DOI: 10.13009/EUCASS2025-409
11TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS)

Analysis of the effect of water injection and the use of hydrogen as a fuel on the efficiency of an aviation hybrid turboelectric power plant within the EFACA project

Yurii Ulitenko[1], Maksym Kirichkov[1], Igor Kravchenko[1]
[1]Zaporizhzhia Machine-Building Bureau Progress
Joint Stock Company named after Academican A.G. Ivchenko
2, Ivanova Str., 69068 Zaporizhzhia, Ukraine
e-mail: y.ulitenko@gmail.com – m.kirichkov@ivchenko-progress.com – i.kravchenko@ivchenko-progress.com
† Yurii Ulitenko

Abstract
To create the concept of a hybrid turbo-electric power plant as a single unit integrated into the power plant of a regional aircraft with a capacity of up to 80 seats and a flight range of up to 1000 km, the effect of water injection and the use of hydrogen as the main fuel on the efficiency of a turboprop engine was investigated. The variants of water injection at the inlet to the compressor and to the combustion chamber were investigated. Hydrogen is supplied at the inlet to the combustion chamber instead of traditional aviation fuel. The results of mathematical modelling were partially verified. Water injection will increase the power of the turboprop engine by up to 10%, and the use of hydrogen will reduce the amount of harmful emissions. The obtained results demonstrate satisfactory convergence of the calculated and experimental data. The error of the results under the assumptions made does not exceed 3%. The proposed measures can be partially implemented at the existing turboprop engines.

Nomenclature

Alt – altitude, m;
EE – electric engine;
FC – fuel cells;
GTE – gas turbine engine;
HTEP – hybrid turbo-electric propulsion;
M – Mach number;
MM – mathematical model;
LHV – Lower Heating Value, kKal/kg;
PP – power plant;
TPE – turboprop engine;
Tt – total temperature, K;
th – ambient temperature, C;
WAR – humidity content;
Wf – fuel consumption, kg/s;

1. Introduction

Fierce competition among aviation companies is forcing aircraft engine manufacturers to improve their fuel efficiency and environmental performance. The impact of aviation emissions on the environment further stimulates the development of new technologies and the use of unconventional schemes in the development of new aircraft engines. The capabilities of an aircraft are determined by the characteristics of the engine as part of the PP. Today, TPEs are widely used in most types of aircraft due to their high fuel efficiency. With each new generation of TPE, their specific power increases. At the same time, the use of high-tech technologies leads to a significant increase in the cost of new

DOI: 10.13009/EUCASS2025-409

engines. Therefore, today, the most pressing issues are the deep modernization of the existing fleet of turboprop aircraft and the reduction of operating costs through the use of hybrid power plants.
There is also a need to gradually switch transport to alternative energy sources. Particular attention should be paid to hydrogen. Research on the use of fuel cells to combine technologies for their use as a source of water to increase TPE power and the use of hydrogen as the main fuel will allow the regional aviation sector to solve some of the environmental problems.
At the same time, one of the scientific and technical issues is the study of heat transfer processes in a multiphase gas flow based on the injection of various mixtures into an aircraft engine. The development and improvement of methods for studying the working process of advanced TPEs is an urgent and pressing issue for aircraft engine developers.
The presented results are based on research carried out within the framework of the EFACA project (Environmentally clean aviation for all classes of aircraft), financed by the European Commission through the program "Horizon Europe" (Grant agreement No. 101056866), included in the cluster "Climate, energy and mobility". EFACA aims to promote a greener aviation sector by developing new technologies using electric and hybrid thermoelectric power plants and new sustainable fuels to combat climate change by 2050 (www.efaca.eu).

2. Literature analysis and task setting

The European Flightpath 2050 program and NASA's Environmentally Responsible Aviation N+ program have set ambitious targets for reducing emissions and external noise from aircraft engines at specific time points. However, improving existing technologies is not enough to achieve them, and a number of breakthrough technologies need to be envisaged and implemented.
To ensure ultra-low or even zero emissions of harmful substances from aircraft, a number of international research and development projects have already been carried out to introduce hybrid-electric technologies [1], [2], [3], [4], [5].
Improving the environmental performance of existing aircraft can only be realized through a comprehensive improvement of the airframe and power plant, in particular through the study of new breakthrough design and physical principles in the field of aircraft engines and power plants, in particular, the introduction of a hybrid turbo-electric propulsion (HTEP) using hydrogen technologies [6].
The introduction of hybrid-electric technology not only challenges traditional schemes, but also provides an opportunity to use the full potential of these technologies through synergistic morphological and system integration of the subsystems of the power plant and the aircraft.
Today, leading aviation companies are exploring various schemes of HTEP. The analysis of such schemes shows the existence of the principle of separation of the required power (thrust) received from a gas turbine engine (GTE) and an electric engine (EE) [7], [8], [9].
The most important issue in the use of an EE in an aircraft PP is the need to store electricity that can be generated in batteries or fuel cells (FC). At the current stage of technology development, it is clear that the energy capacity obtained from batteries is several times less than the energy capacity obtained from hydrogen, taking into account its storage conditions. Therefore, it is expedient to consider the HTEP schemes without using batteries as the main source of energy, and to obtain the necessary energy for the EE from FC. Therefore, the study of the integration characteristics of FC, GTE and other components of hybrid systems (evaporators, heat exchangers, etc.) is important for the efficiency of the aircraft-HTEP system as a whole [10], [11].
That is why the concept of creating a HTEP based on a turboprop engine with EE and FC for a regional aircraft is an urgent scientific and technical task of mutual integration of processes in HTEP components. This will increase its take-off power when operating with FC. Parasitic heat from FC can be used as a coolant for hydrogen evaporation for the needs of FC. Heat from combustion products of the GTE can be used for hydrogen evaporation.
In turn, water, which is a by-product of the physical and chemical processes that take place in FC, can also be used in the GTE operating cycle. Water injection was first used on commercial transport aircraft more than 75 years ago. At that time, the technology of injecting water into an aircraft engine was used to increase power or thrust during take-off [12]. On the first jet aircraft, water was sprayed at the inlet to the engine's air intake or compressor to cool the air. This made it possible to increase the flow of working fluid through the engine and its thrust during take-off on a hot day [13]. Later, water injection to increase thrust was used in Boeing 707-120 Stratoliner aircraft powered by Pratt & Whitney JT3C-6 engines and in Boeing 747-100 and 200 aircraft powered by Pratt & Whitney JT9D-3AW and -7AW engines [14], [15]. Papers [14] and [15] present research on finding the optimum between fuel consumption and water consumption to reduce NO_X emissions on takeoff for a specific aircraft with a specific engine type.
For TPEs, water injection is an alternative to replace the most common short-term performance improvement method for turbojet engines, the afterburner. The use of water injection without increasing power leads to a reduction in NO_X emissions. Paper [16] presents the results of studies on the impact of water injection on the technical, environmental, and economic characteristics of the engine.
The cooling effect of water injection leads to a decrease in the temperature of the working fluid not only at the injection point, but also throughout the gas-air path of the engine [17]. In turn, the operation of the engine at lower temperatures

DOI: 10.13009/EUCASS2025-409

of the working fluid will increase the service life. It is expected that the cost of complicating the design and operation of an aircraft with water injection will be offset by savings in engine maintenance and an increase in its service life. These savings will create sufficient market demand for the development and implementation of water injection systems as an additional technology to improve engine performance and reduce aircraft emissions [18].
There are two common methods of injecting water into the flow path of an aircraft engine:
– water injection at the compressor inlet. Paper [19] considers the effect of water injection into the compressor only on the characteristics of a gas turbine. Papers [20] and [21] demonstrate the results of studies on the effect of water mist injection in the intermediate stages of the compressor. However, works [20] and [21] do not reflect the effect of water injection on the engine parameters as a whole. Paper [22] describes the results of mathematical modelling of the effect of coolant injection into the compressor only for a turbojet twin-circuit engine;
– water injection into the combustion chamber [23]. Work [23] describes the results of mathematical modelling of the effect of coolant injection on engine parameters only at the outlet of the combustion chamber.
Injecting water into the compressor or combustion chamber will improve performance. Water injection at the compressor inlet has been shown to have a positive effect on engine performance [24] and at the same time reduces the gas temperature at the turbine inlet. In addition, water injection at the compressor inlet can reduce NO_X emissions by up to 50% [25]. Work [24] shows the effect of water injection on the performance characteristics of various types of engines. However, work [24] does not indicate the effect of water injection on reducing harmful emissions. Paper [25] presents the results of studies of the effect of water injection into the compressor on the gas temperature in the turbine and NO_X emissions only for a turbojet engine.
In turn, the injection of water and the use of hydrogen as the main fuel requires the improvement of the mathematical model of the working process of the TPE based on changes in the thermophysical properties and phase transitions of the working fluid. There is a need to conduct experimental work to verify the results obtained.
Paper [26] presents a method for modelling a one-dimensional multiphase workflow to study the effect of water injection into a compressor. The multiphase workflow takes into account the heat transfer during the phase transition of water, and the general model uses heat transfer and gas properties to simulate the properties of the working fluid. The combined models are validated using experimental data and information on the operating cycle of the FT8 onshore industrial gas turbine. Parametric studies were carried out to determine the change in the performance of the fan and axial compressor in the event of water or water vapour ingress during aircraft operation on aircraft carriers. Paper [27] demonstrates the results of experimental studies of the effect of water injection on the characteristics of the TV3-117 engine.
Thus, the injection of water and the use of hydrogen as the main fuel in the TPE have prospects for simultaneous implementation when creating the concept of a hybrid turbo-electric power plant. However, further research is needed to determine and improve the performance characteristics of an aircraft with a TPE as part of a hybrid turbine-electric propulsion system concept. It is necessary to identify ways to solve the problems of mathematical modelling and ensuring the performance of the TPE when using water injection and hydrogen as the main fuel. Overcoming these problems will improve performance and reduce engine emissions. The combination of water injection and the use of hydrogen as the main fuel will allow the aviation sector to solve some of the environmental and environmental protection tasks.

3. Aims and objectives of the research

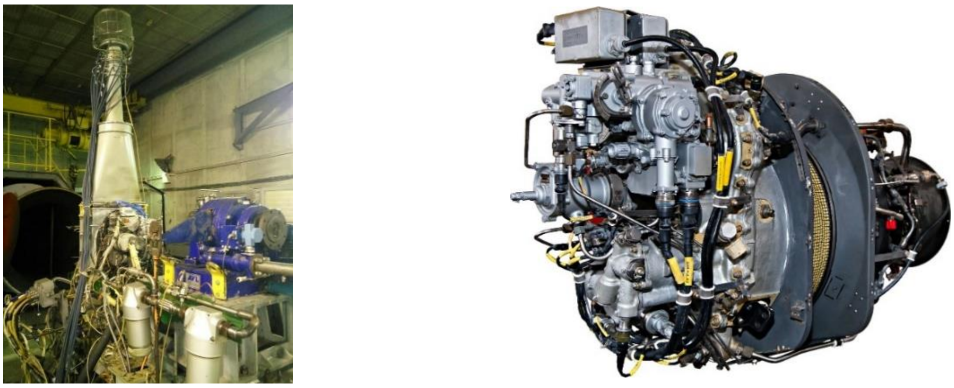
The aim of the research is to improve the methodology for modelling the operation of the TPE based on water injection and the use of hydrogen as the main fuel to increase the efficiency of a HTEP with a TPE as part of a regional aircraft with a capacity of up to 80 seats and a flight range of up to 1000 km. The improved methodology will allow for further research to improve the efficiency of a HTEP with a TPE as part of a regional aircraft with a capacity of up to 80 seats and a flight range of up to 1000 km.
To achieve the research goal, the following tasks need to be solved:
– to verify the developed methodology for changing the thermophysical properties and phase transitions of the working fluid during water injection into the TPE;
– to verify the results of mathematical modelling of the engine operating process with experimental data;
– to investigate the impact of the water injection point on the performance characteristics of the TPE;
– to study the impact of water injection and the use of hydrogen as the main fuel on the performance of the TPE.
To solve the tasks, scientific methods and the theory of work processes of air-jet engines, system analysis, mathematical modelling, computational mathematics and computer-aided design systems were used.

DOI: 10.13009/EUCASS2025-409

4. Materials and methods of the study

MM of TPE has been built on the basis of a general approach to solving the system of basic equations [28]. The system of basic equations of gas motion is a mathematical apparatus that describes the gas-dynamic, thermodynamic, and physical relations in the elements of the engine. The system includes the following equations [29], [30]:
– continuity equation;
– energy conservation equation;
– equation of the first law of thermodynamics in relation to the flow of gas;
– Bernoulli's generalized equation;
– Euler's equation on the amount of motion;
– Euler's equation on the momentum of the amount of motion.
MM is a method for solving a system of nonlinear equations implemented in the Fortran programming language [31], which provide for the following:
– the thermodynamic consistency of engine components and elements;
– the invariability of the geometric parameters of the engine;
– the preservation of physical and gas-dynamic links between the components and elements of the engine;
– fulfillment of the equation of continuity of flow of working medium for all components and elements of the engine;
– maintaining the specified control parameters.
A given approach [32]:
– provides the necessary modeling accuracy at the early stages of research work;
– makes it possible to make a choice of rational thermodynamic parameters;
– makes it possible to select the law of controlling the injection of coolant in TPE at the specified characteristics of the units.
The thermodynamic calculation methodology is based on the temperature dependence of the thermodynamic properties of air and combustion products with relative fuel consumption (FAR). The dissociation of molecules is not taken into account.
Changes in the thermophysical properties of the working fluid are taken into account depending on its composition and temperature. For a given fuel [33], the gas composition depends only on the excess air ratio. Instead, the MM uses the relative fuel consumption (FAR). The values of enthalpy (i), gas entropy (S), gas constant (R), and isentropic coefficient (k) are given as polynomial dependencies for the average process temperature (T).
The MM determines the thermodynamic properties of the working fluid depending on the amount of injected liquid. According to the available properties of gases: N_2 (diazote), O_2 (dioxygen), Ar (argon), CO_2 (carbon dioxide), H_2O (water), [34], [35], the following are determined:
– the percentage composition of gases in the air and the thermodynamic properties of this air (C_P, i, S, R, k);
– the percentage composition of gases in the formed combustion products and the thermodynamic properties of these combustion products (C_P, i, S, R, k).
The algorithm for calculating the thermodynamic parameters of the engine and its MM has been supplemented to study the workflow for water injection into the TPE. The additions take into account:
– the required amount of injected water and its effect on the properties of the working fluid;
– adjustment of the characteristics of TPE components with regard to water;
– thermodynamic properties of the working fluid depending on the amount of injected water.
Experimental studies were carried out at the stand of the experimental research complex of the Joint-Stock Company (JSC) "Ivchenko-Progress" (Zaporizhzhia, Ukraine) (Fig. 1, a). The turbine engine manufactured by JSC "Ivchenko-Progress" (Zaporizhzhia, Ukraine) was chosen as the object of research (Fig 1, b) [36]. A set of experimental and research works on the design and preliminary testing of a water injection system for the application of a 30-minute power mode at high ambient temperatures up to plus 35 °C was carried out [37], [38]. According to the plan of experimental work:
– the terms of reference for the development of a water injection system for the engine;
– a bench water injection system was designed. According to the adopted scheme, water injection is carried out by boosting the water tank with compressed air using the engine compressor;
– a manifold with injectors was designed for water injection into the engine inlet. To avoid mechanical clogging of the nozzles, a filter is installed in front of the water collector;
– an electrical control circuit for water injection was developed;
– bench tests of the water injection system were performed.

DOI: 10.13009/EUCASS2025-409



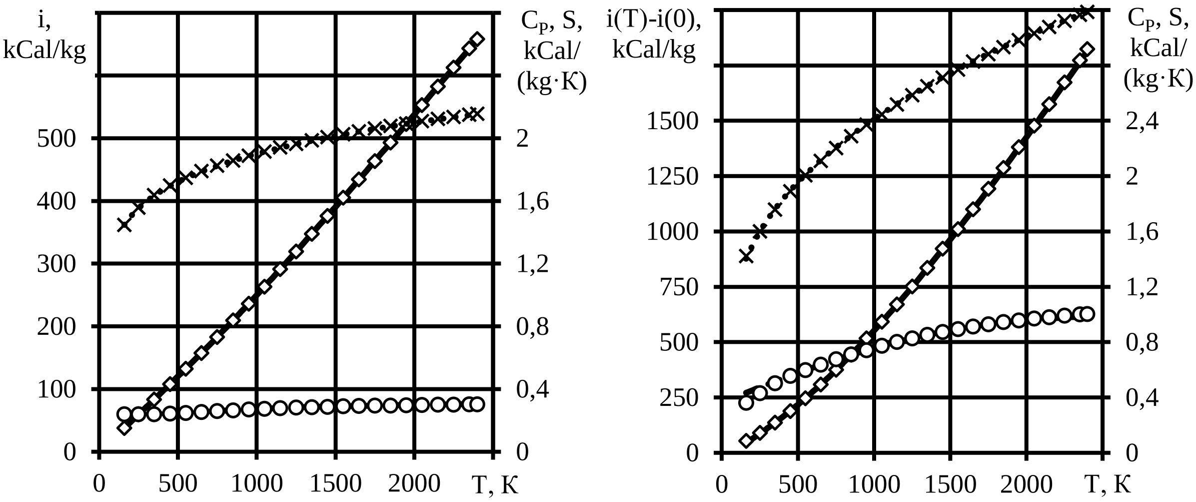
a *b*

Figure 1: Experimental research base:
a – test bench at JSC "Ivchenko-Progress"; b – engine manufactured by JSC "Ivchenko-Progress"

On the basis of the improved MM, a software module was developed to study the performance characteristics of the TPE with water injection.

5. Verification of the developed methodology for changing the thermophysical properties and phase transitions of the working fluid

In order to verify the developed methodology for calculating the thermodynamic properties of the working fluid and clean fuel combustion products, a comparative analysis of the results obtained with the data of calculations by other authors was carried out [39]. Fig. 2 shows a comparison of the heat capacity, enthalpy, and entropy for dry air and pure kerosene combustion products depending on temperature.
The results of the calculation coincide with the calculations of other authors with sufficient accuracy [39]. The calculation error does not exceed 3%, which can be explained by the assumptions made in the calculations. The developed methodology for determining the thermodynamic properties of the working fluid makes it possible to assess the impact of other fuels and mixtures on the engine's operating process.



a *b*

Mass enthalpy [39];
Calculated mass enthalpy;
Mass heat capacity [39];
Calculated mass heat capacity;
Mass entropy [39];
Calculated mass entropy.

Figure 2: Thermodynamic properties:
a – dry air depending on temperature; b – pure kerosene combustion products depending on temperature

DOI: 10.13009/EUCASS2025-409

6. Results of the TPE workflow study

Based on the results of the tests, the MM for calculating the parameters of an engine with water injection was verified. A comparative analysis of the results of mathematical modelling with experimental data was carried out (Table 1). The data in Table 1 are presented in relative terms. The data obtained from the experiments were taken as indicator (1). The results of the calculations have a satisfactory agreement with the experiment (Table 1), and the error under the assumptions made does not exceed 2%.

Table 1: Comparative analysis of the calculation results with experimental data (normal operating conditions – Alt=0; M=0; th=+15 °C)

Parameter	Range			
	Maximum take-off		Take-off	
	Test	MM	Test	MM
Output shaft power	1	1.0137	1	1.0076
Wf	1	1.0045	1	1.0032
Specific equivalent fuel consumption	1	0.9907	1	0.9949

Subsequently, using the verified MM, computational studies were carried out to assess the effect of water injection on engine parameters under hot operating conditions for take-off, as well as the change in the NO_X emission index depending on the engine operating mode. Table 2 shows the main results of modelling water injection at the inlet to the compressor and combustion chamber of the engine in take-off mode in relative terms. For comparison, the ratio of the considered parameters for the variant without water injection is taken as indicator (1). The calculated value of the moisture content (WAR) for studying the effect of water injection at the inlet to the compressor and the engine combustion chamber is assumed to be the same and has a value of WAR=0.04.

Table 2: Main modelling results (hot operating conditions – Alt=0; M=0; th=+30 °C)

Parameter	Without injection	Injection at the compressor inlet	Injection at the combustion chamber inlet
Output shaft power	1	1.1100	1.0213
Tt41	1	1.0015	0.9519
Wf	1	1.1391	1.0484
Specific equivalent fuel consumption	1	1.0257	1.0268

It follows from Table 2 that for engine modes where it is necessary to maintain a constant value of power at the propeller shaft, fuel consumption will be lower with the use of water injection, which will have a positive effect on the environmental characteristics of the engine and the aircraft as a whole. In addition, water injection at the inlet to the combustion chamber can significantly reduce the temperature of the working fluid at the inlet to the turbine, which will have a positive impact on the engine's service life.
Figure 3 shows the dependence of the change in the NO_X emission index ($EI(NO_X)$) on the fuel flow rate through the combustion chamber (Wf) without water injection (WAR=0) and with water injection (WAR=0.004).

DOI: 10.13009/EUCASS2025-409

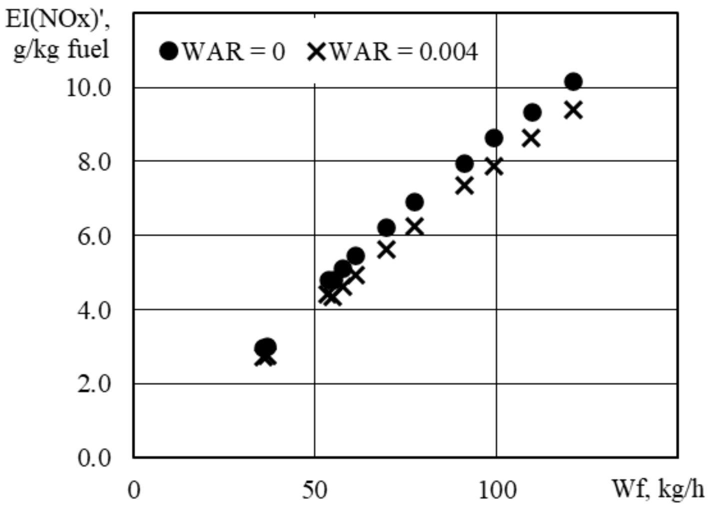


Figure 3: Dependence of the NO_X emission index change on the fuel flow in combustion chamber

The data in Figure 3 confirm that water injection alone can reduce NO_X emissions by up to 2%, depending on the operating mode.
To analyses the impact of using hydrogen as the main fuel, two different engine operation strategies were investigated:
– with the same temperature at the turbine inlet (Tt41);
– with the same power at the propeller shaft compared to the case of using aviation kerosene.
Hydrogen is supplied to the engine in the state of gas with a temperature of 80 °C. The results in Table 3 show that:
– in the operation mode with the same temperature at the turbine inlet (Tt41), the different properties of the gases produced during the combustion of hydrogen (compared to kerosene) lead to an increase in turbine power and, as a result, to an increase in power at the propeller shaft by 7.95%. The specific energy consumption remains virtually unchanged when replacing kerosene with hydrogen gas;
– in the same power mode at the propeller shaft, the turbine inlet temperature (Tt41) decreases by 1.44%, but the specific energy consumption increases by 2.84% when replacing kerosene with hydrogen gas.
From the results obtained (Table 3), it can be concluded that for operation with the same power at the propeller shaft, the decrease in the temperature at the turbine inlet (Tt41) is compensated by an increase in the specific energy consumption. Since for an aircraft with no changes in its design and payload weight, an increase in power is not required for takeoff, the case of the engine operating at the same turbine inlet temperature (Tt41) is not considered further.

Table 3: Main results of modelling the use of hydrogen as the main fuel (hot operating conditions – Alt=0; M=0; th=+30 °C)

Parameter	Aviation kerosene use	Steady-state temperature at the turbine inlet	Steady-state power at the propeller shaft
Output shaft power	1.0000	1.0795	1.0000
Tt41	1.0000	1.0000	0.9856
LHV, kKal/kg	10250	28670	28670
Energy fuel input (LHV), kKal	1.0000	1.0880	1.0284
Power spesific energy consumption (LHV), kKal/h.p.	1.0000	1.0079	1.0284

A study of the effect of simultaneous injection of water into the combustion chamber and the use of hydrogen as the main fuel on the efficiency of a TPE is presented in Table 4.

DOI: 10.13009/EUCASS2025-409

Table 4: The main results of modelling the simultaneous injection of water into the combustion chamber and the use of hydrogen as the main fuel on the efficiency of a turboprop engine (operating conditions – Alt=0; M=0; th=+30°C)

Parameter	Aviation kerosene use	Use of hydrogen and water injection at the combustion chamber inlet
Output shaft power	1.0000	1.0000
Tt41	1.0000	0.9300
LHV, kKal/kg	10250	28670
Energy fuel input (LHV), kKal	1.0000	1.0520
Power spesific energy consumption (LHV), kKal/h.p.	1.0000	1.0520

The results obtained (Table 4) show that the temperature at the turbine inlet (Tt41) decreases by 7%, but the specific energy consumption increases by 5.2% when replacing jet fuel with hydrogen gas. Operation of the engine at lower temperatures of the working fluid will increase its service life.

Conclusion

The analysis of the results of the study on the effect of water injection and the use of hydrogen as the main fuel on the efficiency of a turboprop engine allows us to draw the following conclusions:
1. In order to reduce the level of harmful substances in the engine operation mode with constant power, it is advisable to use water injection at the inlet to the combustion chamber, as this reduces the temperature of the working fluid.
2. The simultaneous injection of water into the combustion chamber and the use of hydrogen as the main fuel can reduce the temperature at the turbine inlet by about 7%: water injection by about 5% and hydrogen use by about 2%. Reducing the temperature at the turbine inlet will increase the engine's service life.
3. Although the simultaneous use of water injection into the combustion chamber and the use of hydrogen leads to an increase in specific energy consumption, the use of hydrogen as the main fuel will significantly reduce NO_X emissions and eliminate CO_X emissions altogether.
4. To reduce the specific energy consumption, additional studies of the effect of the injected hydrogen temperature are needed.
5. To study the effect of water injection and the use of hydrogen as the main fuel, it is necessary to analyse the characteristics of the TPE as part of the aircraft. The system should be designed as a single object with a given purpose and using typical flight cycles. This is a separate area for further research.
6. A separate area for further research is to improve the mathematical model of the water evaporation chamber to analyze the effectiveness of design solutions when used as part of a TPE.

References

[1] Strategic Research and Innovation Agenda. - URL: https://clean-aviation.eu/sites/default/files/2024-09/2024-Clean-Aviation-SRIA.pdf. – Accepted 09.2024.
[2] ACARE Vision. – URL: https://www.acare4europe.org/acare-vision/. – Accepted 03.2023.
[3] Roland Berger. 2020. Hydrogen - A future fuel for aviation? – 48 p.
[4] Tashie-Lewis, B. C., Nnabuife, S. G.. 2021. Hydrogen Production, Distribution, Storage and Power Conversion in a Hydrogen Economy - A Technology Review. *Chemical Engineering Journal Advances*. - Volume 8, 100172. - https://doi.org/10.1016/j.ceja.2021.100172.
[5] Dan Tang, Guang-Lei Tan, Guo-Wei Li, Jin-Guang Liang, Shah Masood Ahmad and other. 2023. State-of-the-art hydrogen generation techniques and storage methods: A critical review. // *Journal of Energy Storage*, Volume 64, 107196. - https://doi.org/10.1016/j.est.2023.107196.
[6] Lebreton, Th., Way, G., Ebenhoch, G. A. Technology Roadmap for Future Aircraft Propulsion Systems. The 8th European Tandem Aeronautics Days. Bucharest. 27–30 May 2019; Advancing Hybrid-Electric Propulsion Systems for Sustainable Flight. - https://www.techbriefs.com/component/content/article/tb/pub/features/applications/45207. - Accessed 02.2022.
[7] FlightGlobal. Embraer Shifts ‘Energia’ Focus to New Hybrid- and Hydrogen-Powered Concepts. Available online: https://www. flightglobal.com/airframers/embraer-shifts-energia-focus-to-new-hybrid-and-hydrogen-powered-concepts/151225.article (accessed on 30 November 2022).

DOI: 10.13009/EUCASS2025-409

[8] Airbus. Airbus Reveals Hydrogen-Powered Zero-Emission Engine. Available online: https://www.airbus.com/en/newsroom/ press-releases/2022-11-airbus-reveals-hydrogen-powered-zero-emission-engine (accessed on 30 November 2022).

[9] Shi, M., Ozcan, M., Cinar, G., Gladin, J. and Mavris, D. N.. 2022. Finalized Design and Performance Analysis of a Hybrid Turbo-Electric Regional Jet for the NASA ULI Program. 2022 IEEE Transportation Electrification Conference & Expo (ITEC), Anaheim, CA, USA, 2022, pp. 444-449, doi: 10.1109/ITEC53557.2022.9814048.

[10] Michele Sparano, Marco Sorrentino, Giovanni Troiano, Giovanni Cerino, Giuseppe Piscopo, Marco Basaglia, Cesare Pianese. 2023. The future technological potential of hydrogen fuel cell systems for aviation and preliminary co-design of a hybrid regional aircraft powertrain through a mathematical tool. - Energy Conversion and Management. - Volume 281, 2023, - https://doi.org/10.1016/j.enconman.2023.116822.

[11] Concept Analysis of an Electrical Fuel Cell Integration in Modern Aircraft. -URL: https://www.hsu-hh.de/ees/en/research-cluster-aeronautics/concept-analysis-of-an-electrical-fuel-cell-integration-in-modern-aircraft. – Accessed 20.03.2023.

[12] Rowe, M., Ladd, G. 1946. Water injection for aircraft engines. SAE *Technical Paper 460192*. doi: https://doi.org/10.4271/460192.

[13] Daggett, D., Ortanderl, S., Eames, D., Snyder, C. et al. 2004. Water Injection: Disruptive Technology1 to Reduce Airplane Emissions and Maintenance Costs. *SAE Technical Paper #2004-01-3108*. doi: https://doi.org/10.4271/2004-01-3108.

[14] Daggett, D. L., Fucke, L., Hendricks, R. C., Eames, D. 2010. Water injection on commercial aircraft to reduce airport nitrogen oxides. *NASA/TM-2010-213179*. doi: http://dx.doi.org/10.2514/6.2004-4198.

[15] Daggett, D.L. Water Injection Feasibility for Boeing 747 Aircraft; NASA Contractor Report 2005-213656. 2005. Available at: https://ntrs.nasa.gov/citations/20060004124.

[16] Daggett, D. L. 2004. Water misting & injection of commercial aircraft engines to reduce airport NO_X. *NASA/CR-2004-212957*. doi: https://10.2514/6.2004-4198.

[17] Liu C., Li, X., Zhang, H., Zheng, Q. 2017. Heat and mass transfer characteristics of water droplets in wet compression process. In: *ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition*, Charlotte, 1–14. doi: https://doi.org/10.1115/GT2017-63516.

[18] Mourouzidis, C., Igie, U., Pilidis, P., Singh, R. 2015. Water injection on aircraft engines: a performance, emissions and economic study. Water injection on aircraft engines: a performance, emissions and economic study. In: *ISABE 22nd International Symposium on Air Breathing Engines 2015 Phoenix*, AZ, USA, 25-30. doi: http://dspace.lib.cranfield.ac.uk/handle/1826/15176.

[19] Roumeliotis, K. 2010. Evaluation of water injection effect on compressor and engine performance & operability. Applied Energy Journal, 4 (87), 1207-1216. doi: http://dx.doi.org/10.1016/j.apenergy.2009.04.039.

[20] Wang, T., Khan, J. R. 2010. 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*, 2(3), 031001 (10 hages). doi: https://doi.org/10.1115/1.4002754.

[21] Wang, T., Khan, J. R. 2010. Overspray and interstage fog cooling in gas turbine compressor using stage-stacking scheme. Part II: *Case study Journal of Thermal Science and Engineering Applications*, 2(3), 031002 (10 hages). doi: https://doi.org/10.1115/1.4002755.

[22] Tudosie, A. N. 2014. Mathematical model for a jet engine with cooling fluid injection into its compressor. Proceedings of International Conference of Scientific Papers (AFASES 2014), volume I, 265-272. doi: https://10.1109/CARPATHIANCC.2018.8399608.

[23] Tudosie, A. N. 2014. Mathematical model for a jet engine with cooling fluid injection into its combustor. Proceedings of International Conference of Scientific Papers (AFASES 2014), volume I, 273-280.

[24] Sun, L., Sun, T., Wang, Y., Yang, W. 2016. Numerical simulation of pollutant emission of a turbojet engine with water injection. ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition GT2016, Seoul, 1–9. doi: https://doi.org/10.1115/GT2016-57074.

[25] Tudosie, A. N. 2016. Aircraft gas-turbine engine with coolant injection for effective thrust augmentation as controlled object. 2016 International Conference on Applied and Theoretical Electricity (ICATE). doi: https://10.1109/ICATE.2016.7754686.

[26] Hale, A., Klepper, J., Hurwitz, W. 2005. A numerical capability to analyze the effects of water ingestion on compression system performance and operability. *ASME Turbo Expo 2005*, June 2005, GT2005-68480, 113-125. doi: https://doi.org/10.1115/GT2005-68480.

[27] Favorskii, O. N., Alekseev, V. B., Zalkind, V. I., Zeigarnik, Y. A., Ivanov, P. P., Marinichev, D. V, Nizovskii, V. L., Nizovskii, L. V. 2014. Experimentally Studying TV3 117 Gas Turbine Unit Characteristics at Superheated Water Injection into a Compressor. Thermal Engineering, 61(5), 376-384. doi: https://10.1134/S0040601514050024.

[28] Egorov, I. N., Kretinin, G. V., Leschenko, I. A. 1988. Osobennosti matematicheskogo modelirovaniya aviatsionnykh GTD. Moscow: VVIA im. prof. N. E. Zhukovskogo, 177.

DOI: 10.13009/EUCASS2025-409

[29] Nechaev, Yu. N., Fedorov, R. M. 1977. Teoriya aviatsionnykh gazoturbinnykh dvigateley. Ch. 1. Moscow: Mashinostroenie, 312.
[30] Shlyakhtenko, S. M. 1975. Teoriya vozdushno-reaktivnykh dvigateley. Moscow: Mashinostroenie, 567.
[31] Barten’ev, O. V. 2000. Sovremenniy Fortran. Moscow: Dialog Mifi, 450. Available at: https://docplayer.com/408341-O-v-bartenev-sovremennyy-fortran-izdanie-trete-dopolnennoe-i-pererabotannoe.html.
[32] Kozyrev, A. M., Butov, L. A. 1993. Matematicheskoe modelirovanie rabochego protsessa aviatsionnykh dvigateley. Moscow: VVIA im. prof. N. E. Zhukovskogo, 144.
[33] Dubovkin, N. F. 1962. Spravochnik po uglevodorodnym toplivam i ikh produktam sgoraniya. Moscow: Gosudarstvennoe energeticheskoe izdatel’stvo, 288.
[34] Glushko, V. P. 1971. Termodinamicheskie i teplofizicheskie svoystva produktov sgoraniya. Vol. 1. Metody rascheta. Moscow: izdatel’stvo AN SSSR, 497.
[35] Glushko, V. P. 1978. Termodinamicheskie svoystva individual’nykh veschestv. Vol. 4. Moscow: «Nauka», 559.
[36] Kirichkov, M. A., Yelansky, A. V., Kravchenko, I. F. 2013. Developing a small-size family of gas turbine engine based on single core. Aviatsionno-kosmicheskaya tekhnika i tekhnologiya, 10, 37–41. Available at: http://nti.khai.edu:57772/csp/nauchportal/Arhiv/ AKTT/2013/AKTT1013/Kirichk.pdf
[37] Proverka rabotosposobnosti dvigatelya AI-450M (AI-450M1) pri imitatsii popadaniya v nego dozhdya. Tekhnicheskiy otchet, T/o No. 114/2012-450M, GP «Ivchenko-Progress» (2012). Zaporozh’e.
[38] Otsenka sistemy vpryska vody dvigatelya AI-450M. Tekhnicheskiy otchet, T/o No. 570/2018-450M, GP «Ivchenko- Progress» (2018). Zaporozh’e.
[39] Rivkin, S. L. 1984. Termodinamicheskie svoystva vozdukha i produktov sgoraniya. Moscow: Energoatomizdat, 104.