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PRINCIPLE OF MODERNIZATION OF THE AIRCRAFT AN-148, AN-158, AND AN-178 FOR IMPROVING THEIR FUEL EFFICIENCY AND INCREASING COMPETITIVENESS

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Для створення нових конкурентних переваг середніх магістральних літаків Ан-148 і Ан-158 розглядається застосування на цих літаках двигуна Д-436-148ФМ. Це дозволить розширити експлуатаційний діапазон польотів літаків, зменшити шум на місцевості та емісію шкідливих викидів з двигуна.

Відмінною особливістю є досягнення тяги двигуна Д-436-148ФМ на максимальному надзвичайному режимі на 19,4 % вище тяги двигуна Д-436-148Д. Це стало можливим шляхом оптимізації вентилятора, удосконалення камери згоряння і турбінного каскаду.

Виконано необхідний обсяг стендових і льотних випробувань. В даний час завершується сертифікація двигуна. На ДП «Антонов» і ДП «Івченко-Прогрес» вивчено питання по установці двигуна Д-436-148ФМ на літаки сімейства Ан-148 і Ан-158. Будь-яких змін конструкції двигуна і літака не потрібно. Двигун встановлюється на тіж пілони без змін мотогондоли і капотів двигуна.

Досліджені енергозалежні системи, які пов'язані з двигуном. На режимах застосування двигуна згідно Керівництва з льотної експлуатації літаків в принципових змінах пов'язаних систем потреби немає.

Виконано інженерний аналіз порівняння льотно-технічних і злітних характеристик літака Ан-158 з двигуном Д-436-148Д і Д-436-148ФМ. Дані отримані в результаті обробки льотних випробувань сертифікованого літака Ан-158 з урахуванням трубних досліджень, льотних випробувань літака Ан-178, даних Керівництва з льотної експлуатації літака Ан-158 і висотно-швидкісних характеристик двигунів Д-436-148Д та Д-436-148ФМ. Прийняті в розрахунку висотно-швидкісні характеристики двигуна Д-436-148ФМ підтверджені в льотних випробуваннях літака Ан-178.

Виконана техніко-економічна оцінка заміни двигунів, яка заснована на порівнянні техніко-економічних характеристик літака Ан-158 з двигуном Д-436-148Д і Д-436-148ФМ при експлуатації в різних атмосферних умовах.

Запропоновано принцип створення сімейства літаків транспортної категорії різної конфігурації та призначення на базі одного двигуна

Ключові слова: сімейство літаків, авіаційний двигун, аеродинамічні характеристики, висотно-швидкісні характеристики, експлуатаційні витрати

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1. Introduction

Under current conditions of intensive improvement and rapid generational change of some aircraft models by others, the ratio between development and operational time intervals changes significantly, towards the reduction of the latter, changes significantly. This general trend in technology brings to the fore the task of reducing costs, including temporal, at the development stage [1, 2]. This, in turn, requires the development of relatively non-labor-intensive methods for the reasonable selection of consistent indicators of a complex technical system being created in the early (pre-sketch) stages of development. The theoretical basis for such methods seems to be methods of comparing and evaluating design options at the conceptual level.

As it is known, the main indicator of the comparative assessment of modern transport and passenger aircraft (AC) is the level of competitiveness in the aviation market. One way to maintain the fleet of transport and passenger aircraft at the level of modern competitiveness requirements is to improve the traction and economic characteristics of the power plant (PP) by replacing the engine.

It is known that the technical perfection of the PP predetermines the achievement of qualitatively new indicators of flight and technical characteristics of an aircraft, thus there is a priority need to study the power plant in an

AC system. The use of an aircraft PP is determined by the requirements set for AC. In this case, a PP is the object of evaluation while an AC acts as a means of evaluating adopted technical solutions. Such a task is resolved through flight tests with a deep justification for economic performance. Therefore, the feasibility study of engine replacement within a PP, based on comparing the technical and economic characteristics of the aircraft with the new engine when operating in different atmospheric conditions, is a relevant scientific and technical task.

2. Literature review and problem statement

As it is known, of the greatest interest in replacing the engine in AC is the issue of operating costs, which is proportional to fuel efficiency. Therefore, it is advisable to analyze the products made by the world's major aviation engineering enterprises, which produce engines for regional aircraft.

In the field of aviation engine construction, a promising direction is the development and use of more economical and reliable PPs – conventional TFE and PP new designs, which include engines of the changing cycle, turbo-propeller-fan engines, as well as combined PP. The implementation of scientific and technical development programs (IHPTET, VAATE, UEET, ANTLE, CLEAN SKY) of the world's leading aircraft engine companies was aimed at improving PP in improving fuel efficiency, reducing harmful emissions into the atmosphere, and reducing noise [3].

More than 70 years of development of passenger aircraft with jet engines have helped reduce the cost of fuel per passenger-kilometer by more than 80 % and almost 50 % of the reduction was achieved through the modernization of the aircraft engine [4, 5]. The improvement in civilian aircraft engine performance comes with the constant tightening of noise and emissions requirements [6–8]. At present, the environmental characteristics of aviation equipment are one of the main indicators determining its competitiveness in the world market, as well as the unhindered operation by international airlines [9]. Many airlines cannot fulfill these requirements [10]. The main ranges of changes in environmental characteristics for promising aviation equipment have been identified, which requires the implementation of fundamentally new layout schemes of the AC and the engines [11, 12].

The world's aviation engine industry employs a limited number of companies from America and Europe, which are the leading manufacturers of aircraft engines and are fully responsible for their design, production, sale, and after-sales service [4]. They include General Electric (GEA viation), Rolls-Royce (Civil and Military), United Technologies Corporation (Pratt & Whitney and Pratt & Whitney Canada), and SAFRAN Group (Safran Aircraft Engines). The independent global manufacturers with a full cycle of engine work are also Honeywell International (the Air Transport division of Honeywell Aerospace), Williams International, which supply engines for business aviation and regional aircraft, as well as the Ukrainian aviation engine companies Ivchenko-Progress and Motor Sich.

Analysis of the technologies for the development of next-generation aircraft and engines [13] shows that for the past two decades, European science and technology programs have been actively developing to improve various engine systems and nodes. The execution sequence of these programs (Fig. 1) has significantly improved the fuel efficiency of modern and promising aircraft, as well as power plant engines.

Paper [14] describes possible improvements in fuel efficiency for different aircraft when implementing the ENOVAL demonstrator engine concept. However, the demonstrator must be created by 2025; its application in AC has not yet been investigated.

The 7th FP7 Framework Program funded three large projects, LEMCOTEC, EBREAK, and ENOVAL, to conduct research on new technologies aimed at increasing full pressure (OPR) and a bypass ratio(BPR) of aircraft engines [15, 16]. The main type of aircraft for the use of the new technology engine has not yet been approved.

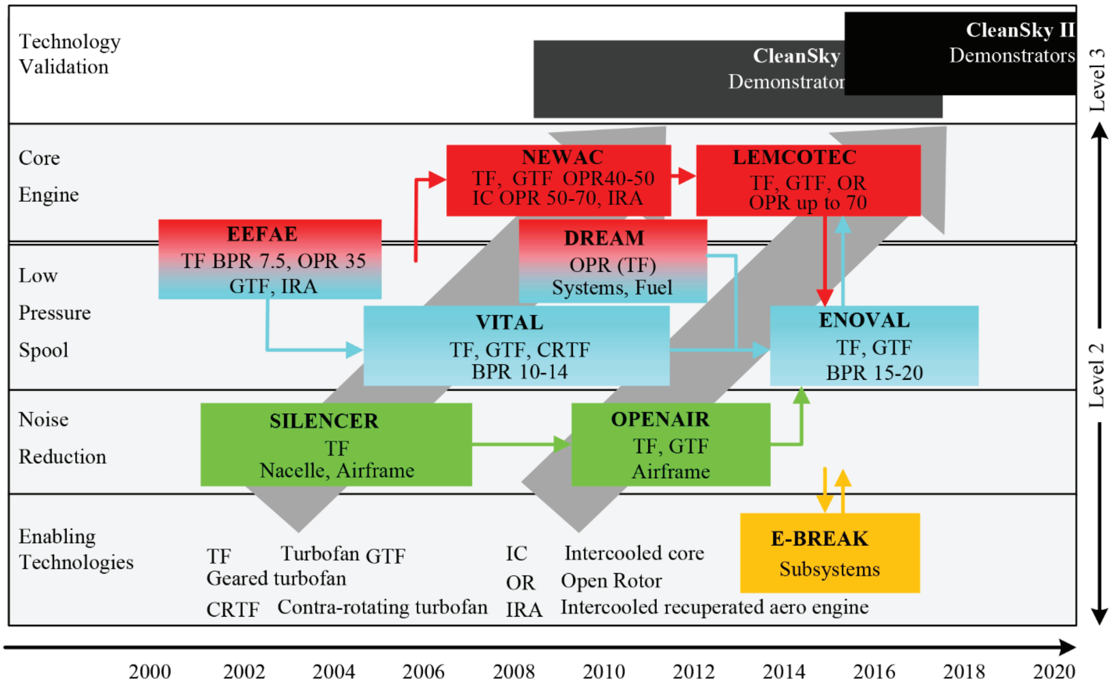

Fig. 1. New technology programs in aviation

As of the end of May 2018 [4, 17], the leading position in the aircraft engine market for the entire fleet of passenger aircraft (Fig. 2) in operation was occupied by CFM International (a joint venture between General Electric and Safran, ~44 %) and General Electric (~22 %). In the engine segment for the long-haul narrow-body aircraft, the leaders are CFM International (~71 %, the CFM56 TFE family) and the International Aero Engines (~19 %, the V2500 TFE family).

In the engine segment for regional aircraft: General Electric (~72 %, the CF34 TFE family), and Rolls-Royce (~17 %, the AE3007 TFE family). In the engine segment for wide-body aircraft: General Electric (~51 %, the CF6, GE90, and GEnx TFE families), and Rolls-Royce (28 %, the RB211 and Trent TFE families).

Aircraft companies are currently exploring many different options for upgrading their aircraft, including the possibility of installing several models of next-generation engines. In addition, company specialists are exploring other ways to modernize future aircraft in addition to the use of new PPs. Among the upgrade options under consideration are the use of a completely new wing and an increase in the height of the chassis racks, which would make it possible to install engines with a high bypass ratio on the aircraft, which could reduce fuel consumption by 10 % compared to existing models. Composite winglets and electronic steering system can also appear on remotorized aircraft.

One way to improve the performance of AC is to replace aircraft engines with more modern ones. However, the replacement of one engine with another entails a change in the aircraft's FTCs due to the disagreement of the characteristics of the PP and the AC airframe. In addition, this could lead to a change in the parameters for harmonizing AC elements, which would have a negative impact on the feasibility of AC application.

The integration of the PP and the AC airframe in the face of uncertainty of initial engine information should be addressed by considering the possible uncertainty of information on the aircraft airframe [1, 2]. Changes in the process of creating the technical design of the AC would lead to changes in the parametric performance of the engine and its operating conditions.

Analysis of the structural layout of the AN-158-type aircraft shows [18, 19] that these aircraft have a good chance for successful modernization even without a significant change in the design of the airframe and systems. The modern layout of the wing and the engine nacelle makes it possible to install engines with a high degree of bypass ratio. However, in this case, the question arises about the parametric alignment of the integrated characteristics of subsystems, as well as the choice of approaches to solving the problem on optimizing the multi-criterion system [2].

Different ways of harmonizing the airframe and the PP are used to justify the engine selection [1, 20]. They make it possible to justify the requirements that are imposed on the projected PP, to determine the basic parameters and laws of control, the mass and geometric characteristics, at the initial stage of design. At present, these principles are developed and supplemented, serving as part of the automated engine design systems of the PP and AC [21]. However, there is no single method for optimal engine selection under the predefined requirements for the AC.

Existing approaches and methods [2, 21] do not fully disclose the formation of the parametric performance of the PP integrated with airframe of the transport or passenger AC. That makes it impossible to analyze the integration of its individual subsystems, even taking into consideration experimental studies [22]. The practical experience of designing PP and the AC airframe elements shows [3, 23] that existing regulations do not reflect solutions to the issue of investigating the integrative properties of the technical systems being created. When conducting flight tests of an aircraft, such FTCs are often obtained that differ from the set ones, due to the emergence of new integrative properties, which cannot be revealed during the design and coordination of AC characteristics.

An analysis of the modern scientific and methodological apparatus on the problem of the integration of the PP and the airframe of the AC for transport purposes [23, 24] does not make it possible to determine unambiguous ways of solving it. In this regard, based on the results of our analysis, one of the main tasks to improve the scientific and methodical apparatus of systemic research can be considered the further development and improvement of the system approach in the construction of a scientific and methodical apparatus to form the parametric performance of the PP when it is integrated with the AC airframe.

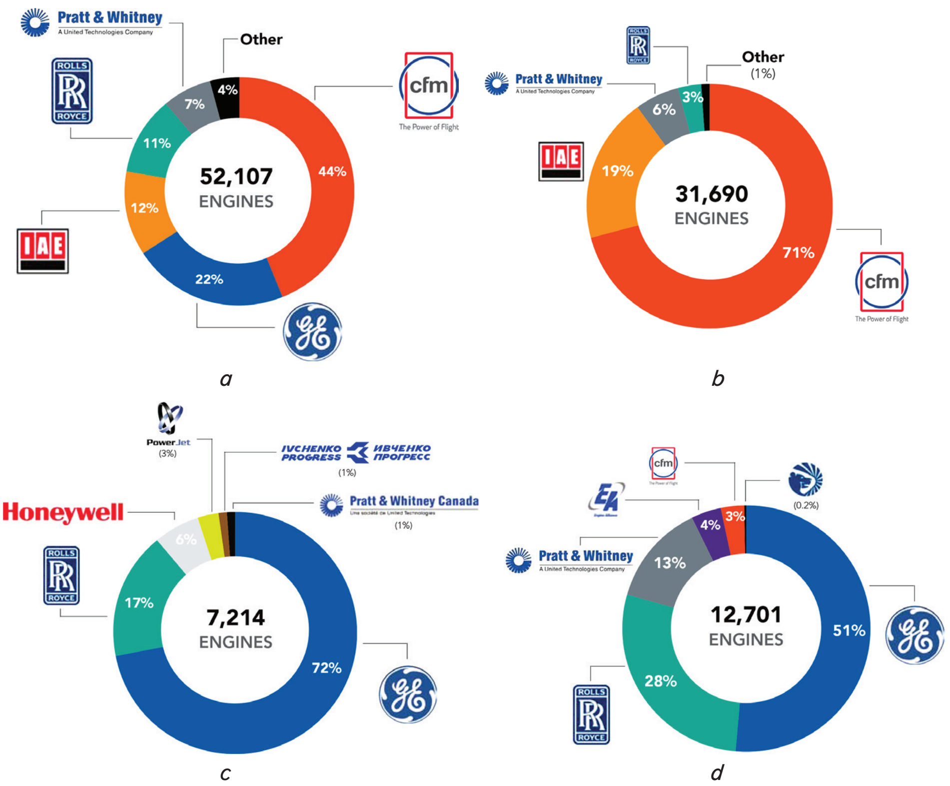

Fig. 2. Distribution of the fleet of passenger aircraft by aircraft engine manufacturers [17]: *a* — overall fleet; *b* — narrow-body aircraft segment; *c* — regional aircraft segment; *d* — wide-body aircraft segment

3. The aim and objectives of the study

The aim of this study is to establish the principle of modernizing the An-158-type aircraft family made by the Antonov State Enterprise, taking into consideration improved fuel efficiency, economic performance, and improving the competitiveness of the AC.

To accomplish the aim, the following tasks have been set:

– to improve the scientific and methodical apparatus of the formation of the parametric appearance of the PP in the AC;

– to analyze the flight and technical characteristics of the An-158-type aircraft;

– to calculate and build a «cargo-range» diagram for the An-158 aircraft equipped with different engines;

– to conduct a feasibility study of the replacement of the D-436-148D engine with the D-436-148FM engine in the PP of the An-158 aircraft.

4. A method for studying the AC operational characteristics

AC development patterns have resulted in a series of new features that exert a significant impact on the process of creating promising aircraft [25]. Such features primarily include:

– the possibility of multivariate development of structural-layout solutions;

– expanding the task of selecting advanced aircraft samples due to the increasing volume of requirements for the level of reliability of the original information, as well as the complexity of its processing methods;

– growth in the material, financial, human resources, as well as the timing of the creation of aviation equipment.

Analysis of these features reveals that they, on the one hand, contribute to an increase in erroneous decisions, and, on the other hand, increase the price of these errors due to tangible economic damage to the state. This situation has a steady tendency to worsen. It is possible to avoid the inappropriate expenditures of time, material, financial, and human resources in two main areas: increasing the volume of research at the earliest stages of AC development and improving the conventional research technology.

The implementation of the first direction led to the need to introduce the conceptual design phase into the development process of AC. The purpose of this phase is to explore all possible options for the technical appearance of an AC, analyze their technical feasibility, create a set of accept Table options that meet the set requirements and choose rational options among them, based on certain criteria.

Conceptual design is characterized by the defining role of the researcher's methods and experience. Opportunities to explore estimation methods, computational software, and analytical procedures are limited. This is largely due to the specificity of the information being processed at a given stage, which includes:

– a high degree of uncertainty and inaccuracy of the original data on the object being created;

– physical and informational heterogeneity, as well as significant difficulties in formalizing a series of factors influencing the decision-making process;

– the need to take into consideration scientific and technological advances in various fields of knowledge.

The second area is related to the introduction of intensive research technology – the creation of automated design systems. However, the AC state-of-the-art automated design systems are constrained by the specified input information flows and are more focused on the stages of technical proposals and sketch design. The main drawbacks of these systems, which makes it difficult to take full advantage of their capabilities during the development phase of an AC concept, are:

– focusing on numerical optimization algorithms that require a huge amount of raw data;

– inability to process informal information;

– the cumbersome, inflexible toolset used, making it difficult to adapt the system to changing types and conditions of problem-solving;

– difficulties in the direct use of databases containing the accumulated experience of designing elements of PP and AC airframe, as well as the knowledge of specialists (experts).

Thus, modern toolset and techniques do not contain all the tools needed to rationally integrate the PP and AC airframe, as a complex technical system, in the early stages of design. In this regard, an improved scientific and methodical apparatus of the formation of the parametric appearance of the PP in the AC (Fig. 3) is presented.

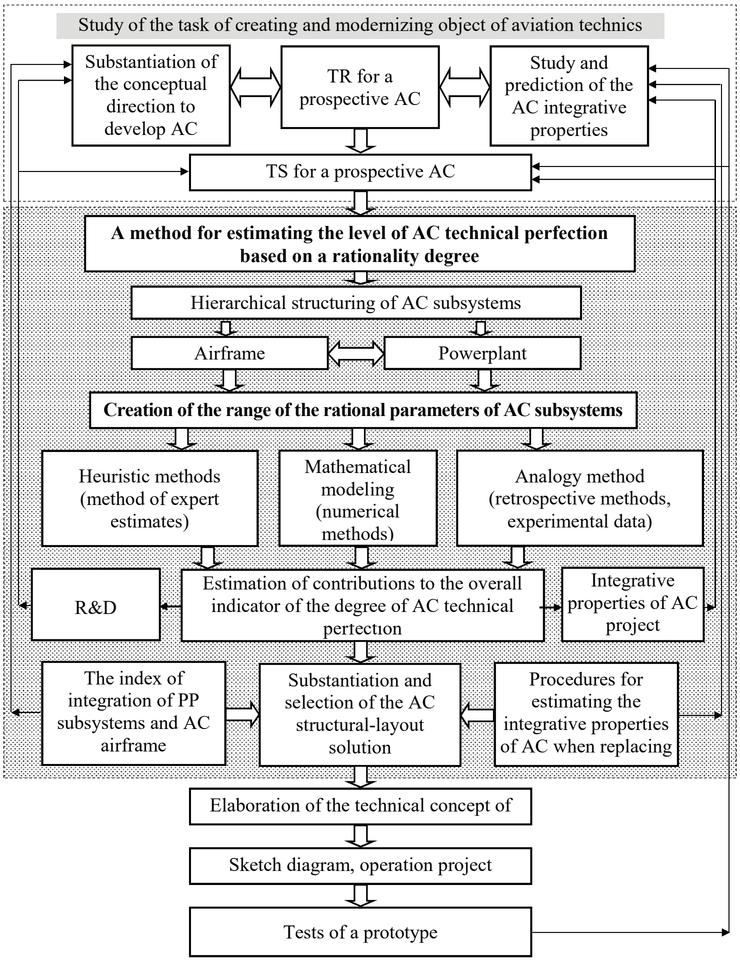

Fig. 3. The scientific and methodical apparatus to form the parametric appearance of a power plant in AC

The scientific and methodical apparatus has been improved in terms of determining the dependence of the parametric appearance of the PP engine on the characteristics of the aircraft airframe. In this case, several structural-layout solutions of the airframe and engines within the PP have been created. Refinements of the boundaries for expanding the range of application of experimental data in the analogy method have been made. Experimental studies involved flight data on the family of the An-158-type aircraft, made by Antonov State Enterprise, equipped with different engines in the PP.

Based on our research employing the scientific and methodical apparatus, the basic principle of aircraft modernization has been proposed, which was tested and implemented on the example of the family of the An-158-type aircraft, made by Antonov State Enterprise.

To form the basic principle of aircraft modernization, it is necessary to investigate the characteristics of engines and aircraft. The construction of a cargo-range diagram for the An-158 aircraft, and the feasibility study of engine replacement within the PP, would show the advantages and disadvantages of aircraft remotorization.

5. Studying the flight-technical characteristics of the An-158-type aircraft.

5. 1. Justification and a choice of the research object

The study object is the family of An-1X8 aircraft, which includes aircraft of different passenger capacity – An-148 (Fig. 4), An-158 (Fig. 5), and the transport version of the An-178T aircraft (Fig. 6) [26].

Maximum take-off weight – 43.7 tons;
Maximum number of passengers – 92 people;
Flight range – up to 4,400 km;
Cruising speed – 800...870 km/h;
Cruising altitude – 12,200 m;
Required runway length – 1,900 m

Fig. 4. An-148-100 aircraft

Maximum take-off weight – 43.7 tons;
Maximum number of passengers – 102 people;
Flight range – up to 3,100 km;
Cruising speed – 800...870 km/h;
Cruising altitude – 12,200 m;
Required runway length – 1,900 m

Fig. 5. An-158-100 aircraft

Maximum take-off weight – 52.4 tons;
Maximum capacity – 18 tons;
Flight range with cargo:
– 18 tons→990 km;
– 15 tons →1,900 km;
– 10 tons →3,690 km;
Cruising speed – 750...825 km/h;
Cruising altitude – 12,200 m;
Required runway length – 2,200 m

Fig. 6. An-178T aircraft

Common to the entire family of aircraft is the removable part of the wing, pylons with a suspended engine nacelle, the same tail plumage. In addition, the aircraft are equipped with the same life support systems, almost identical fire and fuel systems, almost the same aircraft remote control system, de-icing systems.

The on-board radar system and the cockpit are as unified as possible.

The production of An-148, An-158, and An-178 aircraft is concentrated in Ukraine at a single plant, the Antonov State Enterprise [26], where the unification of technical processes in the manufacture of units and assembly of aircraft is widely used.

In order to meet the requirements to improve the AC fuel efficiency, economic performance, and competitiveness, a single D-436-148FM engine (Fig. 7) is planned for the entire family of these aircraft [27].

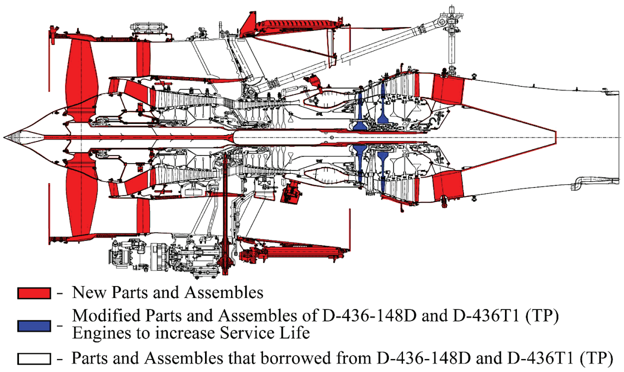

Fig. 7. The dual-circuit turbojet engine D-436-148FM

Next, we investigated the use of a single propulsion system for the aircraft family of An-148, An-158, An-178 at the consolidated modernization of the aircraft's technical appearance. Thus, all the global challenges of our time regarding the stricter regulatory requirements for an engine or aircraft would at the same time be met for the entire family of aircraft at consolidated modernization, including engine replacement (Fig. 6).

5. 2. Analysis of the AC take-off characteristics

The result of our estimation studies is the derived dependence of the maximum allowable take-off weight of the aircraft on the airfield altitude and the temperature of the outer air based on the condition of ensuring a climb gradient of 2.4 % when taking off with flaps released at 20° [19].

Fig. 8 shows the dependences demonstrating the value of the maximum altitude of an air field depending on the temperature of the outer air, which provides for take-off with a climb gradient of 2.4 % with flaps released at 20°.

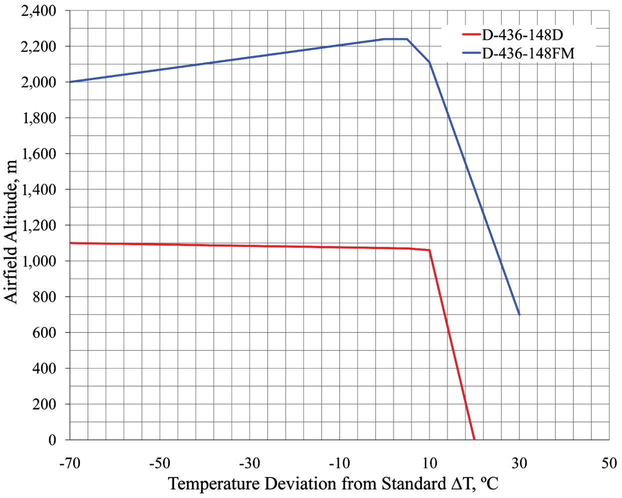

Fig. 8. Take-off data for the An-158 aircraft weighing 4.3t with a gradient of 2.4 %

Fig. 9 and Table 1 illustrate the dependence of the maximum allowable take-off weight on an airfield altitude [19] based on the condition of providing a gradient of 2.4 % with flaps released at 20° for temperature conditions of the standard atmosphere (SA), SA+20 °C and SA+30 °C.

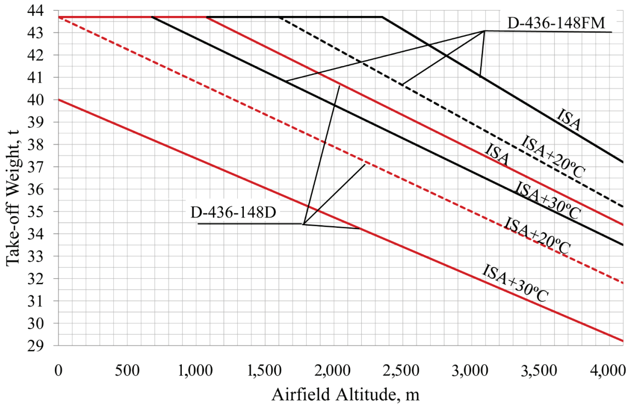

Fig. 9. An-158 aircraft. The maximum allowable take-off weight, which ensures the take-off of the aircraft with a gradient of 2.4 %

The data above show a significant advantage of the An-158 aircraft equipped with the D-436-148FM engine. In this case, as one can see from the data in Table 1, the An-158 aircraft has an excessive thrust with the engine D-436-148D to the temperature of the cut at the altitudes of an airfield not higher than ~1,000 m, and with the engine D-436-148FM – at the altitudes of an airfield not higher than ~2,000 m.

5. 3. Analysis of the AC flight and technical characteristics

The data presented indicate a significant expansion of the area of operation, in terms of the cruising altitude, of the An-158 aircraft when the D-436-148FM engines are installed, especially at elevated outdoor air temperatures.

Table 2, give a comparison of the flight characteristics (practical range, medium-haul hour-long, and medium-haul fuel costs, as well as fuel efficiency in practical range) of the An-158 aircraft equipped with engines D-436-148D [28] and D-436-148FM [29]. The data are valid for transporting a maximum cargo of 9,800 kg with a maximum take-off weight of 43.7 tons, when flying at cruising speeds of 780 km/h and 820 km/h in SA and SA+10 °C.

The data from Tables 2, 3 indicate lower fuel costs and, accordingly, higher fuel efficiency in the operation of an aircraft equipped with D-436-148FM engines relative to the D-436-148D engines. This advantage is increased when operating at elevated speeds and elevated outdoor air temperatures.

Table 1

Maximum allowable take-off weight that ensures the take off with a gradient of 2.4 %

H, m	T, °C	Maximum allowable take-off weight, t		Increase in the maximum payload, t	Increase in the maximum number of passengers	Increase in the maximum range, km
		D-436-148FM	D-436-148D			
2,000	30	39.839	35.018	4.821	50	2,163
3,000	30	36.835	32.594	4.241	44	1,998
4,100	30	33.459	29.500	3.959	41	1,984
2,000	20	42.142	37.914	4.228	44	1,782
3,000	20	38.807	35.048	3.759	39	1,681
4,100	20	35.108	31.639	3.469	36	1,665
2,000	0	43.700	40.833	2.867	30	1,110
3,000	0	41.092	37.837	3.256	34	1,367
4,100	0	37.159	34.481	2.678	28	1,197

Table 2

Comparative characteristic of the An-158 aircraft with different engines

Engine type	Cruising altitude^2	Fuel reserve^1	Practical range	Average fuel consumption by profile	Change in average hourly fuel consumption relative to D436-148D
	m	kg	km	kg/h	%
Cruise speed 780 km/h (indicator speed)					
SA conditions					
D-436-148D	10,970	1,703	2,363	1,874	–
D-436-148FM	11,580	1,681	2,336	1,873	~0
SA+10 conditions					
D-436-148D	9,750	1,811	2,220	1,953	–
D-436-148FM	11,280	1,687	2,330	1,882	–3.6
Cruise speed 820 km/h (indicator speed)					
SA conditions					
D-436-148D	10,970	1,889	2,203	2,008	–
D-436-148FM	11,580	1,818	2,232	1,983	–1.2
SA+10 conditions					
D-436-148D	9,750	2,008	2,059	2,101	–
D-436-148FM	11,280	1,807	2,259	1,970	–6.2

Note: 1 – fuel reserve for 60 minutes of flight at cruising altitude and speed; 2 – residual climb rate at the echelon of 1.5 m/s

Table 3

Comparative characteristic of the An-158 aircraft with different engines

Engine type	Cruising altitude[1]	Average kilometer fuel consumption by flight profile	Change in the average kilometer fuel consumption relative to D436-148D	Fuel efficiency in a practical range	Change in the fuel efficiency relative to D436-148D
	m	kg/km	%	g/(t·km)	%
Cruise speed 780 km/h (indicator speed)					
SA conditions					
D-436-148D	10,970	2.579	–	263.2	–
D-436-148FM	11,580	2.566	–0.5	261.8	–0.5
SA+10 conditions					
D-436-148D	9,750	2.696	–	275.1	–
D-436-148FM	11,280	2.571	–4.6	262.3	–4.6
Cruise speed 820 km/h (indicator speed)					
SA conditions					
D-436-148D	10,970	2.682	–	273.7	–
D-436-148FM	11,580	2.625	–2.1	267.8	–2.1
SA+10 conditions					
D-436-148D	9,750	2.811	–	286.9	–
D-436-148FM	11,280	2.598	–7.6	265.1	–7.6

Note: 1 – residual climb rate at the echelon of 1.5 m/s

When taking off under conditions of the elevated outdoor air temperatures and high altitudes, the increase in the maximum take-off weight of the aircraft equipped with D-436-148FM engines makes it possible:

– to increase the available passenger capacity by 30...50 people at an unchanged flight range;

– to increase the flight range to 1,100...2,100 km – at the same number of passengers.

The results from Table 2 demonstrate that the D-436-148FM engine shows a significant advantage in fuel efficiency.

6. Construction of a cargo-range diagram for the An-158 aircraft equipped with D-436-148D and D-436-148FM engines

The required thrusts, which ensure a cruising flight at the specified altitude and speed, are in the range of 1,400...1,300 kg. The throttle characteristic of the D-436-148D and D-436-148FM engines is shown by the chart in Fig. 10 [18, 19].

The cargo-range diagram of the An-158 aircraft equipped with D-436-148D engines at a speed of 780 km/h (indicator speed) under SA conditions is shown in Fig. 11. This diagram was built by using the engineering and navigational calculation of the aircraft's flight characteristics on a standard flight cycle. Flight conditions: cruising altitude, 10,970...11,890 m (for D-436-148D), and 11,580...12,190 m (for D-436-148FM); cruising speed, 780 km/h (indicator speed); emergency fuel reserve – 60 minutes of flight at cruising altitude and speed at the end of the flight over the echelon. The maximum weight of fuel is 11,750 kg. SA conditions are calm.

The above diagram shows a change in the practical range of the flight with the engines being studied. It is obvious that the average flight hourly and medium-haul fuel costs would also change, as well as fuel efficiency, depending on the practical range of the flight.

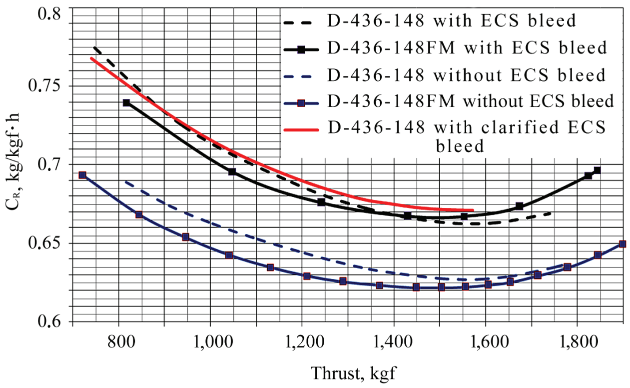

Fig. 10. Throttle characteristic of the engines (at F_{nozzle}=6,800 cm^2) under SA conditions, H=11,000 m, M=0.75

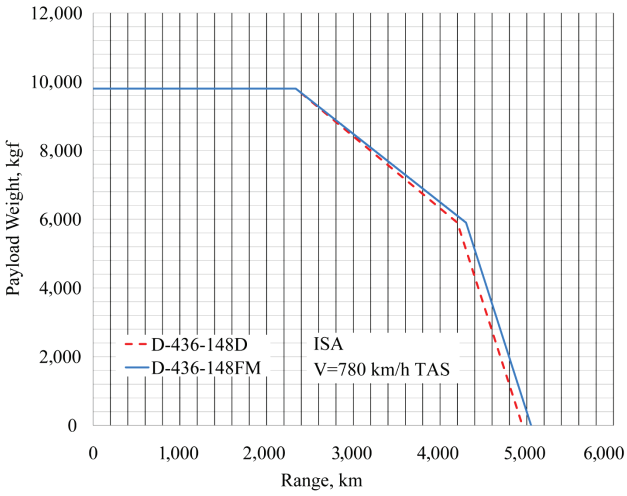

Fig. 11. A cargo-range diagram for the An-158 aircraft (SA conditions, V=780 km/h)

7. Technical and economic assessment of the replacement of the D-436-148D engine with the D-436FM engine in the aircraft An-158

For civil aviation, the main requirement is to ensure the high cost-effectiveness of the AC operation. Therefore, all operational processes, including flight, are evaluated by economic criteria, subject to specified safety requirements. The challenges of improving economic performance and improving AC's competitiveness are being met by optimizing the aerodynamic characteristics of the airframe, design and technology solutions, power plant parameters, flight modes, under specified restrictions and operating conditions. If AC reliability issues are not addressed, nor the associated costs of maintenance, repair, and delays, the economic efficiency of a transport AC would primarily be determined by the available payload and the required fuel costs. The payload determines the size of an airline's possible revenue per flight while fuel costs are one of the main items of expenditure. As an indicator of the economic efficiency of an AC, a certain function is usually considered, depending on six groups of factors [30, 31]:

– a combination of aerodynamic and mass characteristics of AC;

– a set of parameters that characterize the flight mode;

– a combination of altitude-speed and throttle characteristics of engines;

– a combination of passenger comfort and safety characteristics;

– a combination of operational factors;

– a combination of technical-economic parameters.

The main task of research to improve flight efficiency is to find the optimal combination of parameters that provide an extreme value of the objective function.

In this work, the main indicators adopted for the feasibility study were the level of fuel consumption, the number of passengers transported over a year, the cost of passenger-kilometer in different operating conditions. The main indicators are determined on the basis of studying the flight and technical characteristics of aircraft in different atmospheric operating conditions.

The base of the feasibility study is:

1. Comparison of the difference in prices for the industrially produced An-158 aircraft equipped with the D-436-148D and D-436-148FM engines at the predefined release program.

2. Determining the fuel efficiency of the aircraft, annual passenger flow, depending on the flight and operational (take-off, resource) characteristics of the compared engines.

3. Comparison of direct operating costs (DOC) per passenger-kilometer, taking into consideration the technical and resource indicators of each engine, depending on the route network with different atmospheric conditions separately.

4. Analysis of the impact of the take-off of the An-158 aircraft equipped with the D-436-148-FM engine under regimes that reduce the engine's operating modes and improve its operational (resource) characteristics, namely, the impact of the «Maximum Long» mode on the cost of DOC per passenger-kilometer.

Comparative assessment of the performance of the An-158 aircraft equipped with the engines D-436-148D and D-436-148FM, which has the greatest potential of demand and sales, was carried out depending on the annual flight, the route network for different atmospheric conditions.

For the feasibility study, the price of the An-158 industrially produced aircraft was accepted with the cost of experimental-development operations (Fig. 12).

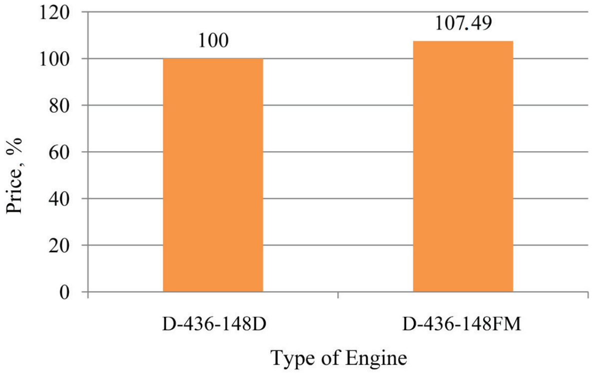

Fig. 12. Comparison of the price of the An-158 aircraft depending on the type of engine

The technical and economic assessment of the operation of the An-158 aircraft with different engines was performed at a yearly flight time of 2,500 hours, on routes with a distance of 1,000–3,000 km, depending on the altitude of an airfield, outdoor temperatures.

To compare the passenger flow and DOC for the corresponding types of atmospheric conditions, the runway length of the aircraft equipped with the D-436-148D engines is reduced to the runway length of the aircraft equipped with the engine D-436-148FM. In this case, the maximum take-off mass of the An-158 aircraft equipped with the engine D-436-148D has limits on the length of the runway.

To assess the operation of the aircraft equipped with the engine D-436-148FM exclusively when flying under the mode of «Maximum duration», we took into consideration the effect of a given regime on the number of planned visits to the shop by the engine and, as a result, on the cost of maintenance.

The fuel efficiency assessment was carried out in the European Region under comparable conditions, without taking into consideration the possible increase in the annual flight by the An-158 aircraft equipped with the D-436-148FM engines by expanding the network of operation on flights with high outdoor temperatures and high altitudes; the results are given in Table 4.

Table 4

Fuel efficiency of the An-158 aircraft under maximum payload on the compared engines

Operating conditions	Engine type	Flight range, km				
		1,000	2,000	2,200	2,400	3,000
SA	D-436-148D	28.2	25.7	25.4	25.2	28.2
	D-436-148FM	28.0	25.5	25.3	25.0	27.9
SA+10 °C	D-436-148D	29.3	25.7	26.5	27.2	30.8
	D-436-148FM	28.4	25.5	25.3	25.6	28.0
SA $H_{airfield}$=2,000 m	D-436-148D	28.0	28.6	29.5	30.5	36.0
	D-436-148FM	27.8	25.5	25.3	25.5	27.9
SA+20 °C $H_{airfield}$=2,000 m	D-436-148D	35.0	39.6	41.9	44.6	58.1
	D-436-148FM	28.2	26.2	27.1	27.9	32.0

Table 5 gives the cost of maintenance of the aircraft An-158 equipped with engines D-436-148D and D-436-148FM.

Table 5

Maintenance cost (USD per hour)

Flight duration, f. h. Annual flight, f. h.	Engine type	1 hour	2 hours	3 hours	4 hours
1,500	D-436-148D	875	650	575	564
	D-436-148FM	851	656	615	604
2,000	D-436-148D	857	628	553	541
	D-436-148FM	833	634	593	581
2,500	D-436-148D	846	618	538	527
	D-436-148FM	822	624	578	567
3,000	D-436-148D	832	611	529	518
	D-436-148FM	808	617	569	558

We compared the maximum number of passengers transported per year by the An-158 aircraft equipped with engines D-436-148D and D-436-148FM at 100 % of the passengers loading the aircraft on flights over 1,000–3,000 km. The results of the comparison are shown in Fig. 13, 14.

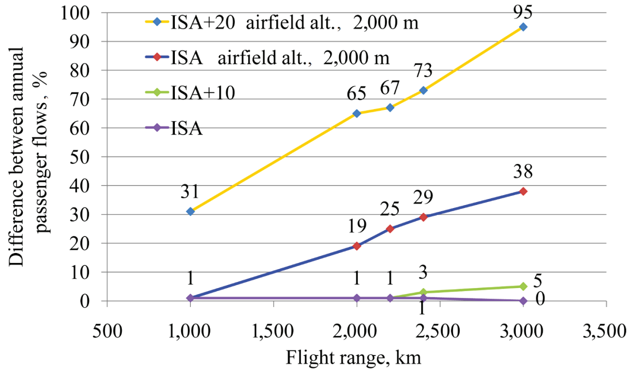

Fig. 13. The difference in the annual passenger flows of the An-158 aircraft equipped with two types of engines in relative terms, depending on the atmospheric operating conditions

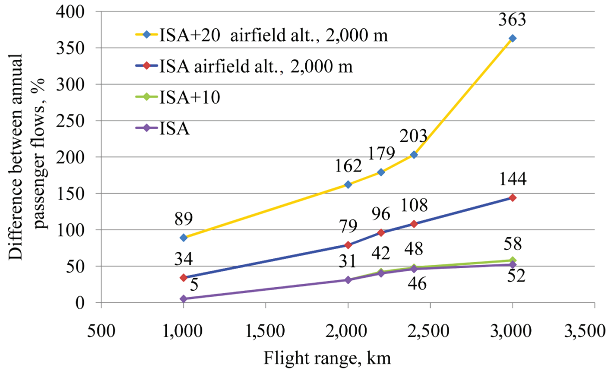

Fig. 14. The difference in the annual passenger flows of the An-158 aircraft equipped with two types of engines in relative terms, depending on atmospheric operating conditions when taking into consideration a take-off distance limit

Fig. 15 shows the comparison of DOC, pass-km, for the An-158 aircraft equipped with the engines D-436-148FM and D-436-148D, depending on the speed flight modes, the percentage of flights under different temperature and altitude operating conditions for the range of 2,400 km.

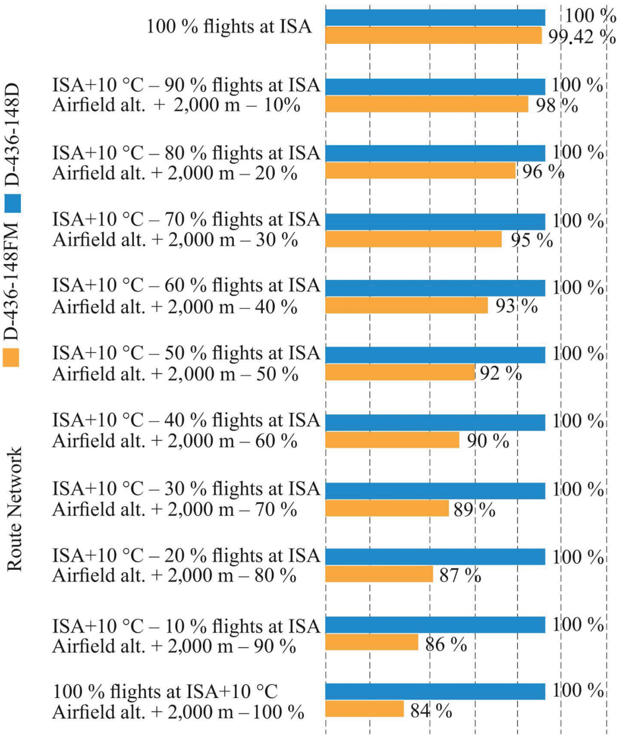

Fig. 15. Comparison of DOC per passenger-kilometer of the An-158 aircraft

We considered conditions of the standard atmosphere (+10 °C) and an airfield altitude along a route network $H_{airfield}$=2,000 m.

8. Discussion of results of studying the aircraft characteristics

Based on the results of our study in to the aircraft performance (Fig. 7, 8), we can argue that the use of the D-436-148FM engines on the An-148-100 and An-158 aircraft leads to an improvement in the take-off characteristics of these types of aircraft compared to the D-436-148D engine. In this case, the aircraft equipped with the engine D-436-148FM has maximum cruising altitudes with two operating engines, exceeding the corresponding characteristics of the aircraft equipped with the engine D-436-148D (Table 2):

– by ~500...600 m – under conditions of SA...SA+5 °C;
– by ~1,100...1,400 m –under conditions of SA+10 °C;
– by ~2,000...2,100 m – under conditions of SA+20 °C.

The aircraft equipped with the D-436-148FM engine has guaranteed ceilings with a single running engine, exceeding the corresponding characteristics of the aircraft equipped with the engine D-436-148D:

– by ~300...600 m – under SA conditions;
– by ~500...750 m –under conditions of SA+10 °C;
– by ~750...1,100 m –under conditions of SA+20 °C.

The An-158 aircraft equipped with the D-436-148FM engine has almost the same range at a cruising speed of 780 km/h (indicator speed) under SA conditions (Fig. 10).

When flying at cruising speeds of 820 km/h (indicator speed) under SA conditions, the advantage in the range of flight with the D-436-148FM engine is 1.3...3.3 %, and under temperature conditions ofSA+10 °C and above reaches

4…7 % (780 km/h, indicator speed), and 9…12 % (820 km/h, indicator speed) (Table 2).

Increasing the maximum takeoff weight of the An-158 aircraft equipped with D-436-148FM engines (Table 1) under conditions of elevated outdoor air temperatures and highlands makes it possible to increase passenger capacity by 30…50 people or increase the range to 1,100…2,100 km.

The comparison of the fuel efficiency of the An-158 aircraft equipped with two types of engines (Table 3) shows that regardless of flight range, temperature, and altitude operating conditions, the An-158 aircraft equipped with D-436-148FM engines has advantages due to lower fuel costs per flight and higher maximum loading.

The comparison of passenger traffic by the An-158 aircraft equipped with two types of engines (Fig. 12, 13) shows the advantage of using the D-436-148FM engines. The aircraft can carry more passengers at all distances and under atmospheric conditions due to the difference in the payload load of the aircraft, from 5 % to 36.3 % (Table 4).

When using the engine D-436-148FM exclusively under the mode of operation «maximum length», working hours before the first and subsequent scheduled visits to the repair shop would increase (Table 5). Under normal operating conditions, by working out 40,000 hours, the number of planned visits to the workshop will be reduced from three to two. The first scheduled visit to the workshop: 12,000–14,000 hours or 4,500–6,000 cycles, the second scheduled visit to the workshop: 25,000–27,000 hours or 10,500–11,500 cycles. This will lead to a 10.4 % reduction in the cost of an engine's flight hour (with a flight cycle of 2 hours) and, as a result, will reduce the DOC value.

The comparative analysis of the operation of the An-158 aircraft equipped with different engines (Fig. 14) shows that DOC per passenger-kilometer for the aircraft equipped with D-436-148FM engines decrease when the temperature of operation increases, and in the high lands, relative to the aircraft equipped with the D-436-148D engines.

Further research into the development of next-generation engines for passenger and transport aircraft needs to separately investigate the extent of integrating aPP with the AC airframe. The new engines would significantly exceed modern design developments in terms of performance. The technologies used in them would be aimed not only at reducing fuel (energy), noise, and emissions but also at reducing all components of the cost of a life cycle.

9. Conclusions

1. We have refined and presented the scientific and methodical apparatus for the formation of the parametric appearance of aPP in the AC. Using a single procedure of studying the performance of the aircraft and the engine, the basic principle of aircraft modernization has been proposed and justified – the installation of the aircraft engine D436-148FM on the An-158-type family of aircraft made by the Antonov State Enterprise. Implementation of this principle would improve fuel efficiency, economic performance, and increase the AC competitiveness.

2. Our analysis of the flight and technical characteristics of aircraft equipped with different engines has shown the advantage of using the engine D436-148FM. When flying at cruising speeds, the advantage in the range of flight is 1.3…3.3 %, and, under temperature conditions of SA+10 °C and above, reaches 4…7 % (780 km/h), and 9…12 % (820 km/h).

3. The change in the practical range of the aircraft equipped with the examined engines has been illustrated by a «cargo-range» diagram. The use of the D-436-148FM engine under various atmospheric conditions provides the An-158 aircraft with the ability to fly approximately 7–12 % more compared to the D-436-148D engines.

4. Based on our investigation of the performance of the engine and the An-158 aircraft, a feasibility study has been carried out to replace the D-436-148D engine with the D-436-148FM as part of the aircraft's PP. The use of a single engine D-436-148FM for the family of AN-1X8 aircraft shows a clear advantage of such modernization. The data obtained demonstrate that, based on placing a single engine D-436-148FM in the PP system of aircraft the type of An-158, it becomes possible to create a competitive family of aircraft of a given type. Such activities could be proposed for practical implementation at the Antonov Company State Enterprise.

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