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THE IMPACT OF PHYSICO-CHEMICAL PROPERTIES OF THE JET FUEL AND BIOFUELS ON THE CHARACTERISTICS OF GAS-TURBINE ENGINES

S. ARDESHIRI[1]
[1]Air Transport Bureau at the International Civil Aviation Organization, Montreal, Canada

ABSTRACT

The current development trend of global civil aviation is the growth of passenger and freight traffic, which entails the consumption of jet fuel. Under these conditions, increasing the efficiency of jet fuel used is of great importance. Global energy consumption is constantly growing, and, first of all, the question of diversification of oil resources arises, resources from which the bulk of motor fuels is produced. Other types of raw energy sources (natural gas, coal, bio-mass) currently account for only a small part. However, an analysis of the development of jet fuels indicates that work is underway to obtain these from other sources of raw materials, especially bio-fuels. Much attention is given to obtaining bio-fuels from renewable sources – such as algae. The issue of the mass transition of civil aviation to alternative fuels is complex and requires the solution of intricate technical as well as economic issues. One of these is the assessment of the impact of new fuels on GTE performance. It is important to give an objective and quick assessment of the use of various types of fuels on the main characteristics of the engine – i.e., throttle and high-speed characteristics. In this case, it is necessary to take into account chemical processes in the chemical composition of new types of fuel. To assess the effect of fuels on the characteristics of a gas turbine engine, it is proposed to use a mathematical model that would take into account the main characteristics of the fuel itself. Therefore, the work proposes a mathematical model for calculating the characteristics of a gas turbine engine taking into account changes in the properties of the fuel itself. A comparison is made of the percentage of a mixture of biofuels and JetA1 kerosene, as well as pure JetA1 and TC-1 kerosene. The calculations, according to the proposed model, are consistent with the obtained characteristics of a gas turbine engine in operation when using JetA1 and TC-1 kerosene. Especially valuable are the obtained characteristics of a gas turbine engine depending on a mixture of biofuel and kerosene. It was found that a mixture of biofuel and kerosene changes the physicochemical characteristics of fuel and affects the change in engine thrust and specific fuel consumption. It is shown that depending on the obtained physicochemical properties of a mixture of biofuel and kerosene, it is possible to increase the fuel efficiency and environmental friendliness of the gas turbine engines used.

Key words: biofuel, kerosene, physical and chemical properties, mathematical model, thrust, specific fuel consumption, throttle and altitude characteristics of the engine.

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INTRODUCTION

The intensive use of civil aviation in passenger and cargo transportation puts forward a demand for increasing the fuel efficiency of aircraft. The use of traditional and new schemes of the aircraft and engine, although increases the efficiency of their application, but it is approaching its maximum limit. It is becoming clear that they can radically improve their performance and reduce CO_2 emissions without the development of new engine configurations and airframe layouts, as well as without the use of alternative fuels[1] [1]. However, alternative fuels, as shown by studies [2], have physicochemical properties that are somewhat different from traditional aviation kerosene. Analysis of research in this area shows that many world airlines are conducting research on the possible use of alternative fuels in gas turbine engines[2] [3–6].

As can be seen, in order to solve the question of the further use of alternative types of fuels, it is necessary to analyse their influence on the characteristics of gas turbine engines and, first of all, high-speed and throttle. Such an analysis can be carried out on the basis of a mathematical model of a power plant taking into account the variable properties of the fuel [7]. Therefore it is necessary to develop a mathematical model that takes into account changes in the parameters of fuel mixtures such as calorific value, heat capacity, saturated vapour pressure, viscosity, etc. This approach allows us to expand the possibility of studying the influence of new types of fuel on the efficiency of their use in gas turbine engines.

FORMULATION OF THE PROBLEM

The main task of mathematical modelling of a gas turbine engine is to calculate its operational characteristics, that is, to determine the thrust and specific fuel consumption under given flight conditions (H and MH) at a given steady-state mode of operation, that is, the parameters of the gas flow at any point in the engine's flow part are taken, unchanged in time. It is assumed that before the start of the simulation, the calculated engine parameters are known. These parameters can be obtained experimentally or by gas-dynamic calculation of the engine, which is included in the mathematical model as an independent module, or are known in advance.

When calculating the operational characteristics of a gas turbine engine, the flight conditions and its operation mode are specified by setting control factors. It is believed that in the configuration of turbofan engines considered below (figure 1) there is only one control factor – i.e., fuel supply to the main combustion chamber (GT). Therefore, using this control factor, only one (controlled) parameter can be controlled, for example: the reduced rotor speed npr; the physical rotor speed n; the gas temperature in front of the turbine T_g^*; and the engine thrust F.

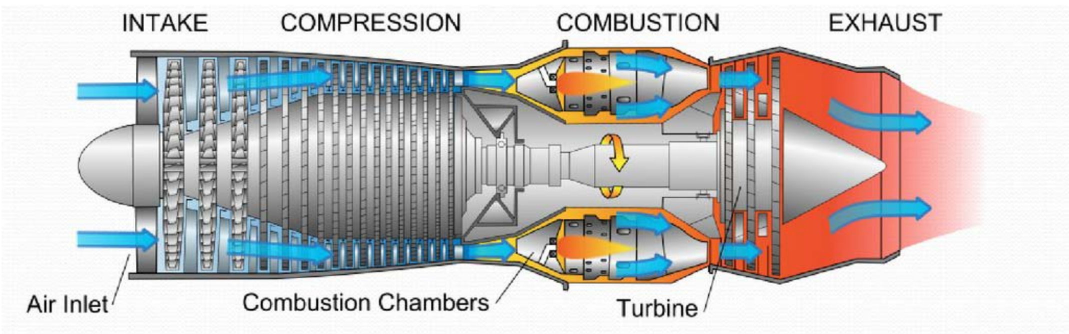

Fig. 1. Scheme of turbojet engine

Since this is an arbitrary choice, it is used in this paper as a managed (modal) physical parameter of selected rotor speed n.

To assess the effect of new fuels on the characteristics of gas turbine engines, a fuel mixture of FT SPK biofuel with JetA1 fuel in the ratio of 50:50, 17% HDO SAK in HEFA SPK was selected as a

[1] ICAO Secretariat. Alternative Fuels. Potential Effects of Alternative Fuels on Local and Global Aviation Emissions ICAO Environmental Report

[2] Alternative aviation fuels. Proceedings of the meeting on international aviation and climate change. ICAO HLM-ENV/09-WP/9.

working fluid and a comparison was made with the obtained characteristics when using pure JetA1 and TC-1 kerosene.

FT SPK biofuel is produced from coal by Fischer-Tropsch synthesis (FT) and is characterized by a low content of aromatic hydrogens and sulfur[3,4].

HDO SAK is a hydro deoxygenated synthesized aromatic kerosene, which consists of approximately 95% mono-aromatic compounds.

HEFA SPK is used to denote biologically active biofuels based on biogenic hydrocarbon raw materials – i.e., a wide range of vegetable oils and fats.

The properties of the working fluid, which is fuel, primarily include the adiabatic exponent k and the gas constant R. In approximate calculations, they can be considered constant, taking the value k = 1.4 for air, and for gas, i.e., mixtures of air and fuel combustion products, – kg = 1.25...1.33. The gas constant for air is taken equal to R = 287.05 J / (kg · K), and for gas – Rg = 287.6 J / (kg · K).

For more accurate calculations, it is recommended to use approximation dependencies. So, the adiabatic exponent for air can be determined by the following formula:

$$k = \frac{(1+1.5\cdot10^{-3}T^{*})}{(0.672+1.2\cdot10^{-3}T^{*})} \tag{1}$$

where T^{*} – is the absolute temperature in the corresponding design section.

To calculate kg, there is a similar expression:

$$k_g = \frac{(1+1.5\cdot10^{-3}T^{*})}{(0.672+1.2\cdot10^{-3}T^{*})} - 0.7g_т + 1.1g_т^2 \tag{2}$$

where the relative amount of fuel consumption g_t in the main combustion chamber is equal to:

$$g_т = \frac{c_p(T_g^{*} - T_к^{*})}{\eta_g H_u} \tag{3}$$

H_u is the calorific value of the fuel. The conditional heat capacity of the heat supply process in the combustion chamber c_p, kJ / (kg · K) is determined by the following formula:

$$C_p = 0.883 + 2.09\cdot10^{-4}(T_g^{*} + 0.48\cdot T_к^{*}) \tag{4}$$

The gas constant can be calculated by the following approximate formula:

$$Rg = 287.05 + 24.5g_т \tag{5}$$

The coefficient taking into account the physical properties of air or gas in any section of the engine and included in the flow rate formula is determined by the expression:

$$m = \sqrt{\frac{k}{R}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \tag{6}$$

When calculating, it is necessary to take into account that the adiabatic exponent and gas constant are substituted into these formulas for air or gas. All expressions given here, with the exception of (3) and (6), are semi-empirical. Their validity was tested for a wide class of tasks.

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3 A new alternative source of fuel for aircraft. Available at: http://spacefacts.ru/news/planet-earth/eco/725-novyy-alternativnyy-istochnik-topliva-dlya-samoletov.html (accessed 09.12.2019).

4 Aviation needs alternative fuels. Available at: http://www.aviaport.ru/news/2012/07/27/238185.html (accessed 09.12.2019).

Given the information above, as the initial data for calculating the effect of new types of fuel on the characteristics of gas turbine engines, the following variable parameters of fuel mixtures were selected:

- H_u – calorific value of the fuel, kJ/kg;
- η_g is the coefficient of heat generation (completeness of combustion);
- c_p – conditional heat capacity of the heat supply process during the combustion of kerosene in air;
- kJ/(kg · K);
- k_g is the adiabatic exponent;
- g_T is the relative fuel consumption in the combustion chamber.

For the studied fuels, these characteristics are summarized in Table 1.

As a rule [8, 9], in the process of operation, mainly 12 basic properties of aviation fuels are used. However, their determination in the Russian Federation and abroad differs by the determination methods and experimental conditions. This complicates their objective comparison. As can be seen from the data presented, the main physicochemical properties of the studied fuels differ from 5 to 8%. However, as will be seen from the calculations, this affects the resulting characteristics of the gas turbine engine.

Table 1

Initial data for the mathematical model of fuels

№ п/п	Fuel grade	H_u, kJ/kg	η_g	k_g	$g_т$	c_p, kJ/(kg · K)
1	JetA1	42800	0.98	1.11	0.02	2.01
2	50% FT SPK в Jet A-1	44200	0.995	1.14	0.0196	1.98
3	TC-1	43000	0.98	1.33	0.031	1.276
4	17% HDO SAK в HEFA SPK	43600	0.99	1.13	0.0198	2.0

PRIMARY PROVISION

The operational characteristics of an aircraft gas turbine engine are the dependencies of thrust and specific fuel consumption on flight conditions and engine operating conditions. The operational characteristics include high-speed and throttle characteristics.

Along the line of limit modes, an engine control program is formed at maximum speed. GTE are usually equipped with on-board systems for measuring parameters such as: n – rotor speed; T_k^* – air temperature at the inlet to the compressor; T_t^* – temperature behind the turbine, by which one can indirectly monitor the temperature in front of the turbine T_g^*. In our case, we do not change the gas turbine engine regulation program, but we only change the characteristics data of the jet fuel used (Table 1).

High-speed characteristics are composite of high-speed and high-altitude characteristics of a gas turbine engine.

Based on the obtained values of thrust and specific fuel consumption, depending on the fuel used, the graphs $P = f(M_H)$ and $C_{ud} = f(M_H)$ are constructed, as shown in Figures 2 and 3.

According to the obtained dependencies (figure 2 and 3), it can be seen that the engine thrust and specific fuel consumption decrease with increasing height when using all types of fuel.

Such changes in traction parameters and specific fuel consumption are associated with a decrease in pressure, temperature and density of atmospheric air with a rise to a specific altitude.

The use of new types of fuel affects the gas turbine engine working process (thrust P and specific fuel consumption) mainly by the heat of combustion of the fuel, as well as the thermo-physical properties of the products of combustion of this type of fuel in the air [10]. We can say that the efficiency of a gas turbine engine, in this case, will depend on the energy capabilities of the type of fuel used, which is confirmed by the obtained dependencies of thrust and specific fuel consumption.

As can be seen from Figure 3, at the beginning (with M_H = 0), the specific fuel consumption has the lowest value when P_{ud} has a maximum value, then, with a decrease in specific thrust, the specific fuel consumption increases.

From the foregoing, it is clear that the operation of the engine is advantageous at altitudes of about 11 km, since at these altitudes the specific fuel consumption is the lowest, which characterizes the efficiency of the engine.

Let now analyse the data obtained at these altitudes. As can be seen from Figure 2 and 3, the propulsion system has slightly higher thrust when using Jet A-1 kerosene and a mixture of 17% HDO SAK in HEFA SPK. Slightly lower with 50% FT SPK in Jet A-1. However, the lowest specific fuel consumption was obtained using a mixture of 50% FT SPK in Jet A-1.

As mentioned above, the performance of a gas turbine engine depends on the physicochemical properties of the fuels used. The calculated design characteristics of gas turbine engines are also confirmed by comparing the properties of the studied fuels (Table 2) [11].

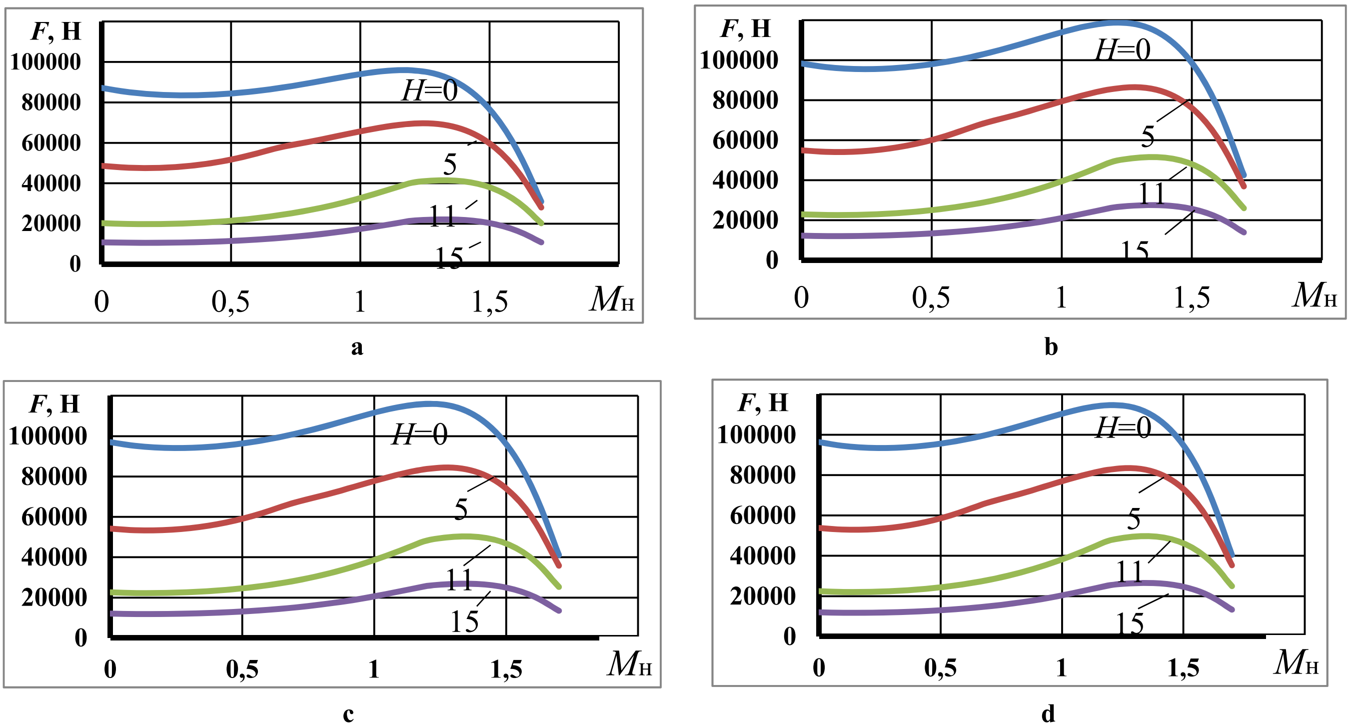

Fig. 2. Dependence of engine thrust on flight speed at different heights when using jet fuel:
a) TS-1; b) JetA1; c) 17% HDO SAK in HEFA SPK; d) 50% FT SPK Jet A-1

Table 2

Comparative data of kerosene and biofuel quality indicators

Fuel characteristics	TC-1	Jet A-1	50% FT SPK в Jet A-1	17% HDO SAK в HEFA SPK
net calorific value, MJ / kg	43.2	43,1	43.6	43.6
volumetric heat of combustion, $MJ/m^3 \cdot 10^3$	33.9	35,1	34.3	33.8
hydrogen content, %	14.0	13,7	15.0	14.43
carbon content, %	86.0	86,1	85.0	85.54
hydrogen / carbon ratio	0.16	0,16	0.18	0.17

Thus, the data obtained allow us to conclude that the use of a mixture of biofuel with kerosene allows under conditions not to reduce the thrust of the gas turbine engine, while reducing the specific fuel consumption. In addition, a change in the percentage of biofuels and kerosene can affect the take-off-speed and throttle characteristics of a gas turbine engine.

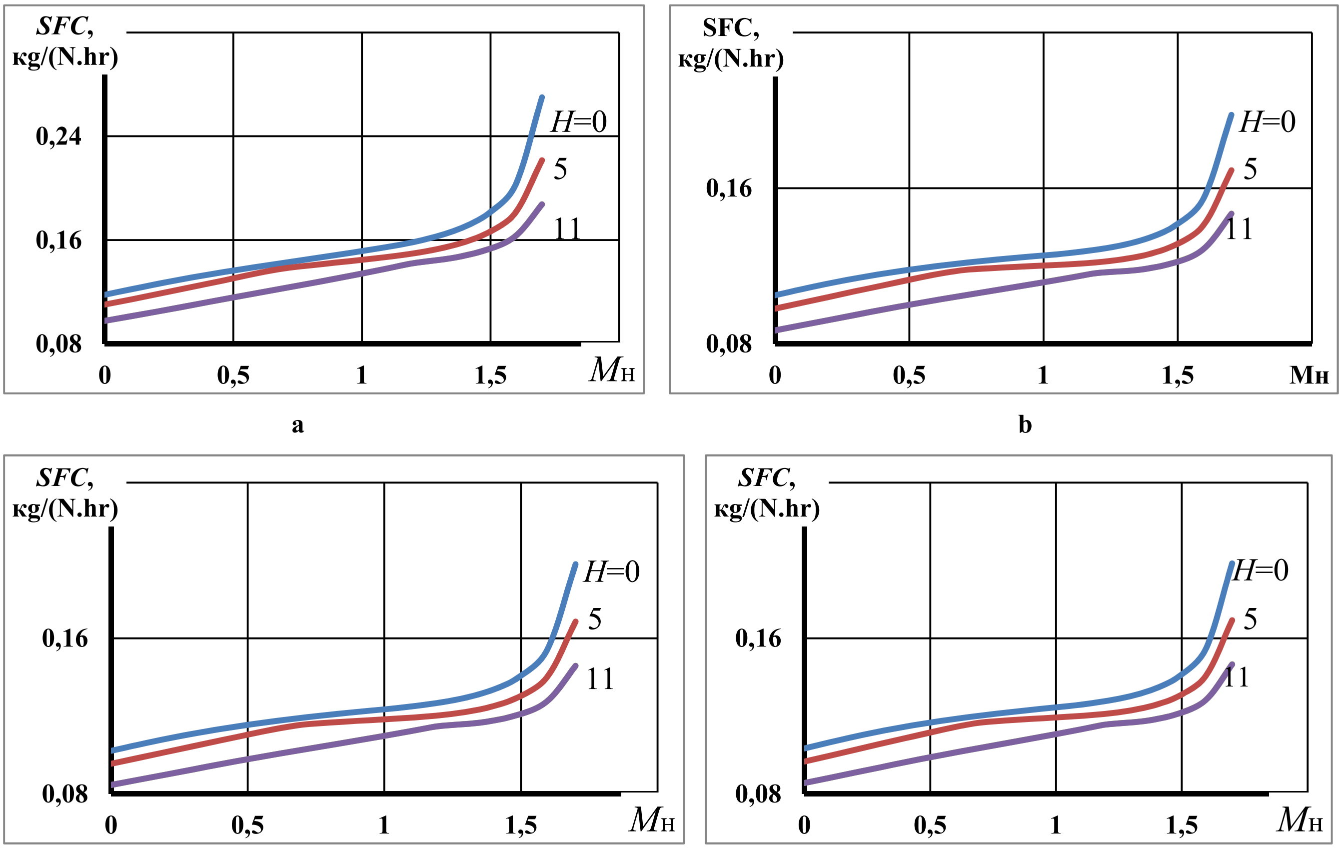

Fig. 3. Dependence of specific fuel consumption on flight speed at different heights in the application including Arctic marks: a) TS-1; b) JetA1; c) 17% HDO SAK in HEFA SPK; d) 50% FT SPK Jet A-1

CONCLUSION

1. A mathematical model has been developed for calculating the characteristics of gas turbine engines depending on the physicochemical properties of jet fuel.

2. The throttle and high-speed characteristics of gas turbine engines obtained by using a mixture of biofuel with kerosene in various proportions were calculated.

3. The reliability of the results is consistent with the results of the throttle and altitude-speed characteristics of the gas turbine engine when using massively used brands of kerosene JetA1 and TC-1.

4. It was found that the use of a mixture of biofuels and JetA1 kerosene allows to obtain higher characteristics of a gas turbine engine.

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INFORMATION ABOUT THE AUTHOR

Ardeshiri Shadi, Junior Research Fellow, Air Transport Bureau at the International Civil Aviation Organization (ICAO), shadiardeshiri@gmail.com.

ВЛИЯНИЕ ФИЗИКО-ХИМИЧЕСКИХ СВОЙСТВ КЕРОСИНА И БИОТОПЛИВ НА ХАРАКТЕРИСТИКИ ГАЗОТУРБИННЫХ ДВИГАТЕЛЕЙ

Ш. Ардешири[1]
[1]Авиатранспортное бюро в Международной организации гражданской авиации (ИКАО), Монреаль, Канада

Современной тенденцией развития мировой гражданской авиации является рост пассажирских и грузовых перевозок, что влечет потребление авиакеросина. В этих условиях важное значение приобретает повышение топливной эффективности применяемого авиатоплива. Мировое потребление энергоресурсов непрерывно возрастает, и прежде всего встает вопрос о диверсификации ресурсов нефти, из которой производится основная доля моторных топлив, на другие виды сырья (природный газ, уголь, биомассу) в настоящее время приходится только незначительная часть объема производства. Однако анализ развития авиатоплив свидетельствует, что интенсивно ведутся работы по получению авиатоплив из других источников сырья, и особенно биотоплива. Большое внимание уделяется получению биотоплива из восстанавливаемых источников – водорослей. Проблема массового перехода гражданской авиации на альтернативные виды топлива является сложной и требует решения комплексных как технических, так и экономических вопросов. Одним из таких вопросов является оценка влияния новых видов топлива на служебные характеристики ГТД. Важно дать объективную и быструю оценку влияния применения различных видов топлив на основные характеристики двигателя – дроссельную и высотно-скоростные. При этом необходимо учитывать сложные химические процессы в химмотологической системе новых видов топлива. Для оценки влияния топлив на характеристики ГТД предлагается применить математическую модель, которая бы учитывала основные характеристики самого топлива. Поэтому в работе предложена математическая модель расчета характеристик ГТД с учетом изменения свойств самого топлива. Проведено сравнение процентного соотношения смеси биотоплива и керосина JetA1, а также чистых керосинов JetA1 и ТС-1. Данные расчеты по предложенной модели согласуются с получаемыми характеристиками ГТД в эксплуатации при использовании керосинов JetA1 и ТС-1. Особенно ценным являются полученные характеристики ГТД в зависимости от смеси биотоплива и керосина. Установлено, что смесь биотоплива и керосина изменяет физико-химические характеристики топлива и влияет на изменение тяги двигателя и удельного расхода топлива. Показано, что в зависимости от получаемых физико-химических свойств смеси биотоплива и керосина можно повысить топливную эффективность и экологичность применяемых ГТД.

Ключевые слова: биотопливо, керосин, физико-химические свойства, математическая модель, тяга, удельный расход топлива, дроссельная и высотная характеристики двигателя.

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СВЕДЕНИЯ ОБ АВТОРЕ

Ардеширн Шади, младший научный сотрудник, Авиатранспортное бюро в Международной организации гражданской авиации (ИКАО), Монреаль, Канада, shadiardeshiri@gmail.com.

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