injection effects on GTK-10 gas turbine to illustrate possibilities of the complex application.

In 2015, A. Kler et al. [70] presented results of technicoeconomic optimization for ground combined-cycle and gas-turbine plants with water injection in the compressor. The authors made conclusion that, CLIS utilization under constant efficiency allows to decrease in specific investments considerably. Thus, for efficiency of 32 %, CLIS effect makes 90 $/kWt, but for efficiency of 40 % — 280 $/kWt.

In 2015, Ch. Mourouzidis et al. [15] investigated characteristics, emissions and economical aspects of water injection with different concentration to LPC and combustor during takeoff for turbofan of middle and high bypass ratio using in-house software (versions 1/2/4aB/C). The authors denote that, water injection in LPC can offer thrust increase from 10 % (under normal temperature) till 25 % (under high temperature); while the combustor water injection decreases engine available thrust; in addition water injection decreases NO_x emissions by 25...85 % depending on injection point, and it also decreases specific fuel consumption up to 10 %.

In 2016, F. Sorohin et al. [71] attempted thermodynamic approach for estimation of ground gas turbine drive efficiency and proposed calculation methodology of energy and economic indexes, which characterize gas turbine drive efficiency with cooling system.

In 2017, F. Sorohin [72] presented approximate method for GTU parameters calculation (power, effective efficiency, air and fuel flow) depending on inlet temperature and throttling.

In 2017, M. Bianchi et al. [73] considered liquid water injection in stationary gas turbine combustion chamber to reduce NO_x emission (version 4aC). The authors have improved analytical mathematical model for water droplet evaporation and showed its application results [74, 61].

In 2018, A. Tudosie [36] presented mathematical models of engine with cooling liquid injection of two types (combustible or neutral) into compressor or combustor (versions 2/4a/cB), some versions and schemes of control system were also investigated. The author also stresses necessity of «optimization studies, concerning the coolant injection mass flow rate, injection strategy, duration and storage tank's capacity» [36].

In 2018, D. A. Block et al. in the first part of their publication [75] considered GTE characteristics improvement due to cooling water injection at application in 2 or 3-spool compressors (version 2aB), in wide range of various ambient conditions for different droplet sizes and injection rates, using thermo-analytical compressor model and evaporating cooling model.

In the second part of their work [76], D. A. Block et al. investigated external condition influence on thrust increase and specific fuel consumption decrease (by 5.3 % and 7.8 % respectively), and also on reduction in nitrogen oxide emissions (over 50 %) using own mathematical models of 2 and 3-spool turbofans with compressor water injection (versions 2aB/C).

In 2022, Yu. Ulitenko et al. [37] considered water or water-methanol mixture injection in turboshaft engine in front of LPC or in the combustor to improve engine properties and to mitigate NO_x emission at (versions 2/4a/cB/C). Results of calculation using their mathematical model are validated with experiments. The authors note that, inlet water injection gives more power (by 9 %) and TIT (by 5 %), than combustor water injection. When maintaining a constant TIT, combustor water injection gives more power (by 8 %) and fuel consumption, comparing with dry operation. Methanol injection increases power and decreases fuel consumption. The authors stress that, inlet pure methanol injection can significantly reduce fuel consumption, but does not change engine power. The authors reached a conclusion that, coolant injection in front of LPC is a more economical way to boost the engine; but combustor coolant injection results in better environmental performance. The authors also stress safety issues in case of coolant injection system failure/malfunction during takeoff which results in power drop.

In 2023, H. Kadhim et al. [77] considered ground GTU power and efficiency increase in high temperature conditions by means of inlet fogging (version 1aB) (2.9 % water-to-air ratio). As a result of inlet fogging system calculation, it is shown that, GTU net power and thermal efficiency increase by 7.7 % and 2.4 % respectively.

In 2023, J. Kok et al. [78] considered ground aero derivative GTU (GE LM6000) which utilizes steam injection to increase its efficiency (version 2bB). In this case, the steam is generated by use of the turbine exhaust heat. The authors briefly describe thermodynamic model to simulate the simple cycle gas turbine, steam generation and effects of steam injection. The authors stress that, as a result of stream injection, GTU efficiency increases by 11 % and its output power grows by 45 %.

In 2023, A. Bassily [79] considered ground combined cycle GTU inlet air cooling to increase output power and to reduce NO_x emissions (versions 1aB/C). The author reports that, this technology application results in output power increase 0.3…0.6 % per °C rise in ambient temperature (as opposite to power lost by 0.75…0.80 % per °C without cooling), an efficiency improvement up to about 0.5 %, and can give up to 25 % NO_x emissions reduction.

4. Analysis of CLIS Application in A/C

4.1. Using CLIS to Extend Airplane Flight Envelope

In 2004, J. Lopata et al. [80] analyzed water and liquid oxygen injection system application in compressor of carrier aircraft within the frame of RASCAL satellite launch program to increase maximum Mach number (>3) and flight altitude (90000 ft [27432 m]), at which rocket vehicle separates from carrier aircraft (version 1aA).

In 2013, Yu. Ulitenko et al. [81] considered application of water injection to extend operation range of combined power plant (afterburning turbofan + scramjet) for the first stage of space transport system (version 1aA).

In 2014, the same authors [82] considered afterburning turbofan modernization by means of inlet water injection (version 1aA) with the goal to decrease temperature of engine parts, and to extend its operation range.

In 2015, U. Mehta et al. [83] considered cooling water injection in front of turbojet (turbofan) compressor of carrier aircraft to increase maximum Mach number and flight altitude, at which rocket vehicle separates from launch aircraft (version 1aA). It is denoted that, the modified aircraft distinguishes with water tank presence and enlarged air intakes. The authors denote that, the compressor water injection system allows increasing in maximum flight altitude and Mach number considerably, decreasing in time of their reaching and total fuel consumption due to lowering of optimal angle-of-attack.

In 2016, Yu. Ulitenko et al. [84] considered inlet water injection for scramjet engine of unmanned air vehicle to extend its operation range (version 1aA). The authors show results of required water flow calculations for air cooling till the specified temperature. They stress that, just high temperature of working medium is a factor, which limits maximal airspeed when using traditional structural materials.

In 2016, the same authors [85] considered effect of water injection at ramjet engine inlet of carrier aircraft (version 1aA). The authors denote that, water injection system application allows increasing in thermodynamic efficiency and extend operational envelop of ramjet engine (up to flight speed corresponding to M=5 and up to flight altitude of 40 km) using available materials to develop competitive ramjet engines for high-speed aircraft.

In 2019, Yu. Ulitenko et al. [86] considered inlet water injection system for afterburning turbofan to extend its operation range (version 1aA). The author notes that, water injection allows to increase thrust and specific thrust (under the limited temperature in front of turbine and at the afterburner outlet) and, thus, to extent range of flight Mach numbers, but it results in fuel consumption increase, and also in necessity of storing considerable water storage onboard.

In 2022, Yu. Ulitenko et al. [87] considered possibility of operational envelop expanding (till M=3), thermodynamic efficiency improvement, and short-term augmentation of afterburning turbofan of carrier aircraft using available materials, due to water injection at HPC inlet (version 2aA). The authors also denote that, application of water injection results in decrease in aircraft payload weight or flight range, which requires investigations as for water injection influence on aircraft performance.

In 2023, the same authors [88] compared influence of water injection place (engine inlet and HPC) on thrust of afterburning turbofan and flight speed range of carrier aircraft (versions 1/2aA). The authors reach a conclusion that, greater flight speed can be obtained by means of HPC water injection at low altitudes, and at the engine inlet at high altitudes; but the latter version requires far more water and fuel consumptions.

In 2023, X. Meichao et al. [89] considered effect of water spray on tip leakage flow in inlet stage of HPC of high-altitude high-speed turbine engine (version 1aA) by Euler-Lagrange method. The authors report that, the inlet mass flow and tip leakage flow rate increase with the growth of injected mass flow rate and the decrease of droplet size.

4.2. Using CLIS to Increase Aviation GTE Thrust/Power

When the ambient temperature increases by 1 °C, the output power is reduced by 0.54…0.90 % [90]. It results in required runway length increase or limits maximum takeoff mass (thus forces to decrease payload or fuel storage – so flight range) in high temperature conditions.

The compressor water injection system was first used on Boeing-707-120 commercial airplane with PW JT3C-6 as long ago as in 1959 to increase engine thrust [30, 31, 24]. In this system (Fig. 3), water from fuselage tank was delivered by an electric driven pump to all four engines, and next an engine-driven pump increased the pressure to about 400 psi [2.75 MPa] for injection before LPT (under the ambient temperature above 40 ºF [4.4 ºC]) or in front of HPC (under the ambient temperature between 20 ºF [-6.7 ºC] and 40 ºF [4.4 ºC]).

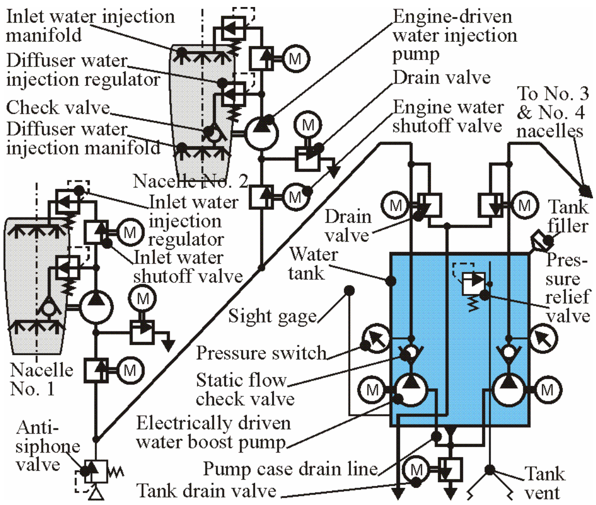

Fig. 3. Water injection system of B-707-120 airplane [2]

Late, this system was used in Boeing-747-100/200 airplanes with PW JT9D-3AW/-7AW (where water was injected behind HPC directly in front of the combustor). In this design (Fig. 4), the water distribution was not as well controlled as in later industrial water injection systems. This leaded to considerable temperature distribution nun-uniformity in front of HPT. Thermal stressing of the casing and surrounding metal structures was also reported, presumably due to the sudden introduction of the cool water which then impinged on the hot metal surfaces [2].

CLIS was also used in DC10-40 [16] and B-47 (with six J47-GE-25A turbojets) [91] airplanes. During takeoff of B-47, CLIS provided a 20 % increase in thrust. In 1970-th, when more powerful turbofans appeared, this system was removed from airplanes [31, 30].

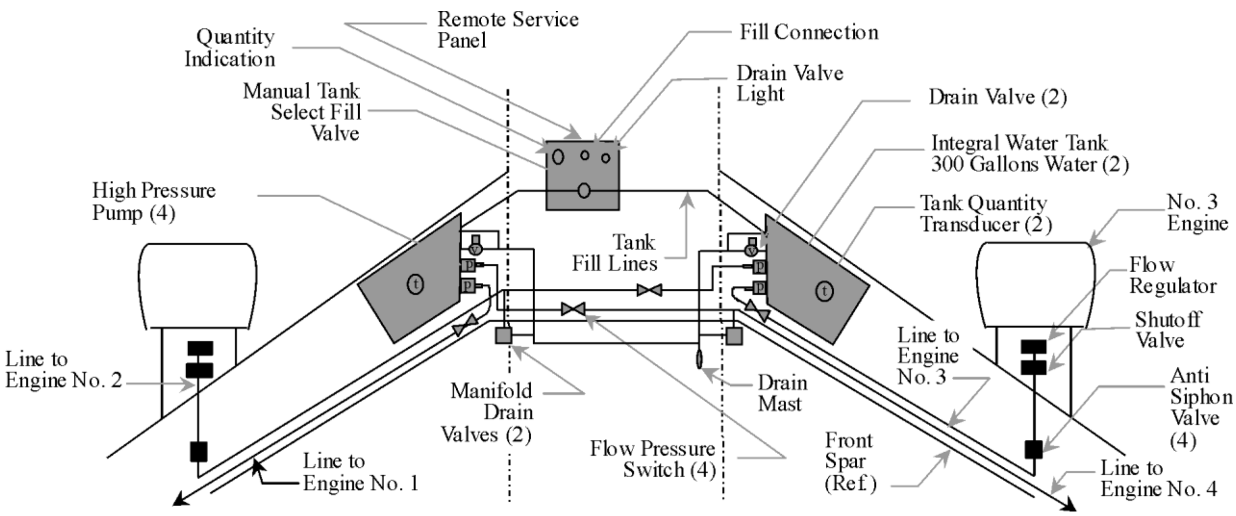

Fig. 4. Water injection system of Boeing-747-200 airplane [2]

CLIS of AV8B Harrier airplane with Rolls-Royce Pegasus F402 turbofan enables rotors rpm to be increased for a given turbine entry temperature to sustain short lift wet and normal lift wet ratings at temperature up to +15 °C [92].

Rolls-Royse Allison used water-methanol injection on T56-A-425 engine for carrier based A/C. 1.88 % of water/methanol injection to engine inlet results in a 13.9 % power boost. 3.45 % of water/methanol injection gives 25 % power increase. A mixture by volume of 33 % methanol and 67 % de-ionized water was provided to the individual engines from a common, centrally located, aircraft-mounted tank [93].

According to consideration of aforementioned systems, the following conclusions are made:

1) eliminate the APU water injection system, reducing total aircraft system weight some 25 % [2];

2) do not carry water to the destination for use in water injection during descent, taxi-in and gate arrival, saving some 750 lb [340 kg] on a 747-sized aircraft [2];

3) evaluate keeping the engine's water-to-fuel injection ratio at or below a 0.5:1 ratio to prevent large increases in HC and CO. This also reduces the NOx reduction effectiveness somewhat, but overall system performance will most likely improve [2];

4) utilize improved engine water injection schemes (such as water misting injection) to avoid the large SFC penalties estimated for the previous study. The SFC penalty is typically 3 % for modern combustor water injection systems and will probably reduce substantially for the water misting intercooler system. The older Pratt & Whitney style water injection system was estimated to contribute a 10 % SFC penalty [2];

5) use corrosion-resistant steel, titanium or composite materials instead of aluminum alloys for CLIS components dealing with demineralized water [16];

6) place water tanks in warm zones of A/C to avoid water freezing [16];

7) once the water is exhausted after takeoff, any residual water needs to be drained through a heated drain mast. If water were to be used all the way to top of climb, the tanks would need to be protected from freezing [16];

8) now, one powerful electric pump is much heavier and more sensitive to cavitation, than some smaller pumps of the same capacity [16].

Fig. 5 shows schematic of water/methanol injection system for project of passenger vertical take-off and landing (VTOL) A/C [93]. The system delivers 1.35 lb/s [0.612 kg/s] of water/methanol mixture to 10 atomizing nozzles of the engine during one engine inoperative (OEI) operation for 2.5 min. The pump has a capacity of 2 lb/s [0.907 kg/s] at 250 psid [1.724 MPa]. This requires 26 gal [98.42 kg] supply tank located in the aft wing fairing at the top of the fuselage.

The tank containing enough fluid for 4 minutes of OEI operation at the maximum flow rate of 1.446 lb/s [0.6559 kg/s] would add approximately 350 lb [158.76 kg] to the aircraft weight. The aircraft tank and plumbing would weigh 64.6 lb [29.3 kg] and the engine-mounted hardware 6.2 lb [2.8 kg] per engine. Total weight penalty per engine would be 213.5 lb [96.84 kg] or about 19.7 %. The learned-out cost of the system hardware is calculated to be 1.25 % of the baseline engine costs. The direct maintenance cost (DMC) increase for this system is estimated to be 1.5 %. This concept reduces DMC by -3.60 % over the baseline engine sized to perform the OEI requirement.

In 2016, N. Troittskiy et al. [94] consideryd short-term GTE power augmentation on the example of auxiliary GTE with various methods (water injection in front of compressor (version 2aB), short-term turbine inlet temperature increase and supply of an additional compressed air from bottles into the combustor). According to authors' calculations, injection of 1 % of water increases power by 17 %.

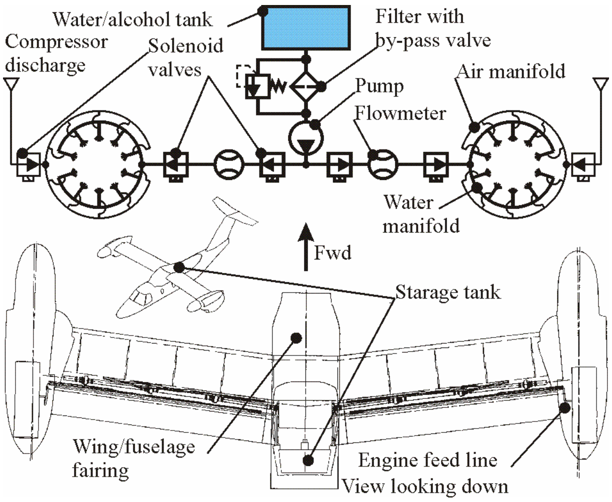

Fig. 5. VTOL aircraft water/methanol injection system schematic

The authors stress that, advantages of short-term (10...20 s) turbine inlet temperature increase are: increase in turbine work, which (under the compressor work constant) increases cycle work and GTE power. Its disadvantages are increase in hazard, due to decrease in blade long-term strength and leading edge possible overheating, and also increase in fuel consumption. Application of thermal-barrier coating can increase augmentation time by a little (till 40...60 s).

The authors denote that, compressed air supply from onboard bottles can be used in small and auxiliary GTE only, when required air quantity can still be stored in the onboard bottles. Advantages of this method are: increase in turbine work, which (under the compressor work constant) increases the cycle work and GTE power. The disadvantages are: limited operation time (about a minute), additional mass of the bottles and compressor, and also increase in fuel consumption.

4.3. Using CLIS to Decrease NO_x Emissions During Takeoff

M. Stettler et al. [95] taking into account 20 of the busiest airports in the UK, concluded that around 72 % of NO_x emissions are produced at take-off and climb (remaining 10 % at taxi and 18 % at landing). It is clear from the Fig. 6 [96], which NO_x emissions increase with increasing power; thus its production rate is highest under take-off and climb. The reason is that, NO_x emission rate is proportional to gas pressure and temperature (Fig. 7) [30, 31], as well as gas residence time in the combustor. A. Lefebvre [96] also proposes five formulas for NO_x emission index dependence on combustion pressure, temperature and other parameters. This indicates that aero-engines with higher pressure ratio or higher operating temperature will produce more NO_x emissions [10].

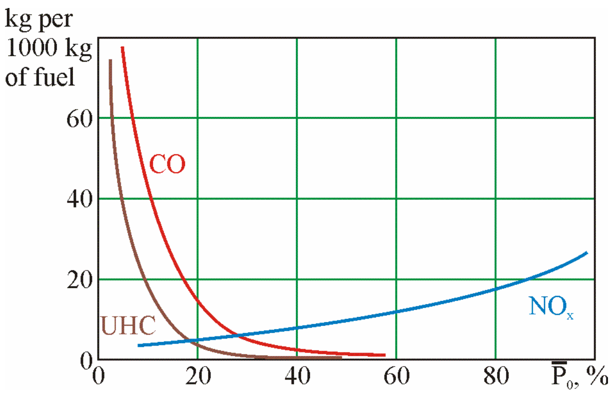

Fig. 6. Different Emissions vs. Percent of Takeoff Thrust

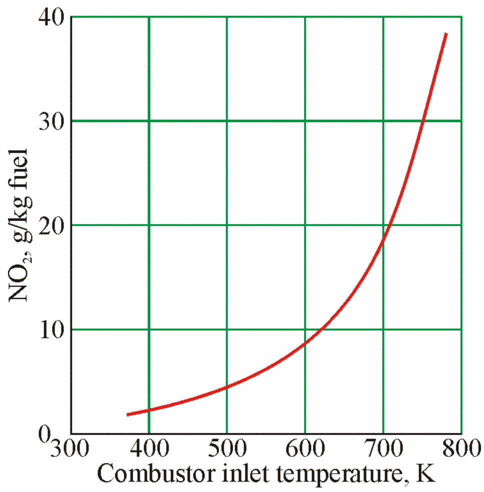

Fig. 7. NO_x emissions vs. combustor inlet temperature

Majority of methods proposed in the open literature [9] for airport emission reduction are based on reducing the time the engines run at low power settings (during taxiing). They can reduce CO and HC emissions substantially (see left-hand side in Fig. 6), but could do little to reduce NO_x emissions [10]. In the same time, according to ICAO data [97, 98], just during Landing and Take-Off (LTO) cycle (Table 1) engines are operating close to maximum thrust (see right-hand side in Fig. 4), where NO_x emissions are produced in plenty [10].

Summing up products of these times by engine fuel flow at these modes and by emission indexes from the formula (1) [2] or from formulas presented in [96] or from ICAO engine emission data bank [99], we get an engine emission per one LTO cycle. Multiplying it by the number of engines in the aircraft and by the number of LTO cycles per the assessment period, we get emissions generated by the specific aircraft per this time period [98, 100].

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

Table 1

Landing/Takeoff Cycle (LTO) [97, 98]

Mode	Time, min	Thrust, %
Takeoff	0.7	100
Climb to 3000 ft.	2.2	85
Approach from 3000 ft.	4.0	30
Idle/Taxi	26.0	7

D. Daggett in NASA report [2] used the following NASA equation to predict how mach NO_x would be generated:

$$EINOx = 33.2\left(\frac{p_3}{432.7}\right)^{0.4} e^{\left(\frac{T_3}{349.9}-4.25075797\right)}, \quad (1)$$

where p_3 is pressure of compressor exit, psia; T_3 is temperature of compressor exit, °R.

D. Daggett et al. [30, 31, 24] used software of Boeing and NASA to calculate water injection impact on engine performance with a goal to achieve 50 % NO_x emission reduction. These calculations agree fairly with the data of former tests. Further authors develop water injection system for combustors (Fig. 8) and compressors (almost similar to Fig. 4) for Boeing-777 airplane, which works during takeoff and climb till 3000 ft [914 m]. 3D-model of Rolls-Royce Corporation was used for water injection process simulation in LPC.

Results of investigations show (Fig. 9) that, to achieve NO_x emission reduction by 50 %, combustor water injection system requires about half the water storage [30, 31, 24].

Results of investigations show (Fig. 9) that, to achieve NO_x emission reduction by 50 %, combustor water injection system requires about half the water storage [30, 31, 24].

Water tank arrangement in fuselage (see Fig. 8) increases loads on wings during climb, otherwise arrangement of water tanks in wing dry bays above engines (see Fig. 4) can cause water freezing. Water lines and water dump mast must be heated to avoid freezing. The authors present parameters of pumps (534...1000 psig [3.7...6.9 MPa], 26000 lb/hr. [11793 kg/h] and estimate mass of the system without water as 360 lb [163 kg]). Mass of water for the combustor water injection system is estimated as 1127 lb [511 kg], but for the compressor water injection system — 2505 lb [1136 kg]. Presence of water injection system onboard causes slight fuel storage decrease (although the third part of the water is used during takeoff run). In the first case, it results in flight range decrease by 7 nm [13 km], in the second one, in flight range decrease by 80 nm [148 km] [30, 31, 24].

Water injection increases mass air flow and engine thrust. To maintain specified thrust it is necessary to reduce engine power settings, which leads to noise reduction by 0.61 dB [30, 31, 24].

The authors also denote that, droplets larger than 10 μm in diameter under the influence of inertia forces inside compressor can glue to casing and cause its icing, thus nozzles should ensure lower droplet sizes. This should also prevent compressor blade erosion from water droplet impingement. The authors assume that, decrease in compressor surge margin detected previously during tests can be caused by big droplet sizes, which freeze to the casing, reducing the compressor blade tip clearance and causing their rub, which caused compressor surge margin [2, 7].

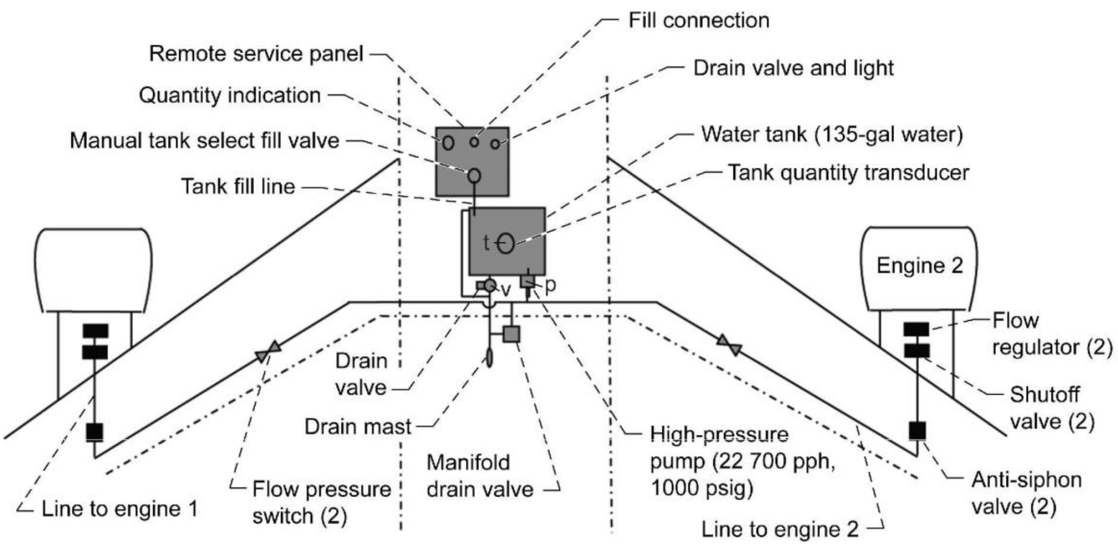

Fig. 8. Water system of Boeing-777-class airplane for water injection in turbofan combustors

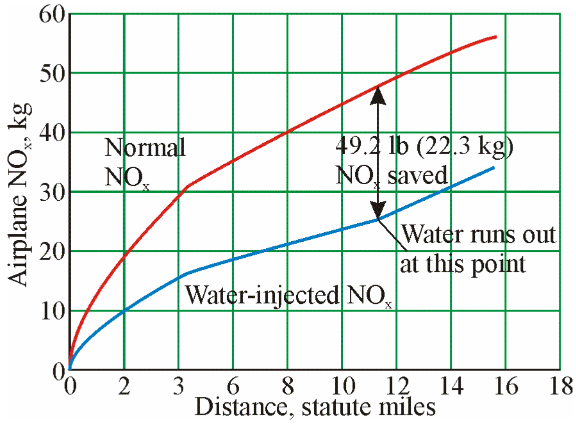

Fig. 9. Reduction of NO_x emission due to water injection during takeoff and climb of Boeing-777-class airplane

It is stressed that, water injection up to 3000 ft [914 m] altitude ensures turbine inlet temperature decrease by 436 ºR [545 ºC], which increases the turbine service life 1.5 times. If, after reaching this altitude, water injection does not terminate but reduces – only to reduce the turbine inlet temperature by 20...50 ºR [25...62.5 ºC], then the turbine service life increases 1.8...2.6 times. In spite of considerable advantages of the compressor water injection system, the authors assume that the combustor water injection system is preferable, because this system has been operating many years in the industrial gas turbines and require lower amount of water onboard airplane [30, 31, 24].

H. Urbach et al. [35] stressed that, during a crashback maneuver, the combustor water injection system of shipboard gas turbine should very quickly (within 0.2 s) drop (or terminate) water supply to avoid flameout. The problem can also become critical for aviation GTE reversing during aborted takeoff. The authors also propose three approaches to solve this problem. Firstly, utilization of duplex fuel manifold, outer (secondary) one of which is used to deliver fuel-water mix, but inner (primary) one delivers only fuel. Secondly, turning the ignition system to continuous operation mode, during rapid fall of power. Thirdly, increase in fuel flow at idle power settings.

Conclusions

1. There are a lot of publications devoted to analysis of influence of cooling liquid injection in GTE compressor or combustor on engine performance. But influence of CLIS installation on TCA performance (such as flight range and payload) has been studied insufficiently. In available literature, it becomes impossible to find a methodology for new TCA designing as well as existing TCA modification taking into account CLIS installation in it.

Hereupon water injection is widely used in ground gas turbines, but is not practically applied in aviation gas-turbine engines now. **Thus, the problem is to research influence of CLIS installation on TCA performance, to reveal obstacles which prevent this technology returning in aviation, and to find ways for the obstacles overcoming**.

2. Thereby, it is possible to assume reasonable to set a goal of the following studies: performance improvement of TCA and their power plants due to introduction of system of cooling liquid injection into GTE gas flow duct.

3. To achieve the goal, it is necessary to solve the following problems:

– Develop efficiency criterion for system of cooling liquid injection into GTE gas flow duct application, which must take into account this system influence on TCA performance;

– Develop mathematical model of TCA power plant with GTE and system of cooling liquid injection into GTE gas flow duct;

– Develop designing method for system of cooling liquid injection into GTE gas flow duct;

– Validate this method on existing engine.

Contribution of authors: conceptualization – **Sergii Yepifanov**; review and analysis of information sources – **Ruslan Tsukanov**.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, author ship or otherwise, that could affect the research and its results presented in this paper.

Financing

The study was performed without financial support.

Data availability

Manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

All the authors have read and agreed to the published version of this manuscript.

References

1. *Kyoto Protocol to the United Nations Framework Convention on Climate Change:* official text. United Nations, 1998. 21 p. Available at:

https://unfccc.int/resource/docs/convkp/kpeng.pdf (accessed 30.11.2023).

2. Daggett, D. L. *Water misting & injection of commercial aircraft engines to reduce airport NOx: Technical memorandum NASA/CR-2004-212957,* 2004. 82 p. Available at: https://ntrs.nasa.gov/citations/20040035576 (accessed 04.01.2024).

3. *Waypoint 2050.* Geneva, Air Transport Action Group, 2021. 110 p.

4. *United States 2021 Aviation Climate Action Plan: National Aeronautics and Space Administration Authorization Act of 2022.* FAA, 2022. 40 p.

5. *Innovation for a Green Transition: 2022 Environmental Report.* International Civil Aviation Organization, 2022. 414 p. Available at: https://www.icao.int/environmental-protetion/Documents/EnvironmentalReports/2022/ICAO%20ENV%20Report%202022%20F4.pdf (accessed 30.11.2023).

6. *Global Market Forecast 2023-2042.* Airbus, 2023. 30 p. Available at: https://www.airbus.com/en/products-services/ commercial-aircraft/market/global-market-forecast/ (accessed 30.11.2023).

7. Daggett, D. L., Fucke, L., Hendricks, R. C., & Eames, D. J. H. *Water Injection on Commercial Aircraft to Reduce Airport Nitrogen Oxides. NASA/TM—2010-213179,* NASA, 2010, Available at: https://ntrs.nasa.gov/api/citations/20100015629/downloads/20100015629.pdf (accessed 14.01.2024).

8. *Hydrogen. A future fuel for aviation?* Roland Berger GMBH. Munich Germany, 2020. 28 p.

9. Yepifanov, S., & Tsukanov, R. Analysis of Environmentally Friendly Commercial Aviation Development Ways. *Aviacijno-kosmicna tehnika i tehnologia – Aerospace technic and technology*, 2024, no. 1/193, pp. 4-21. DOI: 10.32620/aktt.2024.1.01.

10. Block, D. A., & Igie, U. Case For Exploring Compressor Water Injection For Airport Emission Reduction GT2017-64780. *Proceedings of the ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition: Volume 3: Coal, Biomass and Alternative Fuels; Cycle Innovations; Electric Power; Industrial and Cogeneration Applications; Organic Rankine Cycle Power Systems,* Charlotte, USA, June 26-30, 2017, article no. GT2017-64780. pp. 26–30. DOI: 10.1115/GT2017-64780.

11. Rowe, M., & Ladd, G. Water injection for aircraft engines. *SAE Journal (Transactions),* 1946, vol. 54, no. 1, pp. 26-37. DOI: 10.4271/460192.

12. Clinton Wilcox, E., & Trout, A. M. *Analysis of Thrust Augmentation of Turbojet Engines by Water Injection at Compressor Inlet Including Charts for Calculating Compression Processes with Water Injection: NACA Report 1006.* 1950. 20 p. Available at: https://ntrs.nasa.gov/api/citations/19930092063/downloads/19930092063.pdf (accessed 05.01.2024).

13. Trout, A. M. *Theoretical turbojet thrust augmentation by evaporation of water during compression as determined by use of a Mollier diagram: NACA Technical note 2104*. June 1950. 52 p. Available at: https://ntrs.nasa.gov/api/citations/19930082907/downloads/19930082907.pdf (accessed 23.05.2024).

14. Hill, P. G. Aerodynamic and Thermodynamic Effects of Coolant Ingestion on Axial Flow Compressors. *Aeronautical Quarterly,* vol. 14, iss. 4, November, 1963, pp. 331-348. DOI: 10.1017/S0001925900002894.

15. Mourouzidis, C., Igie, U., Pilidis, P., & Singh, R. Water injection on aircraft engines: a performance, emissions and economic study. *ISABE 22nd International Symposium on Air Breathing Engines.* Phoenix, AZ, USA, 2015. 12 p. Available at: http://dspace.lib.cranfield.ac.uk/handle/1826/15176 (accessed 30.11.2023).

16. Daggett, D. L. *Water Injection Feasibility for Boeing 747 Aircraft: Technical memorandum NASA/CR—2005-213656,* 2005. 108 p. Available at: https://ntrs.nasa.gov/api/citations/20060004124/downloads/20060004124.pdf (accessed 04.01.2024).

17. Kofar-bai, D. G., Zhang, H., Zheng, Q., & Abdu, S. Flow Assessment on the Effects of Water Droplets on Rotor Region of Wet Compression. *Transfer Phenomena in Fluid and Heat Flows III, Defect and Diffusion Forum,* 2017, vol. 374, pp. 131-147. DOI: 10.4028/www.scientific.net/DDF.374.131.

18. Roumeliotis, I., & Mathioudakis, K. Evaluation of water injection effect on compressor and engine performance and operability. *Applied Energy Journal,* 2010, vol. 4, iss. 87, pp. 1207-1216. DOI: 10.1016/j.apenergy.2009.04.039.

19. Bhargava, R., & Meher-Homji, C. B., Parametric Analysis of Existing Gas Turbines With Inlet Evaporative and Overspray Fogging. *Turbo Expo 2002, Parts A B, 4 A,* 2002, vol. 4 (January 2005), pp. 387–401. DOI: 10.1115/1.1712980.

20. Utamura, M., Takehara, I., Horii, N., & Kuwahara, T. A New Gas Turbine Cycle for Economical Power Boosting. *ASME ASIA 1997 Congres & Exhibition.* Singapore, Sep 30-Oct, 2, 1997, article no. 97-AA-142. 10 p.

21. Tomita, J. T., Bontempo, L. P., & Barbosa, J. R., An Axial Flow Compressor for Operation With Humid Air and Water Injection. *Journal of Eng. Gas Turbines Power,* 2011, vol. 133, iss. 7, article no. 71703. DOI: 10.1115/GT2010-22996.

22. Sun, L., Zheng, Q., Li, Y., Luo, M., Wang, J., & Bhargava, R. K. Numerical Through Flow Simulation of a Gas Turbine Engine with Wet Compression. *Proceedings of the ASME Turbo Expo 2012: Turbine Technical Conference and Exposition. Volume 3: Cycle Innovations; Education; Electric Power; Fans and Blowers; Industrial and Cogeneration.* Copenhagen, Denmark. June 11–15, 2012. pp. 925-937. ASME. DOI.: 10.1115/GT2012-68846.

23. Cumpsty, N., Jet Propulsion a Simple Guide to the Aerodynamic and Thermodynamic Design and Performance of Jet Engines. *Cambridge University Press,* Cambridge, 1997.

24. Daggett, D., Ortanderl, S., Eames, D., & Snyder, C. Water Injection: Disruptive Technology to Reduce Airplane Emissions and Maintenance Costs.

SAE Technical Paper, 2004, article no. 2004-01-3108. 9 p. DOI: 10.4271/2004-01-3108.

25. Askeland, R., D., Fulay, P. P., & Wright, W. J., The Science and Engineering of Materials. *Global Engineering,* 2011. 949 p. Available at: https://anupturnedworld.files.wordpress.com/2016/06/askeland-the-science-and-engineering-of-materials.pdf (accessed 14.01.2024).

26. Kim, K. H., Ko, H. J., & Perez-Blanco, H. Analytical modeling of wet compression of gas turbine systems. *Applied Thermal Engineering*, 2011, vol. 31, iss. 5, pp. 834-840. DOI: 10.1016/j.applthermaleng. 2010.11.002.

27. White, A. J., & Meacock, A. J. An Evaluation of the Effects of Water Injection on Compressor. *Journal of Engineering for Gas Turbines and Power,* 2004, vol. 126, pp. 748-754. DOI: 10.1115/1.1765125.

28. Balepin, V., Ossello, C., & Snyder, C., *NOx Emission Reduction in Commercial Jets through Water Injection, AIAA-2002-3623, NASA/TM-2002-211978.* 2002. Available at: https://ntrs.nasa.gov/citations/ 20020090894.pdf (accessed 05.01.2024).

29. Bhargava, R. K., Bianchi, M., Chaker, M., Melino, F., Peretto, A., & Spina, P. R. Gas Turbine Compressor Performance Characteristics During Wet Compression: Influence of Polydisperse Spray. *Proceedings of ASME Turbo Expo 2009: Power for Land, Sea and Air.* Orlando, FL USA. June 8–12, 2009, article no. GT2009-59907. 13 p. DOI: 10.1115/GT2009-59907.

30. Daggett, D. L., Fucke, L., Hendricks, R. C., & Eames, D. J. H. *Water Injection on Commercial Aircraft to Reduce Airport Nitrogen Oxides. 40th Joint Propulsion Conference and Exhibit cosponsored by the AIAA, ASME, SAE, and ASEE,* Fort Lauderdale, Florida. July 11-14, 2004. 17 p. NASA/TM-2010-213179. Available at: *https://ntrs.nasa.gov/api/citations/20100015629/* downloads/20100015629.pdf (accessed 30.11.2023).

31. Daggett, D. L., Ortanderl, S., Eames, D., & Berton, J. J. Revisiting Water Injection for Commercial Aircraft. *World Aviation Congress & Exposition: Turbine Engine Technologies,* Nov. 2004, Reno, NV, USA. 2004-01-3108. 8 p. Available at: https://www. researchgate.net/publication/287645497 (accessed 30.11.2023).

32. Bahr, D. W., & Lyon, T. F. NOx Abatement In Aircraft-Derivative Turbine Engines. *American Society of Mechanical Engineering,* 1984, 84-NaN-103.

33. Walsh, P. P., & Fletcher, P. Gas Turbine Performance. *Blackwell Science,* Oxford, 2004. 658 p.

34. Becker, A., & Hartford, E., *Engine Company Evaluation of Feasibility of Aircraft Retrofit Water-Injected Turbomachines. Technical report NASA/CR-2006-213871,* 2006. 35 p. Available at: https://ntrs.nasa.gov/api/citations/20060012147/downloads/20060012147.pdf (accessed 14.01.2024).

35. Urbach, H. B., Knauss, D. T., Wallace, B. L., Emory, J., Frese, J., & Bishop, J. W. Water injection into navy gas-turbine combustors to reduce NOx emissions. *International Gas Turbine & Aerospace Congress & Exhibition,* Stockholm, Sweden, June 2-5, 1998, article no. 98-GT-298. 12 p.

36. Tudosie, A. N. Aircraft Gas-Turbine Engine with Coolant Injection for Effective Thrust Augmentation as Controlled Object. *IntechOpen, Aircraft Technology,* pp. 77-103, 2018. DOI: 10.5772/intechopen.76856.

37. Ulitenko, Yu. Loginov, V., Kravchenko, I., Popov, V., Rasstrygin, O., & Yelans'ky, O. Improving the Efficiency of an Aircraft Power Plant with a Turboprop Engine Based on Water-Methanol Mixture Injection. *Eastern-European Journal of Enterprise Technologies,* 2022, no. 2/1 (116), pp. 6–15. DOI: 10.15587/1729-4061.2022.254277.

38. Chaker, M., Meher-Homji, C. B., & Mee, T. Inlet Fogging of Gas Turbine Engines – Part A: Fog Droplet Thermodynamics, Heat Transfer And Practical Considerations. *Proceedings of ASME Turbo Expo 2002.* Amsterdam, June 3-6, 2002, article no. 2002-GT-30562, pp. 413-428. DOI: 10.1115/1.1712981.

39. Chaker, M., Meher-Homji, C. B., Mee, T. R. III, Inlet Fogging of Gas Turbine Engines — Part B: Fog Droplet Sizing Analysis, Nozzle Types, Measurement and Testing. *Proceedings of ASME Turbo Expo 2002,* Amsterdam, The Netherlands, June 3-6, 2002, ASME Paper No: 2002-GT-30563.

40. Petukhov, I. I., Minyachikhin, A. V., Zelenskii, R. L., Zhemanyuk P. D., Sorogin F. G., & Taran, A. I. Effektivnost' gazoturbinnogo privoda s okhlazhdeniem tsiklovogo vozdukha [Efficiency of gas-turbine drive with cooling of cycle air]. *Aviacijno-kosmicna tehnika i tehnologia – Aerospace technic and technology,* 2004, no. 8/16, pp. 13-15.

41. Roumeliotis, I., Mathioudakis K. Water Injection Effects on Compressor Stage Operation. *Journal of Engineering for Gas Turbines and Power,* 2007, vol. 129, iss. 3, PP. 778-784. DOI: 10.1115/1.2718223.

42. Sorogin, F. G., Basov, Yu. F., Zhemanyuk, P. D., Trofimov, V. P., Minyachikhin, A. V., Petukhov, I. I., & Shakhov, Yu. V. Analiz effektivnosti GTP D-336-2 s raspylitel'noi sistemoi okhlazhdeniya tsiklovogo vozdukha [Effectiveness Analysis of the D-336-2 GTU with Cyclic Air Evaporative Fog Cooling System]. *Vestnik dvigatelestroeniya – Engine-designing bulletin,* 2011, no. 9/86, pp. 147–151.

43. Bettocchi, R., Morini, M., Pinelli, M., Spina, P. R., Venturini, M., & Torsello, G. Set Up of an Experimental Facility for the Investigation of Wet Compression on a Multistage Compressor. *Proceedings of ASME Turbo Expo 2010: Wet Gas Compression and Multi-phase Pumping.* Glasgow, UK, June 14-18, 2010. Article no. GT2010-22451, pp. 673-683. DOI: 10.1115/GT2010-22451.

44. Sorogin, F. G., Basov, Yu. F., Shakhov, Yu. V., Petukhov, I. I., & Minyachikhin, A. V. Analiz effektivnosti GTP D-336-2 s otborom vozdukha dlya raspylitel"noi sistemy okhlazhdeniya [Effectiveness Analysis of the D-336-2 GTU with Cyclic Air Recusation For Spray Cooling System]. *Aviacijno-kosmicna tehnika i tehnologia – Aerospace technic and technology,* 2012, no. 8/95, pp. 47-51.

45. Favorskii, O. N., Alekseev, V. B., Zalkind, V. I., Zeigarnik, Y. A., Ivanov, P. P., Marinichev, D. V., Nizovskii, V. L., & Nizovskii, L. V. Experimentally Studying TV3-117 Gas Turbine Unit Characteristics at Superheated Water Injection into a Compressor. *Thermal Engineering*, 2014, vol. 61, iss. 5, pp. 376-384. DOI: 10.1134/S0040601514050024.

46. Sorogin, F. G., Zhemanyuk, P. D., Trofimov, V. P., Shakhov, Y. V., Petukhov, I. I., & Minyachikhin, A. V. Eksperimental"noe issledovanie raspylitel"noi sistemy okhlazhdeniya tsiklovogo vozdukha GTP [Experimental Investigation of the Gas Turbine Unit Cyclic Air Spray Cooling System]. *Aviacijno-kosmicna tehnika i tehnologia – Aerospace technic and technology*, 2015, no. 8/125, PP. 70-74.

47. Burtsev, G. N., Run'ko, V. V., Shleynikov, N. V., Shevelev, D. V., & Gridchin, N. V. Eksperimental"noe issledovanie vliyaniya vpryska vody na parametry gazoturbinnoi ustanovki maloi moshchnosti. [Experimental Investigation of the Effect of Water Injection on Low-Power Gas Turbine Plant Parameters]. *Vestnik MGTU im. N. E. Baumana. Ser. Mashinostroenie – Herald of the Bauman Moscow State Technical University, Mechanical Engineering*, 2017, vol. 5, pp. 122–131. DOI: 10.18698/0236-3941-2017-5-122-131.

48. Petukhov, I. I., Sorogin, F. G., Shakhov, Yu. V., & Minyachikhin, A. V. Energeticheskaya effektivnost' GTP semeistva AI-336 s raspylitel'noi sistemoi okhlazhdeniya tsiklovogo vozdukha [Power Efficiency of the Gas Turbine Drive of an AI-336 set with the Spraying-Type Cycle Air Cooling System]. *Bulletin of NTU "KhPI". Series: Power and heat engineering processes and equipment*, 2017, no. 11/1233, pp. 55–63, DOI: 10.20998/2078-774X.2017.11.09.

49. Balajti, P., & Beneda, K. Experimental Study on the Effect of Water Injection on a Micro Turbojet Engine. *Repüléstudományi közlemények,* 2021, vol. 3, pp. 97–109. DOI: 10.32560/rk.2021.3.8.

50. Barakat, E., Jin, T., Tong, X., Ma, Ch., & Wang, G. Experimental investigation of saturated fogging and overspray influence on part-load micro gas turbine performance. *Applied Thermal Engineering.* Volume 219, Part B, 25 January 2023, article no. 119505. DOI: 10.1016/j.applthermaleng.2022.119505.

51. Hashim, H. S., Kassim, M. S., & Alwan, R. A. Investigation of Inlet Air Fogging as a Heat Transfer Enhancement Technique for Gas Turbines. *International Journal of Heat and Technology*, vol. 41, no. 6, December, 2023, pp. 1453-1460. DOI: 10.18280/ijht.410607.

52. Benini, E., Pandolfo, S., & Zoppellari, S. Reduction of NO emissions in a turbojet combustor by direct water/steam injection: numerical and experimental assessment. *Applied Thermal Engineering, Elsevier,* 2009, vol. 29, iss. 17-18. 24 p. DOI: 10.1016/j.applthermaleng.2009.06.004.

53. Wang, J., Zheng, Q., Sun, L., & Luo, M. The Effective Positions to Inject Water into the Cascade of Compressor. *Proceedings of the ASME Turbo Expo 2012: Turbine Technical Conference and Exposition. Volume 3: Cycle Innovations; Education; Electric Power; Fans and Blowers; Industrial and Cogeneration.* Copenhagen, Denmark. June 11–15, 2012, pp. 979-992. ASME. DOI: 10.1115/GT2012-69158.

54. Roumeliotis, I., Alexiou, A., Aretakis, N., Sieros, G., & Mathioudakis, K. Development and Integration of Rain Ingestion Effects in Engine Performance Simulations. *Proceedings of ASME Turbo Expo 2014.* Düsseldorf, Germany. June 16–20, 2014, article no. GT2014-26443. 11 p. DOI: 10.1115/1.4028545.

55. Liu, C., Li, X., Zhang, H., & Zheng, Q. Heat and Mass Transfer Characteristics of Water Droplets in Wet Compression Process. *Proceedings of the ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition. Volume 3: Coal, Biomass and Alternative Fuels; Cycle Innovations; Electric Power; Industrial and Cogeneration Applications; Organic Rankine Cycle Power Systems.* Charlotte, North Carolina, USA. June 26–30, 2017. V003T23A003. DOI: 10.1115/GT2017-63516.

56. Sexton, M. R., Urbach, H. B., & Knauss, D. T. Evaporative compressor cooling for NOx Supression and Enhanced Engine Performance for Naval Gas Turbine Propulsion Plants. *International Gas Turbine & Aeroengine Congress & Exhibition.* Stockholm, Sweden, June 2-5, 1998, article no. 98-GT-332. 10 p.

57. Chaker, M, Meher-Homji, C. B, & Mee, T, III. Inlet Fogging of Gas Turbine Engines: Part C – Fog Behavior in Inlet Ducts, CFD Analysis and Wind Tunnel Experiments. *Proceedings of the ASME Turbo Expo 2002: Power for Land, Sea, and Air. Volume 4: Turbo Expo 2002, Parts A and B.* Amsterdam, Netherlands. June 3–6, 2002, pp. 443-455. DOI: 10.1115/GT2002-30564.

58. Zheng, Q., Sun, Y., Li, S., & Wang, Y. Thermodynamic Analyses of Wet Compression Process in the Compressor of Gas Turbine. *Journal of Turbomachinery*, 2003, vol. 125, iss. 3, pp. 489-496. DOI: 10.1115/1.1575254.

59. Sanaye, S., Rezazadeh, H., Aghazeynali, M., Samadi, M., Mehranian, D., & Ahangaran, M. K. Effects of Inlet Fogging and Wet Compression on Gas Turbine Performance. *Proceedings of ASME Turbo Expo 2006: Power for Land, Sea and Air.* Barcelona, Spain. May 8-11, 2006, article no. GT2006-90719. DOI: 10.1115/GT2006-90719.

60. Minyachikhin, A. V., Petukhov, I. I., Sorogin, F. G., & Turna, R. Yu. Primenenie isparitel'nykh panelei dlya sistemy okhlazhdeniya vkhodnogo vozdukha gazoturbinnogo privoda. [Evaporation panels application for inlet air cooling system of gas turbine unit]. *Aviacijno-kosmicna tehnika i tehnologia – Aerospace technic and technology,* 2006, no. 7/33, pp. 21-24.

61. Bagnoli, M., Bianchi, M., Melino, F., & Spina, P. R. Development and Validation of a Computational Code for Wet Compression Simulation of Gas Turbines. *Proceedings of the ASME Turbo Expo 2006: Power for Land, Sea, and Air. Volume 4: Cycle Innovations; Electric Power; Industrial and Cogeneration; Manufacturing Materials and Metallurgy.* Barcelona,

Spain. May 8–11, 2006, pp. 641-649. ASME. DOI: 10.1115/GT2006-90342.

62. Basov, Yu. F. Zhemanyuk, P. D., Minyachikhin, A. V., Petukhov, I. I., Sorogin, F. G., & Shakhov, Yu. V. Raspylitel'nye sistemy okhlazhdeniya tsiklovogo vozdukha gazoturbinnogo privoda i ikh effektivnost' [Spray-Type Systems of the Gas Turbine Plant Cycle Air Cooling And Its Efficiency]. *Aviacijno-kosmicna tehnika i tehnologia – Aerospace technic and technology*, 2009, no. 7/64, pp. 38-43.

63. Wang, T., & Khan, J. R. Overspray and Interstage Fog Cooling in Gas Turbine Compressor Using Stage-Stacking Scheme – Part I: Development of Theory and Algorithm. *Journal of Thermal Science and Engineering Applications*, 2010, vol. 2, iss. 3, article no. 31001. DOI: 10.1115/1.4002754.

64. Wang, T., & Khan, J. R. Overspray and Interstage Fog Cooling in Compressor Using Stage-Stacking Scheme: Part 2 – Case Study. *Proceedings of the ASME Turbo Expo 2008: Power for Land, Sea, and Air. Volume 7: Education; Industrial and Cogeneration; Marine; Oil and Gas Applications.* Berlin, Germany. June 9–13, 2008, pp. 111-121. DOI: 10.1115/GT2008-50323.

65. Kudinov, A., & Gorlanov, S. Povyshenie effektivnosti gazoturbinnoi ustanovki putem vpryska vodyanogo para v kameru sgoraniya dvigatelya NK-37. [Efficiency Increase Of Gas-Turbine Installation By Injection Of Water Vapor In The Nk-37 Engine Combustion Chamber]. *Vestnik SGASU. Gradostroitel'stvo i arkhitektura – Herald of the Samara State Technical University. Town building and architecture*, 2014, vol. 1, iss. 14, pp. 103-110.

66. Tudosie, A. N. Mathematical model for a jet engine with cooling fluid injection into its combustor. *Proceeding of International Conference of Scientific Papers AFASES*, Brasov, 22-24 May, 2014, PP. 265-272. Available at: *https://www.afahc.ro/ro/afases/2014/mecanica/Tudosie_combustor.pdf* (accessed 30.11.2023).

67. Tudosie, A. N. Mathematical model for a jet engine with cooling fluid injection into its compressor. *Proceeding of International Conference of scientific paper AFASES*, Brasov, 22-24 May, 2014, 8 p. Available at: https://www.afahc.ro/ro/afases/2014/mecanica/Tudosie_compresor.pdf (accessed 30.11.2023).

68. Lisitsa, A. Yu., Nemchenko, D. A., Petukhov, I. I., & Sorogin, F. G. K voprosu effektivnosti kosvenno-isparitel'nogo okhlazhdeniya tsiklovogo vozdukha GTP [On Efficiency of Indirect Evaporative Cooling For GTU Cyclic Air]. *Aviacijno-kosmicna tehnika i tehnologia – Aerospace technic and technology*, 2014, no. 9/116, pp. 50-55.

69. Berkovich, A. L., Polischuk, V. G., & Nazarenko, A. V. Forsirovanie statsionarnykh gazoturbinnykh ustanovokoptimal'nym vpryskom vody v kompressor [Boosting Gas Turbine Power Plants Through Optimal Water Injection Into Compressor]. *Nauchno-tekhnicheskie vedomosti SPbGPU – Scientific and technical bulletin of Peter the Great St. Peterburg Politechnic University*, 2015, no. 2/219, pp. 33-40. DOI 10.5862/JEST.219.4.

70. Kler, A. M., Zakharov, Yu. B., & Potanina, Yu. M. Otsenka effektivnosti vpryska vody mezhdu chastyami vozdushnogo kompressora dlya GTU i PGU. [Efficiency estimation of water injection between air compressor parts for gas turbine unit and combined-cycle plant]. *Teplofizika i aeromekhanika – Thermal physics and aeromechanics*, 2015, vol. 24, no. 3. pp. 497-505.

71. Sorogin, F. G., Zhemanyuk, P. D., Trofimov, V. P., Shakhov, Y. V., & Petukhov, I. I. K voprosu kompleksnoi otsenki effektivnosti GTP s okhlazhdeniem tsiklovogo vozdukha [The Gas-Turbine Drive with Cyclic Air Cooling Efficiency Integrated Evaluation Problem]. *Aviacijno-kosmicna tehnika i tehnologia – Aerospace technic and technology*, 2016, no. 4/131, pp. 25-33.

72. Sorogin, F. G. Metod rascheta energeticheskikh pokazatelei GTP [The Gas-Turbine Drives Energy Factors Calculation Method]. *Vestnik dvigatelestroeniya – Engine-designing bulletin*, 2017, no. 2, pp. 29–33.

73. Bianchi, M., Pascale, A. De., Melino, F., Peretto, A., & Sasha, S. Water Injection Evaporation in Frame 7EA Gas Turbine Wrapper. *Proceedings of ASME Turbo Expo 2017: Power for Land, Sea and Air.* Charlotte, North Caroline, USA. June 26-30, 2017. article no. GT2017-64189. 12 p. DOI: 10.1115/GT2017-64189.

74. Hartel, C., & Pfeiffer, P. Model analysis of high-fogging effects on the work of compression. *Proceedings of the ASME Turbo Expo 2003, collocated with the 2003 International Joint Power Generation Conference. Volume 2: Turbo Expo 2003.* Atlanta, Georgia, USA. June 16–19, 2003, pp. 689-698. DOI: 10.1115/GT2003-38117.

75. Novelo, D. A. B., & Igie, U. Aero Engine Compressor Cooling by Water Injection – Part 1: Evaporative Compressor Model. *Energy*, 2018, vol. 160, pp. 1224-1235. DOI: 10.1016/j.energy.2018.05.170.

76. Novelo, D. A. B., & Igie, U. Aero Engine Compressor Cooling by Water Injection – Part 2: Performance and Emission Reductions. *Energy*, 2018, vol. 160, pp. 1236-1243. DOI: 10.1016/j.energy.2018.05.171.

77. Kadhim, H. J., Abbas, A. K., Kadhim, T. J., & Rashid, F. L. Evaluation of Gas Turbine Performance in Power Plant with High-Pressure Fogging System. *Mathematical Modelling of Engineering Problems*, 2023, vol. 10, no. 2, pp. 605-612. DOI: 10.18280/mmep.100230.

78. Kok, J. B. W., & Haselhoff, E. A. Thermodynamic analysis of the thermal and exergetic performance of a mixed gas-steam aero derivative gas turbine engine for power generation. *Heliyon*, 2023, no. 9, article no. e18927, pp. 1-12. DOI: 10.1016/j.heliyon.2023.e18927.

79. Bassily, A. M. Performance enhancements and NOx emission reductions using novel exhaust-driven hybrid gas turbine inlet air-cooling techniques. *Proceedings of the Institution of Mechanical Engineers, Part E:*

Journal of Process Mechanical Engineering, 2023, DOI: 10.1177/09544089231210782.

80. Lopata, J., & Carter, P. DARPA's RASCAL: Status, Challenges, and Accomplishments. *18th Annual AIAA/USU Conference on Small Satellites*. Article no. SSC04-X-2. 6 p. Available at: https://www.enginehistory.org/GasTurbines/GE/DARPA_s%20RASCAL_%20Status%20Challenges%20and%20Accomplishments.pdf (accessed 30.11.2023).

81. Ulitenko, Yu. A., Yelansky, A. V., & Kravchenko, I. F. Problemy vybora skhemy silovoi ustanovki dlya pervoi stupeni transportno-kosmicheskoi sistemy [Problems of Selection of Configuration for Powerplant Intended For Space Transportation System Stage 1]. *Aviacijno-kosmicna tehnika i tehnologia – Aerospace technic and technology*, 2013, no. 8/105, pp. 25-30.

82. Ulitenko, Yu. A., Elanskij, A. V., & Kravchenko, I. F. Modernizacija turboreaktivnogo dvuhkonturnogo dvigatelja s forsazhnoj kameroj sgoranija putem vpryska vody v protochnuju chast' vozduhozabornika [Modernization of the turbofan engine with afterburner combustion by water injection into air intake duct]. *Vestnik dvigatelestroenija – Engine-designing bulletin*, 2014, no. 2, pp. 122–129.

83. Mehta, U., Huynh, L., & Hagseth, P. Water injection pre-compressor cooling assist space access. *The Aeronautical Journal*, 2015, vol. 119, no. 1212, pp. 145-171.

84. Ulitenko, Yu. A., Yelansky, A. V., & Kravchenko, I. F. Rasshirenie diapazona ekspluatatsii pryamotochnykh vozdushno-reaktivnykh dvigatelei putem vpryska vody na vkhode v dvigatel' [The Expansion Of The Range Of Operation Of Ramjet Engines By Water Injection At The Inlet To The Engine]. *Sistemi ozbroєnnya i viis'kova tekhnika – Armament Systems and defense technology*, 2016, no. 2/46, pp. 158-163.

85. Ulitenko, Yu. A., Yelansky, A. V., Kravchenko, I. F. Vliyanie vpryska vody na vkhode v pryamotochnyi vozdushno-reaktivnyi dvigatel" na ego kharakteristiki. [The Effect Of Water Injection At The Inlet Of Ramjet Engine On Its Characteristics]. *Aviacijno-kosmicna tehnika i tehnologia – Aerospace technic and technology*,, 2016, no. 8/135, pp. 22-28.

86. Ulitenko, Yu. A. Analiz kharakteristik turboreaktivnogo dvukhkonturnogo dvigatelya s forsazhnoi kameroi sgoraniya s vpryskom vody za vkhodnym ustroistvom [Turbojet bypass engine with after-burner with water injection after input unit performance analysis]. *Aviacijno-kosmicna tehnika i tehnologia – Aerospace technic and technology*, 2019, no. 1, pp. 29-38. DOI: 10.32620/aktt.2019.1.03.

87. Ulitenko, Yu., Minenok, M, Kravchenko, I. Analiz kharakterystyk turboreaktyvnoho dvokonturnoho dvyhuna z forsazhnoyu kameroyu z·horyannya z vporskuvannyam vody na vkhodi do kompresora vysokoho tysku. [Performance Analysis of Turbofan Engine With Afterburner with Water Injection at High-Pressure Compressor Inlet]. *Aviacijno-kosmicna tehnika i tehnologia – Aerospace technic and technology*, 2022, no. 4(sup. 1)/181, pp. 49-57. DOI: 10.32620/aktt.2022.4sup1.08.

88. Ulitenko, Yu. O., Minenok, M. A., & Kravchenko, I. F. Analiz vplyvu mistsya vporskuvannya vody na kharakterystyky turboreaktyvnoho dvokonturnoho dvyhuna z forsazhnoyu kameroyu z'horyannya [Analysis of the Influence of the Place of Water Injection on the Performance of Turbofan Engine with Afterburner]. *Aviacijno-kosmicna tehnika i tehnologia – Aerospace technic and technology*, 2023, no. 4/190, pp. 35-42. DOI: 10.32620/aktt.2023.4sup2.04.

89. Meichao, X., Linsen, S. & Dakun, X. Effect of water spray on tip leakage flow in a inlet stage of high-speed compressor. *Aerospace Science and Technology*, 2023, vol. 142, part B, article no. 108687. DOI: 10.1016/j.ast.2023.108687.

90. Chaker, M., & Meher-Homji, C. B. Gas Turbine Power Augmentation: Parametric Study Relating to Fog Droplet Size and Its Influence on Evaporative Efficiency. *Proceedings of the ASME Turbo Expo 2008: Power for Land, Sea, and Air. Volume 7: Education; Industrial and Cogeneration; Marine; Oil and Gas Applications.* Berlin, Germany. June 9–13, 2008, pp. 357-369. DOI: 10.1115/GT2008-51476.

91. Hendricks, R. C., Shouse, D., & Roquemore, M. Water Injected Turbomachinery. *The 10th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery, Technical memorandum NASA/TM–2005-212632*, 2005. 20 p. Available at: https://ntrs.nasa.gov/api/citations/20050175876/downloads/20050175876.pdf (accessed 30.11.2023).

92. NATOPS Flight Manual. NAVY Model AV-8B/TAV-8B. *Naval Air System Command*, 2008. 714 p.

93. Eames, D. J. H. *Short Haul Civil Tiltrotor Contingency Power System Preliminary Design: NASA report CR–2006-214059*. Available at: https://ntrs.nasa.gov/api/citations/20060006384/downloads/20060006384.pdf (accessed 30.11.2023).

94. Trotskii1, N. I., & Khakimov, Kh. Kh. Analiz vozmozhnykh putei kratkovremennogo forsirovaniya GTD na primere vspomogatel'nogo gazoturbinnogo energoagregata [Analysing the Possible Ways for Short-Term Forcing Gas Turbine Engines in Auxiliary Power Unit]. *Nauka i Obrazovanie. MGTU im. N.E. Baumana. Elektronniy zhurnal – Science and Education of the Bauman MSTU. Electronic Journal*, 2016, vol. 5, pp. 93-103. DOI: 10.7463/0516.0840406.

95. Stettler, M. E. J., Eastham, S., & Barrett, S. R. H., Air quality and public health impacts of UK airports. Part I: Emissions. *Atmospheric Environment*, 2011, vol. 45, iss. 31, pp. 5415–5424. DOI: 10.1016/j.atmosenv.2011.07.012.

96. Lefebvre, A. H., & Ballal, D. R. *Gas Turbine Combustion Alternative Fuels and Emissions.* NY, CRC Press Publ., 2010. 560 p.

97. *Environmental Protection, Annex 16, Volume II Aircraft Engine Emissions*. International Civil Aviation Organization, Chicago, 2008. Available at: https://www.icao.int/environmental-protection/Docume-

nts/EnvironmentalReports/2022/ENVReport2022_Art17.pdf (accessed 24.03.2024).

98. *Airport air quality manual. ICAO,* 2011. Available at: https://www.icao.int/environmental-protection/Documents/Doc%209889.SGAR.WG2.Initial%20Update.pdf (accessed 14.01.2024).

99. *Engine Exhaust Emissions Data Bank*. International Civil Aviation Organization, 2013. Available at: https://www.easa.europa.eu/en/downloads/131424/en (accessed 24.03.2024).

100. *Development of the technical basis for a New Emissions Parameter covering the whole Aircraft operation (NEPAIR).* 2003. Available at: https://cordis.europa.eu/project/id/G4RD-CT-2000-00182. (accessed 14.01.2024).

Надійшла до редакції 10.05.2024, розглянута на редколегії 15.06.2024

АНАЛІЗ СИСТЕМ ВПОРСКУВАННЯ ОХОЛОДНОЇ РІДИНИ В ПРОТОЧНУ ЧАСТИНУ ГТД

С. В. Єпіфанов, Р. Ю. Цуканов

Предметом вивчення в статті є система впорскування охолодної рідини в проточну частину авіаційного газотурбінного двигуна (ГТД). **Метою** є зменшення гостроти протиріч між економічними та екологічними вимогами; екологічними вимогами та технологічними обмеженнями; маркетинговими вимогами та вимогами забезпечення ресурсу, шляхом застосування системи впорскування охолодної рідини в проточну частину ГТД. **Задачі:** розроблення класифікації, виявлення переваг та недоліків різних технологій впорскування охолодної рідини в проточну частину ГТД, аналіз методів дослідження систем впорскування охолодної рідини та досвіду використання цих систем на реальних літальних апаратах (ЛА) та в їх проєктах. Використовуваними **методами є:** пошук відповідних джерел у мережі Internet та їх аналіз виходячи з власного досвіду роботи в авіаційній галузі. Отримано наступні **результати.** На основі знайдених джерел інформації розроблено класифікацію систем впорскування охолодної рідини в проточну частину ГТД; сформульовано переваги та недоліки різних технологій впорскування охолодної рідини; виявлено, що для дослідження систем впорскування охолодної рідини, використовуються три типи методів (експериментальні, обчислюваної гідродинаміки та аналітичні); стисло наведено результати наявних досліджень; проаналізовано використання системи впорскування охолодної рідини на ЛА з метою розширення допустимих режимів польоту літаків, підвищення тяги/потужності авіаційного ГТД та зменшення викидів оксидів азоту на зльоті. **Висновки.** Наукова новизна отриманих результатів полягає в наступному: в одній оглядовій статті зібрано інформацію з багатьох літературних джерел, що висвітлює класифікацію, переваги й недоліки різноманітних технологій впорскування охолодної рідини в проточну частину ГТД, розвиток дослідження цих систем різними методами та досвід їх застосування як на реальних, так і в проєктованих ЛА. Виявлено потребу в розробленні методики проєктування ЛА транспортної категорії з урахуванням встановлення системи впорскування охолоджувальної рідини в проточну частину ГТД. Намічено мету та задачі подальших досліджень у цій галузі.

Ключові слова: газотурбінний двигун; охолодна рідина; система впорскування охолодної рідини; туманоутвореня; вологий стиск; викиди оксидів азоту.

Цуканов Руслан Юрійович – старш. викл. каф. проектування літаків і вертольотів, Національний аерокосмічний університет ім. М. Є. Жуковського «Харківській авіаційний інститут», Харків, Україна.

Єпіфанов Сергій Валерійович – д-р техн. наук, проф., зав. каф. конструкцій авіаційних двигунів, Національний аерокосмічний університет ім. М. Є. Жуковського «Харківській авіаційний інститут», Харків, Україна.

Ruslan Tsukanov – Senior Lecturer at the Airplane and Helicopter Design Department, National Aerospace University «Kharkiv Aviation Institute», Kharkiv, Ukraine,
e-mail: r.tsukanov@khai.edu, ORCID: 0000-0001-8348-8707.

Sergii Yepifanov – Dr. of Sc. in Engineering, Prof., Head of Engine Design Department, National Aerospace University «Kharkiv Aviation Institute», Kharkiv, Ukraine,
e-mail: s.yepifanov@khai.edu, ORCID: 0000-0003-0533-9524, Scopus ID: 6506749318.