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IMPROVING THE EFFICIENCY OF AN AIRCRAFT POWER PLANT WITH A TURBOPROP ENGINE BASED ON WATER-METHANOL MIXTURE INJECTION

Yurii Ulitenko
Corresponding author
PhD*
E-mail: y.ulitenko@gmail.com
Vasyl Loginov
Doctor of Technical Sciences, Professor
Department of Aircraft Engine Design
National Aerospace University «Kharkiv Aviation Institute»
Chkalova str., 17, Kharkiv, Ukraine, 61070
Igor Kravchenko
Doctor of Technical Sciences, Associate Professor
Director of the Enterprise**
Viktor Popov
Doctor of Technical Sciences, Chairman of the Board
Private Joint-Stock Company «FED»
Sumska str., 132, Kharkiv, Ukraine, 61023
Oleksandr Rasstrygin
Doctor of Technical Sciences, Professor
Research Department No. 5
Central Scientific Research Institute of Armament
and Military Equipment of the Armed Forces of Ukraine
Povitroflotskyi ave., 28, Kyiv, Ukraine, 03049
Olexandr Yelans'ky
PhD*
*Department of Advanced
Development and Gas Dynamic Calculations**
**State Enterprise «Ivchenko-Progress»
Ivanova str., 2, Zaporizhzhia, Ukraine, 69068

This paper considers a technique for modernizing the power plant (PP) of a regional aircraft. The modernization is based on the injection of water or a water-methanol mixture into the compressor or combustion chamber of a turboprop engine (TPE). An algorithm has been developed for the thermodynamic calculation of TPE parameters, taking into consideration the injected mixture; the mathematical model (MM) has been improved. Methodical studies of the operability and range of application of the improved MM were carried out. The results of mathematical modeling were validated. For verification, the AI-450M turboshaft engine produced by GP Ivchenko-Progress (Ukraine) was used as an object of research. Based on the improved MM, a software module has been developed to study the performance characteristics of a regional aircraft with a TPE. The influence of water injection and a water-methanol mixture on the TPE operating process and the operational characteristics of a regional passenger aircraft has been studied.

The proposed measures could be implemented in existing TPEs. This would allow the operation of aircraft without significant modernization of the airport infrastructure. For TPE, the injection of water and a water-methanol mixture is an alternative way of boosting in order to temporarily improve performance. A given modernization technique could improve the TPE power up to ~10 %, as well as reduce the amount of harmful emissions.

The results obtained showed a satisfactory convergence of estimated and experimental data. The error of the results under the accepted assumptions does not exceed 3 %. The calculation results demonstrate the advantages of injection at the take-off stage of the aircraft to reduce the take-off distance (up to 45 % in hot conditions TAMB = +30 °C) and reduce the time of climbing the echelon (~10 %)

Keywords: turboprop engine, boosting, performance characteristics, water, mathematical model, harmful emissions

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1. Introduction

In the context of globalization of the aviation market, modern aviation companies compete in terms of price and technical characteristics, quality of services, and environmental requirements. The strict policies of aviation companies and the desire for higher profits force manufacturers of aircraft and aircraft engines to improve their fuel efficiency and environmental performance. Dependence on aircraft imports, volatile fuel prices, and the impact of aviation emissions on the environment further stimulate the development of new technologies.

The capabilities of the aircraft are determined by the characteristics of the PP engine. Due to their high fuel efficiency, TPEs are widely used on most types of aircraft. With each new generation of TPE, their specific capacity increases. At the same time, the use of advanced technologies leads to a significant increase in the cost of new engines. Therefore, the deep modernization of the existing fleet of aircraft equipped with TPEs and the reduction of operating costs based on the use of hybrid PPs have become topical issues.

There is also a need for a gradual transfer of transportation means to alternative energy carriers. Particular attention should be paid to alcohols (in particular methanol). Combining water or water-methanol mixture injection technology with future emission reduction technologies, such as auxiliary PPs using fuel cells, would allow the aviation sector to solve some of the environmental challenges.

At the same time, one of the scientific and technical issues is the study of the heat exchange process in a multiphase gas flow based on the injection of different mixtures. Devising and improving methods for investigating the workflow of promising TPEs is a relevant task for engine designers.

2. Literature review and problem statement

For TPEs, water injection (H_2O) is a suitable alternative for replacing the most common method for turbojet engines (TJEs) to temporarily improve performance – the afterburner combustion chamber. A temporary improvement in performance is especially necessary when operating an aircraft under hot conditions and on high-altitude airfields with a shortened runway. Using water injection without increasing power leads to a reduction in NO_X emissions [1]. Work [1] reports the results of studying the effect of injection of pure water without impurities of other substances only on reducing NO_X emissions.

The cooling action from water injection leads to a decrease in the temperature of working fluid throughout the gas-air path of the engine behind the injection site. This could prolong the resource and reduce the cost of operating the engine and aircraft. Paper [2] reports the results of CFD calculations for modeling the injection in the stage of the axial compressor.

There are two common ways to inject water (or other coolants) into the flowing part of an aircraft engine:

– injection at the inlet to the compressor. Works [3, 4] ree port the results of studying the effect of water mist injection in the intermediate stages of the compressor. The cited works do not reflect the effect of injection on the engine parameters as a whole. Work [5] describes the results of mathematical modeling of the effect of coolant injection into the compressor only for turbofan engine;

– direct injection into the combustion chamber (CC) [6]. Study [6] reports the results of mathematical modeling of the effect of coolant injection on the engine parameters only at the outlet from CC.

Water injection at the compressor inlet demonstrates a positive effect on engine performance [7]. At the same time, it ensures a decrease in the temperature of the gas at the inlet to the turbine. Also, the injection of water at the compressor inlet makes it possible to achieve a reduction in NO_X emissions of up to 50 % [8]. Work [7] displays the effect of water injection on the performance characteristics of different types of engines. However, the cited work does not indicate the effect of water injection on the reduction of harmful emissions. Paper [8] reports the results of studying the effect of pure water injection into the compressor on the gas temperature in the turbine and NO_X emissions only for TJE.

It is expected that the costs of complicating the design and operation of the aircraft with water injection could be compensated by saving on engine maintenance and prolonging its service life. These savings would generate sufficient market demand for the development and implementation of water injection systems as an additional technology to improve engine performance and reduce aircraft emissions [9].

Water injection to increase thrust was practically implemented in Boeing 707-120 Stratoliner aircraft with Pratt & Whitney JT3C-6 engines, and in Boeing 747-100 and 200 aircraft with Pratt & Whitney JT9D-3AW and -7AW engines [1].

Attention should be paid to water-methanol mixtures as an alternative to water. Methanol (CH_3OH) is a promising fuel but the transition to methanol as the main fuel is not considered. The low calorific value of methanol leads to an increase in fuel consumption and an increase in the volume of fuel tanks or a decrease in flight range. In addition, the use of 100 % methanol is limited by its high toxicity and aggressiveness to structural materials [10]. Methanol can be used as an additive in small quantities to increase engine power while reducing the temperature of the working fluid. Also, when using a water-methanol mixture, emissions of combustion products are reduced. Work [11] reports the results of studying the effect of injection of a water-methanol mixture on the temperature of gases and the amount of harmful substances in the combustion products of the internal combustion engine. The issue of injection of a water-methanol mixture into aircraft jet engines and, in particular, TPE, is little studied.

In turn, the injection of water or a water-methanol mixture requires the improvement of MM of the working process of TPE based on changes in the thermophysical properties and phase transitions of the working medium. There is a need to conduct experimental work to verify the results obtained. Work [12] reports the results of experimental studies into the effect of pure water injection only on the performance characteristics of the TV3-117 engine.

Thus, the technology of injection of water and a water-methanol mixture in TPE has prospects for development; further research is needed to improve the performance of aircraft equipped with TPE. It is necessary to identify ways to solve tasks to ensure the operability of TPE when using the injection system. Overcoming these challenges would improve performance and reduce engine NO_X emissions.

3. The aim and objectives of the study

The purpose of this research is to improve the methodology for modeling the working process of TPE based on the injection of water and a water-methanol mixture to increase the efficiency of PP equipped with TPE for a regional passenger aircraft for 100 passengers. The improved methodology could make it possible to carry out further research to improve the efficiency of PP equipped with TPE based on the injection of water and a water-methanol mixture for a regional passenger aircraft for 100 passengers.

To achieve the goal of research, it is necessary to solve the following tasks:

– to verify the devised procedure for changing the thermophysical properties and phase transitions of working medium when injecting water or a water-methanol mixture into a turboprop engine;

– to verify the results of mathematical modeling of the engine workflow with experimental data;

– to investigate the influence of the injection site and the type of injected mixture on the performance characteristics of TPE;

– to study the operational characteristics of TPE with the injection of water and a water-methanol mixture for a regional passenger aircraft for 100 passengers.

4. The study materials and methods

Our MM of TPE has been built on the basis of a general approach to solving the system of basic equations [13]. 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 [14, 15]:

– 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.

Our MM is a method for solving a system of nonlinear equations implemented in the Fortran programming language [16], 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 [17]:

– 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 procedure of thermodynamic calculation is compiled taking into consideration the dependence on temperature of the thermodynamic properties of air and combustion products with relative fuel consumption (FAR). The dissociation of molecules is disregarded.

Changes in the thermophysical properties of the working medium are taken into consideration depending on its composition and temperature. For the specified fuel [18], the composition of the gas depends only on the coefficient of excess air. Instead, our MM uses relative fuel consumption (FAR) [15]. The values of enthalpy (i), gas entropy (S), gas constant (R), and adiabatic indicator (k) are given as polynomial dependences for the average process temperature (T).

MM determines the thermodynamic properties of the working medium depending on the amount of liquid injected. Based on the actual properties of gases: N_2 (dinitrogen), O_2 (dioxygen), Ar (argon), CO_2 (carbon dioxide), H_2O (water), CH_3OH (methanol) [19, 20], the following is 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 resulting combustion products and the thermodynamic properties of these combustion products (C_P, i, S, R, k).

To study the workflow regarding the injection of water and water-methanol mixtures in TPE, the algorithm for calculating the thermodynamic parameters of the engine and its MM has been supplemented. Our additions take into consideration:

– the required amount of injected liquid and its effect on the properties of the working medium;

– adjustment of the characteristics of TPE units taking into consideration the injected liquid;

– the thermodynamic properties of the working medium depending on the amount of liquid injected.

Our experimental studies were carried out at the bench of the experimental research complex at the State Enterprise (SE) «Ivchenko-Progress» (Zaporizhzhia, Ukraine) (Fig. 1, *a*). The chosen object of research is the AI-450M turboshaft engine produced by SE Ivchenko-Progress (Zaporizhzhia, Ukraine) (Fig. 1, *b*) [21]. A set of experimental and research works on the design and preliminary testing of the water injection system for the application of a 30-minute power mode at high atmospheric temperatures up to plus 35 °C was carried out [22, 23]. According to the plan of experimental work:

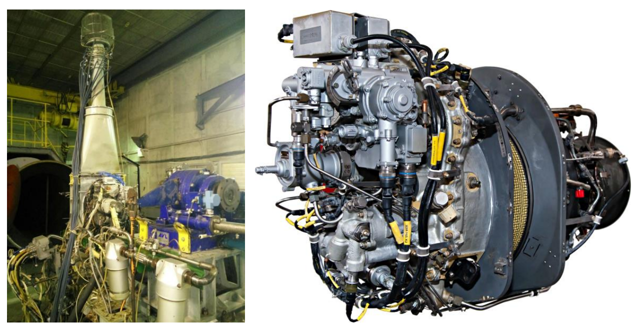
– a technical order was released for the development of a water injection system into the AI-450M engine [24];

– 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 circuit for controlling water injection was developed;

– bench tests of the water injection system were performed.



a *b*

Fig. 1. Experimental research base:
a — test bench at SE «Ivchenko-Progress»;
b — AI-450M engine

Based on the improved MM, a software module has been developed for the study of the operational characteristics of TPE, taking into consideration water and water-methanol mixtures.

5. Results of studying the working process of a turboprop engine

5. 1. Verification of the devised procedure for changing the thermophysical properties and phase transitions of working medium

In order to verify the devised methodology for calculating the thermodynamic properties of working fluid and clean products of fuel combustion, a comparative analysis of the results obtained with the calculation data of other authors was carried out [25]. Fig. 2, 3 illustrate the comparison of heat capacity, enthalpy, and entropy for dry air and pure combustion products of kerosene as a function of temperature.

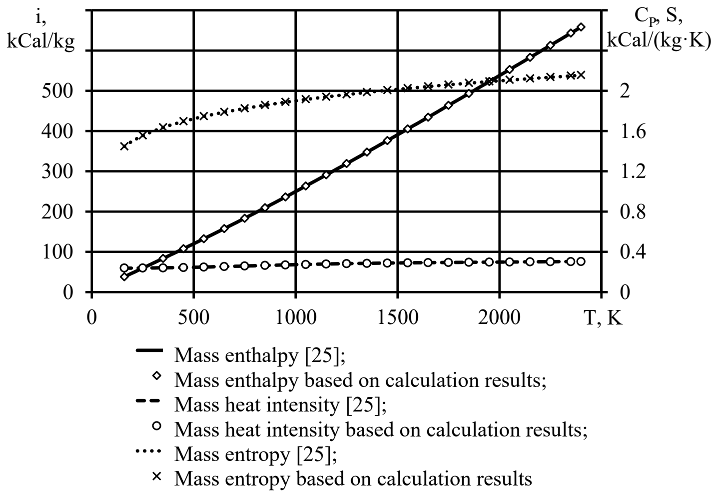


Fig. 2. Thermodynamic properties of dry air depending on temperature

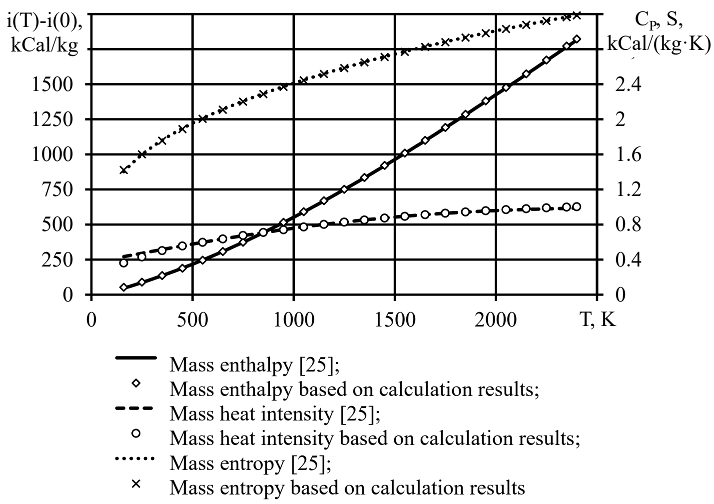


Fig. 3. Thermodynamic properties of pure kerosene combustion products depending on temperature

The calculation results coincide with sufficient accuracy with the calculations of other authors [25]. The error of calculations does not exceed 4 %, which can be explained by the assumptions made in the calculations. The devised procedure for determining the thermodynamic properties of the working medium, if necessary, could make it possible to assess the effect of other fuels and mixtures on the engine workflow.

5. 2. Verification of the results of mathematical modeling of the engine workflow with experimental data

The reliability of the results of mathematical modeling was confirmed in two stages:

– verification of results without injection of additional liquids;

– verification of results for water injection.

A comparative analysis of the obtained results of MM calculation with the data reported in [26], which were confirmed experimentally, was carried out (Table 1). The calculation results demonstrate a satisfactory convergence with the data from technical order [26] (Table 1); an error under the accepted assumptions does not exceed 2 %.

Fig. 4, 5 graphically illustrate a comparison of the test results with the results of calculations using the devised MM (dot with «'» is the estimated point based on MM, which corresponds to the conditions of the experimental point).

Table 1

Comparative analysis of calculation results with technical order data (normal operating conditions – ALT=0; *M*=0; TAMB=+15 °C)

Parameter	Mode			
	Maximal take-off		Take-off	
	Technical order [26]	MM	Technical order [26]	MM
Compressor				
$\overline{WA}$	1	0.9984	1	0.9983
$\overline{PR}$	1	1.0057	1	1.0043
$\overline{ETA}$	1	1.0013	1	1.0012
$\overline{TC}$	1	1.0049	1	1.0048
$\overline{NR}$	const		const	
Combustion chamber				
$\overline{TCH}$	1	1.0088	1	1.0080
Gas generator turbine				
$\overline{TH}$	1	1.0087	1	1.0079
$\overline{PR}$	1	0.9997	1	1.0001
$\overline{ETA}$	1	1.0002	1	1.0001
Free turbine				
$\overline{T}$	1	1.0093	1	1.0084
$\overline{PR}$	1	1.0088	1	1.0085
$\overline{ETA}$	1	0.9949	1	0.9949
Engine parameter				
$\overline{PWSD}$	1	1.0137	1	1.0076
$\overline{WF}$	1	1.0045	1	1.0032
$\overline{ESFC}$	1	0.9907	1	0.9949

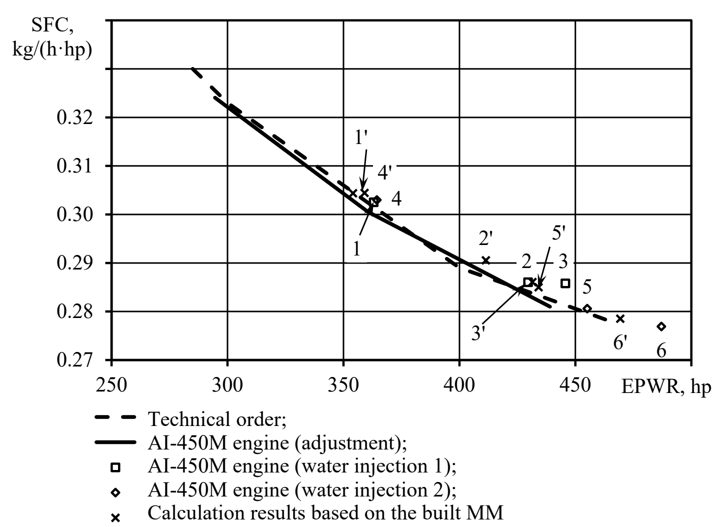


Fig. 4. Change in the specific equivalent fuel consumption (ESFC) depending on engine operating mode and water injection

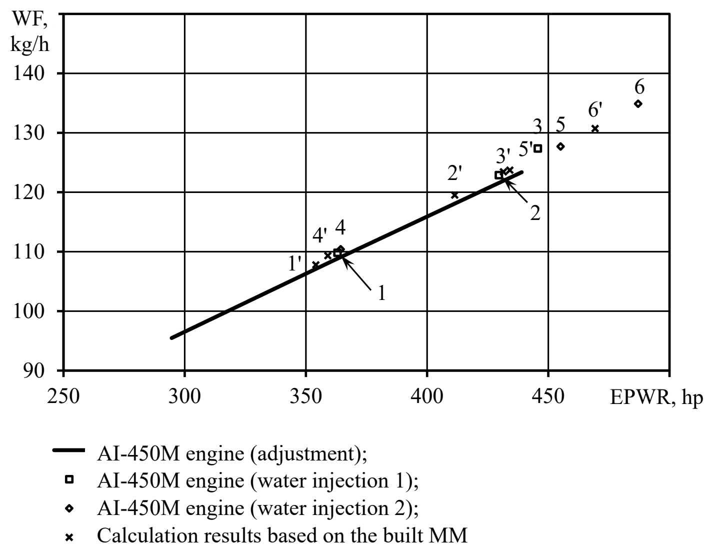


Fig. 5. Change in fuel consumption (WF) depending on engine operating mode and water injection

No deviations and obvious changes in the nature of the dependences in Fig. 4, 5 are observed.

5. 3. Investigating the influence of the injection site and the type of injected mixture on the performance of a turboprop engine

When using the MM constructed, the effect of injection on the engine parameters under hot operating conditions for take-off mode was evaluated. According to the recommendations from the World Meteorological Organization [27], the maximum adopted moisture content value was WAR=0.04 for the conditions ALT=0 m. The maximum concentration of methanol in water in calculations does not exceed 15 % due to its toxicity.

Our calculations for the study of the influence of the injection site were performed using water for two possible options:

– water injection at the compressor inlet;

– water injection at the inlet to the combustion chamber.

The basic results of modeling water injection at the inlet to the compressor and combustion chamber of the AI-450M engine under a take-off mode are given in Table 2.

Table 3 gives the results of modeling the injection of water, a water-methanol mixture, and methanol at the inlet to the compressor of the AI-450M engine under a take-off mode.

Table 2

Basic simulation results (hot operating conditions) – ALT=0; M=0; TAMB=+30 °C

Parameter	No injection	Injection at compressor inlet	Injection at combustion chamber inlet
Inlet parameter			
Compressor			
WAR	0	0.0400	0
$\overline{WA}$	1	1.0363	0.9969
$\overline{PR}$	1	1.0334	1.0065
$\overline{ETA}$	1	0.9928	1.0017
$\overline{TC}$	1	0.9783	1.0012
$\overline{NR}$	const		
Combustion chamber			
WAR	0	0.0400	0.0400
$\overline{WA}$	1	1.0362	1.0368
$\overline{TCH}$	1	0.9916	0.9430
Gas generator turbine			
$\overline{TH}$	1	0.9908	0.9428
$\overline{PR}$	1	0.9957	0.9934
$\overline{ETA}$	1	1	0.9990
Free turbine			
$\overline{T}$	1	1.0015	0.9519
$\overline{PR}$	1	1.0328	1.0116
$\overline{ETA}$	1	1.0003	1.0022
Engine parameter			
$\overline{PWSD}$	1	1.1100	1.0213
$\overline{WF}$	1	1.1391	1.0484
$\overline{ESFC}$	1	1.0257	1.0268

Table 3

Basic results of modeling the injection of water and methanol at the inlet to the compressor of the AI-450M engine under a take-off mode (ALT=0; M=0; TAMB=+30 °C)

Parameter	No injection	H_2O injection	H_2O injection with 15 % CH_3OH	CH_3OH injection
Compressor				
WAR	0	0.0400	0.0400	0
$WARL$	0	0	0.0060	0.0400
$\overline{WA}$	1	1.0363	1.0490	1.0247
$\overline{PR}$	1	1.0334	1.0522	1.0050
$\overline{ETA}$	1	0.9928	0.9859	0.9953
$\overline{TC}$	1	0.9783	0.9824	0.9724
$\overline{NR}$	const			
Combustion chamber				
$\overline{TCH}$	1	0.9916	1.0064	0.9995
Gas generator turbine				
$\overline{TH}$	1	0.9908	1.0050	0.9928
$\overline{PR}$	1	0.9957	0.9943	1.0020
	1	1	1	0.9998
Free turbine				
$\overline{T}$	1	1.0015	1.0203	0.9888
$\overline{PR}$	1	1.0328	1.0500	1.0026
$\overline{ETA}$	1	1.0003	0.9992	1.0005
Engine parameter				
$\overline{PWSD}$	1	1.1100	1.1687	1.0046
$\overline{W_{GAS}}$	1	1.1391	1.0553	0.3882
$\overline{W_{CH_3OH}}$	–	–	0.2767	1.8125
$\overline{WF}$	1	1.1391	1.3321	2.2006
$\overline{ESFC_{GAS}}$	1	1.0262	0.9030	0.3864
$\overline{ESFC}$	1	1.0262	1.1398	2.1905

When performing calculations for verification, the use of our improved MM faced certain difficulties. In a multiphase, heat transfer-aware workflow, finding the values of the explanatory variables that render the residues to near-zero values with the predefined accuracy takes longer.

5. 4. Investigating the performance characteristics of a turboprop engine with injection for a regional passenger aircraft

Based on the analysis of the requirements for modifications of regional aircraft of the passenger category and the preliminary studies conducted on take-off and landing characteristics, weight calculations, preliminary construction of the structural and layout scheme of a regional aircraft for 100 passenger seats was carried out.

In order to study a change in the range of the engine's working process, when equipped with water injection, the following flight stages were selected: take-off, take-off ALT to the circle, acceleration VTAS to climb, climbing the echelon ALT.

To study the performance characteristics of the aircraft, the basic initial data were set such as the engine equivalent power under a take-off mode (TO) (ALT=0 m) EPW=6100 kW, engine output shaft speed NP=1000 rpm. At cruising altitude ALT=9000 m at maximum continuous mode (CM), the engine equivalent power value is EPW=2600 kW, engine output shaft speed NP=850 rpm.

To determine the mass of the equipment related to the water mixture injection system, a modified Khukhorev formula was used to calculate the mass of the fuel system [28].

The time of climb is set from the condition of the rational angle of speed gain, taking into consideration the change in engine equivalent power by flight altitudes. Flight stages, flight altitude, and engine characteristics for the mode of operation under the conditions of the international standard atmosphere (ISA) are given in Table 4.

Table 4

Basic parameters to form the flight profile of the aircraft

Flight stage	ALT, m	M	Mode of operation	EPW, kW	ESFC, kg/(kW·h)	t, min
TO run	0	0.024	TO	6100	0.2558	0.44
	0	0.229	TO	6546	0.2471	
TO to ALT circle	0	0.229	TO	6546	0.2471	0.6
	250	0.298	TO	6658	0.2441	
Acceleration to VTAS climb	250	0.298	TO	6658	0.2441	0.3
	450	0.386	TO	7014	0.2404	
Climbing the echelon ALT	450	0.386	CM	5350	0.2594	6.5
	4000	0.482	CM	3779	0.2492	
	4000	0.482	CM	3779	0.2492	9
	8000	0.635	CM	2631	0.2351	
	8000	0.635	CM	2631	0.2351	2.6
	9000	0.640	CM	2262	0,2336	

Studies have been conducted on changing the characteristics of TPE equipped with water injection. The calculation of the characteristics of TPE and the need for the required mass of the mixture was carried out in two stages:

– without injection of additional liquids;

– when injecting only water with its different content in the airflow (the mass of water in relation to 1 kg of dry air is 0.2 %, 0.4 %, 0.6 %, 0.9 %, 1.3 %).

To substantiate the feasibility of using injection in TPE, a calculation was performed for several conditions of take-off of the aircraft: ISA, ISA+20 °C, and ISA+30 °C.

The results of calculating the characteristics of TPE with an increase in power due to water injection at the specified points of flight of the aircraft under ISA, ISA+20 °C, and ISA+30 °C are given in Tables 5, 6.

As one knows, an increase in the quantitative composition of water cools the air more and this forces us to pay special attention to the choice of engine control laws. The amount of water for the injection system should be optimized when considering in detail the flight cycle of the aircraft.

To calculate the characteristics of the flight cycle of the aircraft, the maximum masses of water necessary to ensure guiding the aircraft to the echelon altitude with maximum speed and minimum time were selected.

The basic results of calculating the characteristics of the flight cycle of the aircraft are given in Table 7.

We studied the take-off characteristics of the aircraft for the following variants:

– ISA, no injection;

– ISA, injection 0.6 % H_2O while maintaining NR=const;

– ISA, ISA +20 °C no water injection;

– ISA, ISA +20 °C, 0.9 % H_2O while maintaining TH=const.

The results of calculating the characteristics of the flight cycle are given in Table 8. The calculation results show the advantages of water injection to reduce the take-off distance and reduce the time of climbing the echelon.

Table 5

Results of calculating the characteristics of TPE during the aircraft take-off under different conditions

Flight stage	ALT, m	Mode of operation	EPW, kW	ESFC, kg/(kW·h)	EPW, kW	ESFC, kg/(kW·h)	ΔEPW, kW
			ISA		ISA+20 °C		
TO run	0	TO	6100	0.2558	5240.4	0.2709	1486.3
	0	TO	6546	0.2471	5643.8	0.2613	1556.1
TO to ALT circle	0	TO	6546	0.2471	5643.8	0.2613	1556.1
	250	TO	6658	0.2441	5737.1	0.2580	1553.2
Acceleration to VTAS climb	250	TO	6658	0.2441	5737.1	0.2580	1553.2
	450	TO	7014	0.2404	6054.0	0.2538	1581.9
Climbing the echelon ALT	450	CM	5350	0.2594	4497.8	0.2819	1503.1
	4000	CM	3779	0.2492	3083.7	0.2774	1092.3
	4000	CM	3779	0.2492	3083.7	0.2774	1092.3
	8000	CM	2631	0.2351	2152.3	0.2611	709.2
	8000	CM	2631	0.2351	2152.3	0.2611	709.2
	9000	CM	2262	0.2336	1846.9	0.2595	618.1

Table 6

Results of calculating the characteristics of TPE during the aircraft take-off under different conditions

Flight stage	ALT, m	Mode of operation	EPW, kW	ESFC, kg/(kW·h)	EPW, kW	ESFC, kg/(kW·h)	ΔEPW, kW
			ISA		ISA+30 °C		
TO run	0	TO	6100	0.2558	4798.1	0.2801	1509.5
	0	TO	6546	0.2471	5158.7	0.2705	1595.3
TO to ALT circle	0	TO	6546	0.2471	5158.7	0.2705	1595.3
	250	TO	6658	0.2441	5244.1	0.2672	1604.4
Acceleration to VTAS climb	250	TO	6658	0.2441	5244.1	0.2672	1604.4
	450	TO	7014	0.2404	5541.6	0.2629	1656.9
Climbing the echelon ALT	450	CM	5350	0.2594	4123.1	0.2955	1399.5
	4000	CM	3779	0.2492	2773.4	0.2953	1115.2
	4000	CM	3779	0.2492	2773.4	0.2953	1115.2
	8000	CM	2631	0.2351	1924.9	0.2794	749.3
	8000	CM	2631	0.2351	1924.9	0.2794	749.3
	9000	CM	2262	0.2336	1648.9	0.2781	651.4

Table 7

Results of calculating the characteristics of the aircraft flight cycle

Parameter name	ISA	ISA+20 °C		ISA+30 °C
	0.6 % H_2O, NR=const	0.9 % H_2O, TH=const	1.3 % H_2O, TH=const	1.3 % H_2O, TH=const
The total mass of the injection system with water, kg	326	566	1100	1100
The mass of fuel that is spent to ensure the operation of the injection system from the TO run to setting echelon ALT, kg	4.3	6.1	12.5	12.2
The mass of fuel that is spent on the transportation of the injection system for the flight cycle, kg	3.8	5.3	10.4	10.2

Table 8

Results of flight cycle characteristics calculation

Parameter name	ISA, no injection	ISA, H_2O 0.6 %	ISA +20 °C, no injection	ISA +20 °C, H_2O 0.9 %, TH=const	ISA +30 °C, no injection	ISA +30 °C, H_2O 1.3 %, TH=const
The total mass of the injection system with a water mixture, kg	0	326	0	1100	0	1100
Maximum engine equivalent power during TO, kW	6100	6755	5240	6727	4798	6308
TO distance, m	1372	1223	1970	1472	2809	1439
Time to climb the echelon ALT, min.	19.44	16.6	22.6	20.1	23.1	21.2
Time to accelerate aircraft to the height of climbing the echelon, s	108.3	97.3	156.4	118.8	192.7	106.8

For each estimated case, it is necessary to specify the flight cycle. When changing the purpose of an aircraft (for example, for military use), there may be several flight cycles. For each flight cycle, it is possible to organize a rational working process in the engine. This would have a positive impact on the performance of the aircraft.

6. Discussion of results of improving the efficiency of the power plant for a regional passenger aircraft

The calculation results on the verification of the constructed MM, given in Table 1, have a satisfactory convergence with the data of the technical order [26]. The error of calculations does not exceed 2 %.

The results of calculations, shown in Fig. 2, 3, on verification of the results of mathematical modeling of the engine workflow with experimental data coincide, with sufficient accuracy, with the calculation data of other authors [25]. The error of calculations does not exceed 4 %.

Our tests of the AI-450M engine (Zaporizhzhia, Ukraine) at the bench of SE «Ivchenko-Progress» (Zaporizhzhia, Ukraine) at an air temperature at the engine inlet of 25...35 °C confirmed the efficiency and performance of water injection.

The data, shown in Fig. 4, 5, on changes in the specific equivalent fuel consumption (ESFC) and fuel consumption (WF) depending on the engine operating mode and water injection demonstrate that there is a slight difference between the calculation results and the tests. No deviations and obvious changes in the nature of the dependences are observed. Our analysis of the results showed that the estimated values have a satisfactory convergence with the test results of the AI-450M turboshaft engine. The maximum error under the accepted assumptions does not exceed 5 %.

The results in Table 2 demonstrate that the injection of water at the inlet to the compressor makes it possible to get ~9 % more power than the injection of water into the combustion chamber. However, the injection of water into the combustion chamber reduces by ~5 % the temperature at the inlet to the impeller of the compressor turbine. The temperature drop is explained by the fact that evaporation in the combustion chamber increases the flow rate and thermodynamic properties of the gas passing through the turbine. This makes it possible to achieve the necessary power to rotate the compressor at a lower temperature value.

When maintaining a constant initial gas temperature in front of the turbine, when water is injected at the inlet to the combustion chamber, an increase in power occurs, by ~8 %. Fuel consumption is also increased. With the injection of methanol, there is also an additional increase in power with a decrease in the consumption of the main fuel.

Thus, our studies on the choice of the place of injection of water or a water-methanol mixture demonstrate that injection in front of the compressor is a more economical way to boost the engine. To improve environmental performance without improving the performance of TPE, it is rational to use injection into the combustion chamber.

Table 3 demonstrates that the injection of pure methanol in front of the compressor can significantly reduce the consumption of the main fuel but there is no effect on power gain. Also, the use of methanol and water-methanol mixtures requires addressing the following issues:

– cleaning the working fluid selected from the engine for the aircraft air conditioning system (due to the toxicity of methanol);

– modernization of the engine cooling system (working fluid with methanol content selected for cooling behind the compressor would ignite when flowing from the turbine blades).

Therefore, for further research on ways to improve the performance of TPE for regional passenger aircraft, the option with the injection of a water-methanol mixture is not considered. It should also be noted that the amount of injected liquid and the maximum increase in power is limited by the reserve of stable operation of the compressors.

The change in the integration properties of the aircraft affects the patterns of the operational characteristics of TPE for a regional passenger aircraft for 100 passengers. Our work takes into consideration the influence of water injection and a water-methanol mixture on the change in the throttle and climatic characteristics of TPE. The impact of changes in the throttle and climatic characteristics of the aircraft on the performance characteristics of the aircraft must be considered in conjunction with the flight cycle of the aircraft.

The results of calculating the characteristics of the flight cycle indicate the efficiency of the injection of 1.3 % of water at the inlet to the compressor when maintaining TH=const starting with ISA+20 °C and above. However, practical implementation requires the following:

– selecting a reasonable place for placing a thermally insulated water tank on the aircraft (to maintain water in a liquid state at ALT>2 km) and equipment for its supply;

– choosing a reasonable injection site and a method to optimize the characteristics of the engine at the stage of designing the TPE;

– selecting sound engine control laws to optimize engine performance when using the water injection system;

– introduction into the laws of engine management of a sign of signaling the occurrence of icing with the subsequent warning of its occurrence;

– revision of the aircraft balance (when water is injected into the engine, there is a rapid change in its mass);

– conducting research on the design of the mixing chamber at the injection site (type, number, and location of injectors) for effective evaporation and mixing of steam with air. The course of these processes has a direct impact on the effect of injection on engine parameters;

– determining the exact altitude-speed range of water injection in order to avoid icing of the inlet part of the compressor.

The verification of the obtained results of mathematical modeling was carried out on the test bench only in terrestrial operating conditions (ALT=0). Additional experimental studies are needed to verify the results of mathematical modeling on the effect of water injection and a water-methanol mixture at other altitudes. The results of such studies can be obtained when testing the engine on a flying laboratory or in a thermobaric chamber at SE «Ivchenko-Progress» (Ukraine). Conducting the studies would also help determine the range of application of the injection system to prevent icing in the gas-air path of the engine.

The devised procedure for defining the thermodynamic properties of the working medium, if necessary, could make it possible to assess the effect of other fuels and mixtures on the engine workflow.

The formation of engine control laws, taking into consideration water injection under different engine operating modes, has a direct impact on the parameters of the entire PP. This issue requires more investigation in separate research work.

For the use of water injection and a water-methanol mixture, it is necessary:

– to optimize the characteristics of the engine gas generator for forced TO;

– for a safe flight, it is necessary to introduce refueling and control of the level of injected liquid into the maintenance regulations. In the case of an insufficient level of injected liquid, the aircraft would not be able to TO from a short runway due to an insufficient thrust-to-weight ratio.

Additional experimental studies are needed to assess the effect of injection of mixtures of different chemical compositions on the gas-dynamic stability of compressors and turbine characteristics. Such studies will make it possible to clarify and verify the module for adjusting the characteristics of the engine components depending on the composition of the injected liquid.

In turn, the improved procedure for calculating thermodynamic parameters can be further advanced when studying the performance characteristics of other types of engines in other types of aircraft.

7. Conclusions

1. Our verification of the results of calculations according to the devised procedure for changing the thermophysical properties and phase transitions of working medium during the injection of water or a water-methanol mixture into TPE with experimental data coincide with sufficient accuracy with the calculation data of other authors. The maximum error does not exceed 4 %.

2. Testing the AI-450M engine (Zaporizhzhia, Ukraine) at the bench of SE «Ivchenko-Progress» (Zaporizhzhia, Ukraine) has confirmed the efficiency and operability of water injection. No deviations and changes in the nature of the estimated and experimental dependences were observed. The estimated values have a satisfactory convergence with the test results. The maximum error does not exceed 5 %. Efficient multi-phase workflow improves performance and reduces NO_X emissions. This requires a change in the workflow and the modernization of the design of the engine elements.

3. Injecting water or a water-methanol mixture in front of the compressor is a more economical way to boost the engine. To improve environmental performance without improving the performance of TPE, it is rational to use water injection into the combustion chamber.

4. The greatest effect of water or a water-methanol mixture injection is achieved at the most important stages of flight – TO, climb, and acceleration of the aircraft. The use of water injection in TPE is advisable to carry out in hot and high-altitude areas of operation in order to temporarily improve performance characteristics to reduce the TO distance of the aircraft. Preliminary results of calculations show the advantages of water injection at the TO stage of the aircraft to reduce the TO distance (up to 45 % under hot conditions, ISA+30 °C) and reduce the time of climbing the echelon (about 10 %). When using 1.3 % water while maintaining TH=const under the conditions of ISA+20 °C, additional fuel consumption (~23 kg) is required to implement water injection in one flight cycle. At the same time, the dimensions of the initial TPE remain unchanged. However, in the air conditioning system, it is necessary to provide measures to ensure the necessary cleanliness and temperature during the intake of air from the engine into the passenger compartment.

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