Determination of specific fuel consumption of air-breathing engines is one of the problems of modeling their performance. As a rule, the estimation error of the specific fuel consumption while calculating air-breathing engine performance is greater than that of thrust. In this work, this is substantiated by the estimation error of the fuel-air ratio, which weakly affects thrust but significantly affects the specific fuel consumption. The presence of a significant error in the fuel-air ratio is explained by the use of simplified methods, which use the dependence of enthalpy as a function of mixture temperature and composition without taking into account the effect of pressure. The developed method to improve the calculation accuracy of specific fuel consumption of air-breathing engines is based on the correction of the fuel-air ratio in the combustor, determined by the existing mathematical models. The correction of the fuel-air ratio is made using the dependences of enthalpy on mixture temperature, pressure and composition. The enthalpy of the mixture is calculated through the average isobaric heat capacity obtained by integrating the isobaric heat capacity, depending on mixture temperature, pressure and composition. The calculation accuracy of the fuel-air ratio was verified by comparing it with the known experimental data on the combustion chamber of the General Electric CF6-80A engine (USA). The average calculation error of the fuel-air ratio does not exceed 3 %. The developed method was applied for correcting the specific fuel consumption for calculating the altitude-airspeed performance of the D436-148B turbofan engine (Ukraine), which made it possible to reduce the estimation error of the fuel-air ratio and specific fuel consumption to an average of 3 %

Keywords: fuel-air ratio, specific fuel consumption, combustor, isobaric heat capacity, air-breathing engine

DEVELOPMENT OF A METHOD TO IMPROVE THE CALCULATION ACCURACY OF SPECIFIC FUEL CONSUMPTION FOR PERFORMANCE MODELING OF AIR-BREATHING ENGINES

Oleh Kislov
PhD, Associate Professor*
E-mail: o.kislov@khai.edu

Maya Ambrozhevich
PhD, Associate Professor
Department of Aerospace Heat Engineering**
E-mail: ambrozhevichmaya@gmail.com

Mykhailo Shevchenko
Postgraduate Student*
E-mail: mikleshevchenko@gmail.com
*Department of Aviation Engines Theory
National Aerospace University "Kharkiv Aviation Institute"
Chkalova str., 17, Kharkiv, Ukraine, 61070

1. Introduction

Mathematical modeling of processes and performance of air-breathing engines is widely used for their designing. Mathematical models have different levels of process detailing. The classification of the mathematical models of air-breathing engines is presented in [1]. First-level mathematical models are used to calculate the performance of air-breathing engines, in which the flow in the gas path is one-dimensional, losses are taken into account by coefficients, and the performance of the nodes is represented by zero-level models. Such models provide an acceptable accuracy of calculating the air-breathing engine performance. The estimation error of the specific fuel consumption c_R is usually much greater than that of thrust [2, 3].

This fact is explained by the calculation error of the fuel-air ratio q_f. The value of error q_f weakly affects thrust R and specific thrust R_s, but significantly affects the estimation error of c_R since

$$c_R = \frac{3{,}600 \cdot q_f}{R_s}.$$ (1)

The weak influence of the error q_f on R and R_s is due to the fact that c_R has the same-order error as q_f, and the other parameters have a 1–2 orders smaller error. So, for example, even with a 10 % estimation error of q_f, the estimation error of G_g is 0.1...0.3 %.

Therefore, the problem of increasing the calculation accuracy of c_R can be reduced to the problem of increasing the calculation accuracy of q_f without recalculating other parameters of the air-breathing engine.

Thus, the problem of calculating the performance of air-breathing engines can be solved by the mathematical models of air-breathing engines, using a simplified dependence of the gas enthalpy on the temperature and composition of the mixture, with subsequent correction of q_f and c_R values. The q_f correction is carried out using the gas enthalpy dependences on the mixture temperature, pressure and composition.

2. Literature review and problem statement

Since the calculation accuracy of c_R depends on the calculation accuracy of q_f, it is necessary to consider methods for determining q_f and choose the most rational one.

In the mathematical modeling of air-breathing engine performance, q_f is determined by the enthalpies of the working fluid at the inlet and outlet of the combustion chamber.

Enthalpy is a function of state, and the state of a single-phase gas is determined by two thermodynamic parameters. The enthalpy of a gas mixture depends on the chemical composition and two thermodynamic parameters. Traditionally, for performance modeling of air-breathing engines, the enthalpy of the working fluid is calculated as a function of the chemical composition of the working fluid and one thermodynamic parameter – temperature. The work [4] presents the polynomials for calculating the isobaric heat capacity c_p as a function of temperature only. The products of fuel combustion in [4] are a mixture of combustion products with the stoichiometric ratio of excess air components. The disadvantage of this approach is the reduced calculation accuracy, since the presence of water vapor, argon, dissociation of combustion products and the dependence of c_p on pressure are not taken into account in the combustion products. In [5], the influence of engine operating parameters on performance was investigated. The heat capacities of gases were set by the fourth-degree temperature polynomials. The calculations in [5] were performed for the temperatures at which thermal dissociation has a significant effect, but the dissociation was not taken into account. In [6], a thermodynamic analysis of a gas turbine engine (GTE) with an evaporative air cooler at the compressor inlet was carried out. The heat capacities of gases were set by the fourth-degree temperature polynomials and water vapor enthalpy – by a linear dependence. The calculation results are not verified. In [7], a method for calculating the efficiency of a GTE with high cycle parameters is presented, but the working fluid was assumed to be an ideal gas. In [8], the correlation of R with combustor parameters was performed. The heat capacity and the adiabatic index of air and combustion products were set constant. This approach gives high errors in engine performance modeling. In [9], an advanced study of the effect of detonation combustion on gas turbine characteristics was carried out. In this work, c_p of combustion products was modeled by the fourth-degree temperature polynomial. The influence of pressure (reaching 3 MPa) and thermal dissociation (outlet temperature of the combustion chamber $T>1,600$ K) also was not taken into account. In [10], a study of the influence of the variable inlet guide vane and air cooling at the compressor inlet on the GTE performance is carried out. The specific isobaric heat capacity of the air components and combustion products is represented by the second-degree temperature polynomials. The advantage of [10] is that air and combustion products are presented as a mixture of individual components. The disadvantage of this work is the modeling of the heat capacity of the components by the second-degree temperature polynomial. In [11], a comparison of GTE operating on natural gas and biofuel was made. The specific isobaric heat capacity of gases was modeled by the fourth-degree polynomial as in [5]. Energy conversion in a turboshaft engine was studied in [12]. The thermophysical properties of the working fluid are represented by the third-degree temperature polynomials at a fixed pressure of 1 bar. In [13], a methodology was developed for the experimental determination and computation of efficiency indicators of the main combustion chambers of GTE based on the results of their autonomous tests on a chamber stand. The advantage of [13] is the presence of an experiment and verification based on it. The influence of air humidity was taken into account for calculating combustion efficiency. The combustion efficiency was calculated by the Il'ichev equation [14], which significantly reduces the calculation accuracy. In [15], a methodology for estimating c_R of a turbofan engine was developed. The polynomial dependences of thermophysical parameters as a function of temperature at constant pressure according to [16] were used for calculating c_R. As mentioned above, this approach leads to a decrease in calculation accuracy. The simplifications made in [4–16] are valid for an ideal gas; however, modern air-breathing engines are characterized by high pressure ratio and temperatures [17], which leads to the dissociation of molecules. Dissociation changes the ratio between enthalpy and temperature, therefore, disregarding dissociation leads to estimation errors of the gas enthalpy [18]. Dissociation depends not only on temperature, but also on gas pressure; therefore, to take it into account correctly, it is necessary to determine the enthalpy as a function of two thermodynamic parameters (temperature and pressure).

In [19], a mathematical model for GTE performance modeling in real time is presented. The thermophysical properties of the working fluid take into account the chemical composition and are functions of temperature and pressure. The polynomials of the thermodynamic parameters were taken from the software package [20]. The main disadvantage is the neglect of the effect of thermal dissociation on the heat capacity and enthalpy of combustion products. This is due to the fact that polynomials [20] do not take into account dissociation. In [21], the approach to modeling thermophysical properties is similar to [19], using the software package [22].

The dissociation of combustion products can be taken into account by two methods. The first method requires solving a system of chemical kinetics equations with a large number of equations [23, 24]. In [23], the system consists of 17 equations and in [24] – 206 equations. The second method uses experimental values of c_p as a function of temperature and pressure.

In [25], dependencies of c_p of gases as a function of temperature and pressure taking into account the effect of thermal dissociation, obtained by approximating experimental data were proposed. These dependencies can be used to determine the enthalpy of combustion products in the combustion chamber of air-breathing engines in the form of $h(T, p, q_f)$.

Thus, only in some mathematical models of air-breathing engines and GTE, q_f is calculated using the dependencies of enthalpy $h(T, p, q_f)$ [19, 21], and in most mathematical models, q_f is calculated using the dependencies of enthalpy on the temperature and composition of the mixture without taking into account the effect of pressure $h(T, q_f)$ [4–16]. Therefore, for models where q_f is calculated using $h(T, q_f)$, it is necessary to correct the q_f value using $h(T, p, q_f)$.

3. The aim and objectives of the study

The aim of the work is to develop and substantiate the method to improve the calculation accuracy of c_R of air-breathing engines by calculating q_f via $h(T, p, q_f)$, obtained using the dependencies $c_p(T, p)$ of gases. This allows, without increasing the level of the mathematical model of the air-breathing engine, increasing the calculation accuracy of engine performance.

To achieve the aim, the following objectives were set:

– to develop a method for calculating c_R using the calculation results of mathematical models of air-breathing engines where q_f is determined via $h(T, q_f)$ followed by correcting q_f via $h(T, p, q_f)$;

– to develop a method for calculating q_f using the dependences of enthalpy $h(T, p, q_f)$ obtained using the dependences $c_p(T, p)$ for individual gases;

– to verify the mathematical model for calculating q_f by comparing it with the known experimental data of combustion chambers;

– to evaluate the influence of correcting q_f via $h(T, p, q_f)$ on the calculation accuracy of c_R by comparison with the known experimental data.

4. Materials and methods of the study

The study uses theoretical methods and mathematical modeling of gas-dynamic processes in air-breathing engines and GTE.

The main hypothesis of the study is that the estimation error of q_f has a negligible effect on all parameters of air-breathing engines and GTE except for c_R.

The second hypothesis of the study is that the estimation error of q_f is caused by using the simplified dependence $h(T, q_f)$, which does not take into account the effect of pressure.

The study was carried out in the following sequence. Initially, the method for calculating c_R using the calculation results of the mathematical model based on the simplified dependence $h(T, q_f)$ and the results of correcting the q_f and c_R values via $h(T, p, q_f)$ was developed.

Correction of q_f requires the development of the mathematical model of $h(T, p, q_f)$. This model was developed based on the dependencies $c_p(T, p)$ of individual gases of the known chemical composition at the inlet of the combustion chamber. In this case, the combustion products are considered as a mixture of complete oxidation products, which are attributed to the real c_p values obtained experimentally. These c_p values correspond to the actual chemical composition of the oxidation products, containing the dissociation products of molecules.

The model developed for calculating q_f based on $h(T, p, q_f)$ was verified by comparing q_f with the known experimental data of the combustion chamber of a General Electric CF6-80A engine [26, 27] and by comparing the obtained values of $c_R=f(H, M_h)$ with the experimental data of the D436-148B engine [28].

5. Method to improve the calculation accuracy of specific fuel consumption

5. 1. Method for correcting specific fuel consumption

The initial data for the method to improve the calculation accuracy of the fuel-air ratio are the results of the calculation by the first-level mathematical models using the enthalpy dependence $h(T, q_f)$.

In particular, the inlet and outlet pressures and temperatures of the air-breathing engine combustor, air flow and combustion coefficient are considered known.

The fuel-air ratio is a definable quantity, so its value, obtained by calculation using the first-level mathematical models is the first approximation, which is then refined by an iterative procedure.

At each iteration, the enthalpies of the gas mixture at the inlet and outlet of the combustor are determined from the known mixture composition, temperatures and pressures, and then q_f is determined from the combustor heat balance equation.

The resulting value of q_f is the initial approximation for the next iteration. The iteration procedure stops when the change of q_f becomes less than a small predetermined value.

The corrected c_R is determined by equation (2), which uses the corrected value of the fuel-air ratio q_{fc}.

5. 2. Method for calculating the fuel-air ratio

If the type of fuel is known, the required stoichiometric amount of air L_o can be calculated based on chemical oxidation reactions. The stoichiometric amount of wet air for the complete combustion of 1 kg of kerosene of a given composition is determined by the chemical oxidation reactions
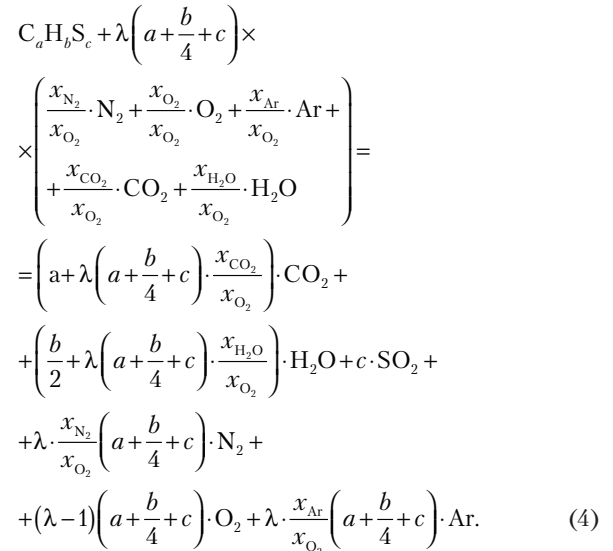
$$\begin{cases} C + O_2 = CO_2; \\ H + \dfrac{1}{4}O_2 = \dfrac{1}{2}H_2O; \\ S + O_2 = SO_2, \end{cases} \tag{2}$$

and by

$$L_0 = \left(\frac{g_C}{\mu_C} + \frac{1}{4}\frac{g_H}{\mu_H} + \frac{g_S}{\mu_S} \right)\frac{\mu_{O_2}}{g_{O_2}}, \tag{3}$$

where g_i – mass fraction of the component; μ, kg/kmol – molar mass of the component.

The chemical combustion reaction of kerosene of the conditional formula $C_aH_bS_c$ with an excess of oxidant λ can be represented by equation (4).

$$C_aH_bS_c + \lambda\left(a + \frac{b}{4} + c\right) \times$$

$$\times \left(\begin{array}{l} \dfrac{x_{N_2}}{x_{O_2}}\cdot N_2 + \dfrac{x_{O_2}}{x_{O_2}}\cdot O_2 + \dfrac{x_{Ar}}{x_{O_2}}\cdot Ar + \\ + \dfrac{x_{CO_2}}{x_{O_2}}\cdot CO_2 + \dfrac{x_{H_2O}}{x_{O_2}}\cdot H_2O \end{array} \right) =$$

$$= \left(a + \lambda\left(a + \frac{b}{4} + c\right)\cdot\frac{x_{CO_2}}{x_{O_2}} \right)\cdot CO_2 +$$

$$+ \left(\frac{b}{2} + \lambda\left(a + \frac{b}{4} + c\right)\cdot\frac{x_{H_2O}}{x_{O_2}} \right)\cdot H_2O + c\cdot SO_2 +$$

$$+ \lambda\cdot\frac{x_{N_2}}{x_{O_2}}\left(a + \frac{b}{4} + c\right)\cdot N_2 +$$

$$+ (\lambda - 1)\left(a + \frac{b}{4} + c\right)\cdot O_2 + \lambda\cdot\frac{x_{Ar}}{x_{O_2}}\left(a + \frac{b}{4} + c\right)\cdot Ar. \tag{4}$$

Denoting

$$\chi = \lambda\frac{\left(a + \dfrac{b}{4} + c\right)}{x_{O_2}}, \tag{5}$$

rewrite equation (4) as

$$C_a H_b S_c + \chi \begin{pmatrix} x_{N_2} \cdot N_2 + x_{O_2} \cdot O_2 + x_{Ar} \cdot Ar + \\ + x_{CO_2} \cdot CO_2 + x_{H_2O} \cdot H_2O \end{pmatrix} =$$

$$= \left(a + \chi \cdot x_{CO_2}\right) \cdot CO_2 + \left(\frac{b}{2} + \chi \cdot x_{H_2O}\right) \cdot H_2O + c \cdot SO_2 +$$

$$+ \chi \cdot x_{N_2} \cdot N_2 + \left(1 - \frac{1}{\lambda}\right) \cdot \chi \cdot x_{O_2} \cdot O_2 + \chi \cdot x_{Ar} \cdot Ar. \tag{6}$$

Equation (6) is an expression of the mass conservation law. The energy conservation law for this reaction is as follows

$$G_f \cdot h_f^* + G_{air} \cdot h_{air}^* + G_f \cdot H_u = \left(G_f + G_{air}\right) h_g^*, \tag{7}$$

where h_f^* and h_{air}^*, kJ/kg – specific enthalpy of fuel and air at the inlet temperature and pressure of the combustor;

h_g^*, kJ/kg – specific enthalpy of combustion products at the outlet temperature and pressure of the combustor;

H_u, kJ/kg – specific lower calorific value for fuel with known composition and can be calculated using the Mendeleev equation

$$H_u = \left(338 \cdot g_C + 1{,}025 \cdot g_H + 108 \cdot g_S\right) \cdot 100. \tag{8}$$

Insofar as

$$q_f = \frac{G_f}{G_{air}}, \tag{9}$$

$$q_f \cdot h_f^* + h_{air}^* + q_f \cdot H_u = \left(1 + q_f\right) h_g^*. \tag{10}$$

Taking into account fuel combustion efficiency η_g

$$q_f \cdot h_f^* + h_{air}^* + q_f \cdot \eta_g \cdot H_u = \left(1 + q_f\right) h_g^*, \tag{11}$$

from (11)

$$q_f = \frac{h_g^* - h_{air}^*}{H_u \cdot \eta_g - \left[h_g^* - h_f^*\right]}, \tag{12}$$

considering [14]

$$h_f^* \approx h_{air}^*,$$

equation (12) after transformations takes the following form

$$q_f = \frac{1}{\dfrac{H_u \cdot \eta_g}{h_g^* - h_{air}^*} - 1}. \tag{13}$$

According to equation (13), q_{fc} is determined using the iterative procedure.

The specific enthalpy of combustion products at the combustor outlet is determined as

$$h_g^* = \sum_{i=1}^{6} g_i h_i^*, \tag{14}$$

$$\Delta h_i^* = c_{p_{aa_i}} \cdot \left(T_i^* - T_0\right) = \frac{1}{p_i - p_0} \int_{p_0}^{p_i} \left(\int_{T_0}^{T_i^*} c_p(T, p) \, dT\right) dp, \tag{15}$$

where $c_{p_{aa_i}}$, kJ/kgK – average integral value of the heat capacity in a given range of temperatures from T_0 to T_i^* and pressures from p_0 to p_i;

T_i^*, K – outlet temperature T_{ex}^* or inlet temperature T_{in}^* of the combustor;

$T_0 = 298$ K – temperature taken as the basic one in the problems of thermochemistry, for which the standard enthalpies of substances formation are known;

p_i and p_0 – partial pressures of the mixture components at the end and at the beginning of the integration process.

Partial pressures are determined through molar fractions of the components

$$p_i = \sum_{i=1}^{n} x_i \cdot p_{mix}, \tag{16}$$

where x_i – molar fraction, p_{mix} – mixture pressure.

The heat capacities for mixtures of air and combustion products are determined using the inlet and outlet partial pressures and temperatures of the combustion chamber

$$c_{p_{aa.mix_i}} = \sum_{i=1}^{n} x_i \cdot c_{p_{aa_i}}. \tag{17}$$

The equations $c_{pa} = f(T, p)$ for the main components of air and combustion products for hydrocarbon fuels, which are united throughout the specified pressure and temperature range (nitrogen $p=0.1...200$ bar, $T=150...2{,}870$ K; oxygen: $p=1...200$ bar, $T=210...2{,}870$ K; argon: $p=1...200$ bar, $T=190...1{,}300$ K; water vapor: $p=0.1...200$ bar, $T=700...2{,}600$ K; carbon dioxide: $p=1...200$ bar, $T=390...2{,}600$ K) are obtained in [29], based on the results of [25]. The specific heat capacity averaged both by pressure and temperature can be obtained by integrating $c_{pa} = f(T, p)$ by pressure.

For nitrogen and oxygen with a linear dependence of heat capacity on pressure, which is characteristic of low-boiling components, after transformations, the formula is as follows

$$c_{p_{aa}} = \frac{1}{T_2 - T_1} \begin{pmatrix} \displaystyle\sum_{i=0}^{6} \frac{f_i}{i+1}\left(T_2^{i+1} - T_1^{i+1}\right) + \\ + \alpha\left(\dfrac{p_2 + p_1}{2} - 1\right) \times \\ \times \displaystyle\sum_{i=0}^{6} \frac{f_i}{i - \beta + 1}\left(T_2^{i-\beta+1} - T_1^{i-\beta+1}\right) \end{pmatrix}, \tag{18}$$

where f_i, α, β – coefficients obtained for nitrogen and oxygen in [29]; T_1 and T_2 – initial and final process temperature.

A similar linear dependence is also used for argon

$$c_{p_{aa}} = \frac{1}{T_2 - T_1} \sum_{i=0}^{6} \frac{f_i + \left(\dfrac{p_2 + p_1}{2}\right) \cdot g_i}{i+1}\left(T_2^{i+1} - T_1^{i+1}\right), \tag{19}$$

where f_i, g – coefficients obtained and presented for argon in [29].

However, taking into account the low partial pressures of argon in the gas mixture, the average heat capacity of argon can be taken as for ideal gas $c_{p_{aa}} = c_p^{ig} = 0.52043 \dfrac{kJ}{kg \cdot K}$ [29].

For carbon dioxide and water vapor

$$c_{p_{aa}} = \frac{1}{T_2 - T_1} \frac{1}{p_2 - p_1} \sum_{j=0}^{n} \frac{\displaystyle\sum_{i=0}^{k} \frac{h_{ij}}{i+1} p^{i+1}}{j+1} T^{j+1}, \tag{20}$$

where h_{ij} – tensor coefficients presented in [29].

However, the tensor coefficients obtained in [29] are inapplicable for low partial pressures of water and carbon dioxide in the air at the combustor inlet. Therefore, instead of them, according to the method presented in [25], new values of tensor coefficients were obtained, which are applicable for water in the range $p=0...10$ bar and $T=273...1,000$ K and for carbon dioxide – $p=0...20$ bar, $T=273...1,800$ K. Tensor coefficients are presented in Tables 1, 2, respectively.

<div style="text-align:right">Table 1</div>

Coefficients h_{ij} of equation (20) for H_2O

j \ i	0	1	2	3	4	5	6
0	2.7896E+00	−9.5510E−03	3.7834E−05	−7.4897E−08	8.2591E−11	−4.7814E−14	1.1338E−17
1	2.2589E+01	−1.9772E−01	7.1427E−04	−1.3603E−06	1.4392E−09	−8.0175E−13	1.8377E−16
2	−3.4763E+00	3.2423E−02	−1.2314E−04	2.4417E−07	−2.6702E−10	1.5292E−13	−3.5875E−17
3	3.6385E−01	−3.2489E−03	1.1904E−05	−2.2910E−08	2.4436E−11	−1.3702E−14	3.1571E−18

<div style="text-align:right">Table 2</div>

Coefficients h_{ij} of equation (20) for CO_2

j \ i	0	1	2	3
0	4.90071E−01	1.45536E−03	−9.26739E−07	−1.00972E−11
1	1.23678E−02	−3.65356E−05	3.41481E−08	−1.00972E−11
2	5.36017E−04	−1.85784E−06	1.90531E−09	−5.94961E−13

The average isobaric heat capacity of sulfur dioxide was taken as a function of temperature [30]

$$c_{p_a}(T) = 1.267996 \cdot 10^{-10} \cdot T^3 -$$
$$-5.496533 \cdot 10^{-7} \cdot T^2 +$$
$$+9.836367 \cdot 10^{-4} \cdot T + 0.5434028. \quad (21)$$

This assumption is valid because the low partial pressures of sulfur dioxide in the combustion products make SO_2 almost an ideal gas.

5. 3. Verification of the method for calculating the fuel-air ratio

Verification of the method was carried out by comparing the calculation results with the results of experimental tests of the combustor of the CF6-80A engine for various operating conditions [26].

The test results of the combustor running on aviation kerosene for various engine operating conditions are presented in Table 3.

<div style="text-align:right">Table 3</div>

Sector combustor operating conditions [26]

Conditions	Combustor inlet			Average outlet temperature, K	Combustion efficiency, %	Fuel flow (aviation kerosene, g/s
	Temperature, K	Pressure, MPa	Airflow, kg/s			
Approach, 30 % thrust	614	1.102	7.09	1,039	99.8	93.9
Climb	772	2.426	13.42	1,339	99.9	282.6
Takeoff	805	2.789	15.02	1,482	99.8	343.1
Minimum Cruise	608	0.621	3.96	985	99.9	55.6
Normal Cruise	686	0.936	5.49	1,207	99.9	100.8
Maximum Cruise	726	1.132	6.4	1,286	99.9	130.4

The total pressure losses of the combustor are taken from [27].

In the calculation, aviation kerosene of the generalized formula $C_{7.15}H_{14.6}S_{0.00628}$ was used as fuel (Table 1, mass fraction of sulfur according to ASTM D1655-20d [31] must not exceed 0.3 %). The molar mass of such a kerosene molecule is 100.79 kg/kmol. Its elemental composition is presented in Table 4.

Atmospheric air is presented as a mixture of gases in Table 5.

The fuel-air ratio was calculated in three ways:

– using the developed calculation method based on the enthalpy $h(T, p, q_f)$, calculated using the temperature and pressure averaged specific isobaric heat capacity $c_{paa}(T, p, q_f)$;

– using the developed calculation method based on the enthalpy $h(T, p, q_f)$, calculated using the specific isobaric heat capacity $c_{pa}(T, p, q_f)$, determined by averaging over temperature at constant pressure. The pressure value corresponded to the inlet conditions of the combustion chamber;

– using the calculation method presented in [32]. This method uses the enthalpy dependence $h(T, q_f)$.

<div style="text-align:right">Table 4</div>

Chemical composition of aviation kerosene

Component	Molar fraction n_i	Mass fraction g_i
Carbon C	0.328641	0.852045
Hydrogen H	0.671070	0.145955
Sulfur S	0.000289	0.002000

<div style="text-align:right">Table 5</div>

Chemical composition of atmospheric air*

Component	Chemical formula	Molar fraction x_i	Mass fraction g_i
Nitrogen	N_2	0.768484	0.747711
Oxygen	O_2	0.206161	0.229120
Argon	Ar	0.009217	0.012788
Carbon Dioxide	CO_2	0.000314	0.000480
Water	H_2O	0.015824	0.009901

*Note: *$p_{atm}=101,325$ Pa; $t_{atm}=27$ °C; $d=10$ g/kg of dry air, molar mass of wet air is 28.792 kg/kmol*

The relative calculation error of q_f was calculated by the equation

$$\delta q_f = \frac{(q_f)_{calculated} - (q_f)_{test}}{(q_f)_{test}} 100 \%, \quad (22)$$

where $(q_f)_{calculated}$ – calculated fuel-air ratio; $(q_f)_{test}$ – experimental fuel-air ratio.

Comparison of the calculation results with the experimental data is shown in Fig 1.
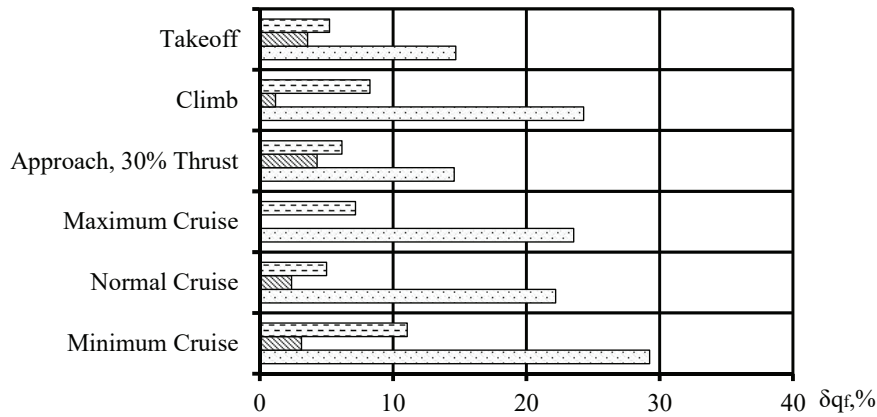
Fig. 1. Comparison of calculation results with experimental data: ▨▨▨ — relative calculation error taking into account temperature and pressure changes $c_{pad}(T, p, q_f)$; ⌐-----⌐ — relative calculation error taking into account the temperature change at constant pressure, corresponding to the inlet conditions of the combustion chamber $c_{pa}(T, p, q_f)$; ⌐·······⌐ — relative calculation error using dependencies $h(T, q_f)$

Fig. 1 shows that the average relative calculation error:

– using the values of enthalpies $h(T, q_f)$ [32] is $\delta q_f = 14...29\ \%$;

– using the enthalpies calculated by the temperature-averaged specific heat c_{pa}, at constant pressure, according to the formula

$$h(T) = h_0(T_0) + \int_{T_0}^{T} c_p(T, p)\,dT =$$
$$= h_0(T_0) + c_{p_a} \cdot (T_i^* - T_0), \tag{23}$$

is $\delta q_f = 5...11\ \%$;

– using the enthalpies calculated by the temperature and pressure averaged specific heat c_{pa}, according to the formula (15) is $\delta q_f = 0...4.3\ \%$.

Thus, the proposed method for calculating q_f significantly increases the accuracy of determining the GTE fuel-air ratio in comparison with the methods using $h(T, q_f)$.

The error $\delta q_f = 0...4.3\ \%$ can be explained by both the calculation error and the experimental error.

5. 4. Estimation of the calculation accuracy of specific fuel consumption of air-breathing engines

Estimation of the calculation accuracy of c_R was carried out by comparing the calculation results with the experimental data presented in the technical description of the D436 – 148B turbofan engine [28].

The first-level mathematical model of a turbofan engine, described in [32–34], was used for the calculation. In this model, the enthalpy was calculated using the dependence $h(T, q_f)$. The obtained calculation results were corrected by recalculating q_f and c_R via $h(T, p, q_f)$, determined by the formula (15).

The hourly fuel consumption G_f was calculated using the obtained values of c_R and R for comparison with the data presented in [28].

The results of comparing G_f and R are presented in Fig. 2, 3.

As can be seen from Fig. 2, the calculated value of the engine thrust practically coincides with the values from the technical description of the engine when the enthalpy $h(T, q_f)$ is used. The calculation error of the engine thrust does not exceed 1 %, and the

calculation error of G_f is up to 15 %. Correction of c_R by the proposed method reduced the estimation error of G_f to 3 %.
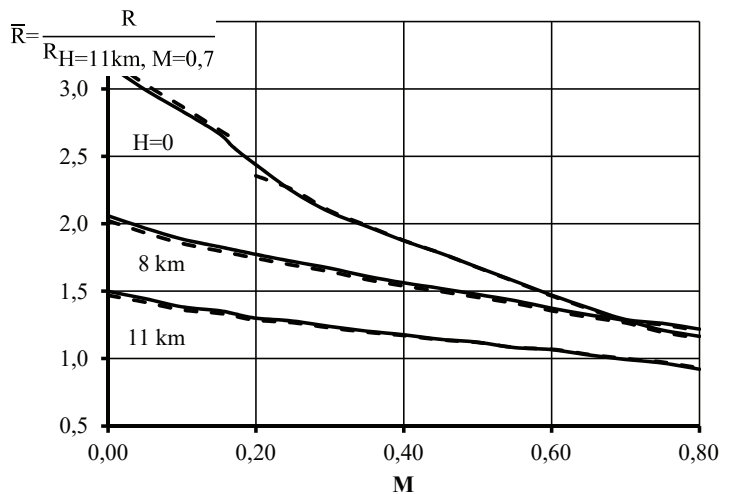

Fig. 2. Change of the engine thrust from altitude and flight speed: —— — calculation at $h(T, q_f)$; – – – — technical description of the engine
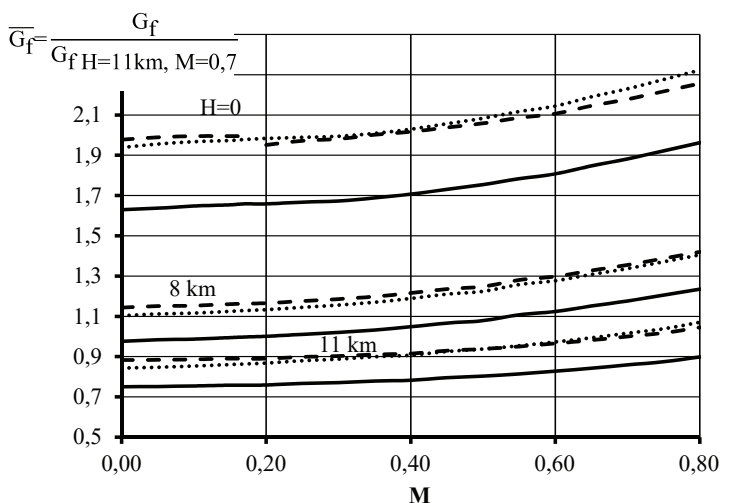

Fig. 3. Change of the engine fuel consumption per hour from altitude and flight speed: —— — calculation at $c_{pa}(T, q_f)$; – – – — technical description of the engine; ········ — calculation at $c_{pad}(T, p, q_f)$

6. Discussion of calculation results of the combustion chamber and turbofan engine performance by the proposed method

Comparison of the calculation results of q_f with experimental data (Fig. 1) shows a significant increase in accuracy when the effect of pressure on enthalpy is taken into account. This is due to the influence of pressure on the dissociation degree of molecules in combustion products.

When using the dependence $h(T, q_f)$ [32], the combustion products are presented as products of complete oxidation, which leads to an estimation error of the enthalpy of a real mixture, in which some of the molecules are dissociated. The estimation error of h leads to an estimation error of q_f according to equation (12). The average relative estimation error of q_f was 14...29 %.

When using the dependence $h(T, p, q_f)$, the enthalpy was determined in two ways: by integrating c_p over temperature and pressure from the standard state (T_0=298 K, p_0=1 bar) to a given state (T_0, p_0) according to equation (15) and according to the simplified equation (23). With the simplified method, h was determined by integrating c_p over temperature at constant pressure.

Considering pressure while calculating $h(T, p, q_f)$ increases the calculation accuracy of q_f. Moreover, the best accuracy is obtained when taking into account the pressure change (δq_f=0...5 %). With the dissociation taken into account by the simplified method (integrating c_p over temperature at constant pressure), δq_f=5...11 %.

Comparison of the calculation results of G_f with experimental data (Fig. 2, 3) shows that the use of enthalpy $h(T, q_f)$ makes it possible to calculate R of the engine with the error of less than 1 %, but leads to a significant estimation error of G_f (up to 15 %).

Correction of c_R by recalculating q_f using the enthalpy $h(T, p, q_f)$ reduced the estimation error of G_f to 3 %.

Thus, the developed method to improve the calculation accuracy of c_R makes it possible to increase the calculation accuracy of air-breathing engine performance by mathematical models using the dependence $h(T, q_f)$.

In addition, this method is advisable to use when creating new mathematical models of air-breathing engines.

The disadvantages of the study include indirect proof of a weak influence of the estimation error of q_f in the combustion chamber on all parameters of the air-breathing engine, except for c_R.

The developed method for calculating q_f using $h(T, p, q_f)$ can be applied in a number of related areas.

These areas are liquid and solid propellant rocket engines, piston engines, and other gas-dynamic processes involving chemical reactions.

A promising area of research using the developed method is the calculation of the gas turbine engine performance when using alternative fuels. Of primary interest are gaseous fuels and methanol.

7. Conclusions

1. The method of correcting c_R by mathematical models of air-breathing engines using the enthalpy $h(T, q_f)$ was developed. Its feature is the absence of feedback between the developed method and the mathematical model of air-breathing engines based on the enthalpy $h(T, q_f)$, which makes it possible to increase the calculation accuracy of c_R without unnecessarily complicating the calculation procedure. This solves the problem associated with the calculation error of c_R in the mathematical modeling of air-breathing engine performance using $h(T, q_f)$.

2. The method for calculating q_f using the enthalpy dependences $h(T, p, q_f)$ underlying the correction of c_R was developed. Its feature is the implicit account of molecular dissociation for enthalpy using experimental data for the heat capacity of gases as a function of temperature and pressure. This improves the calculation accuracy of enthalpy in the combustion chamber. This solves the problem of increasing the calculation accuracy of q_f, which is the main source of the calculation error of c_R.

3. Verification of the method was carried out by comparing the calculation results with the results of experimental tests of the CF6-80A engine combustor. Using $h(T, p, q_f)$ made it possible to reduce δq_f to 0...5 % depending on operating conditions.

4. Using the developed method to improve the calculation accuracy of c_R for calculating the altitude-airspeed performance of D436-148B made it possible to reduce the estimation error of the hourly fuel consumption to 3 %.

References

1. Khoreva, E. A., Ezrokhi, Yu. A. (2017). Ordinary Mathematical Models in Calculating the Aviation GTE Parameters. Aerokosmicheskiy nauchniy zhurnal, 3 (1), 1–14.

2. Boldyrev, O. I., Gorynov, I. M. (2012). Influence of thermal dissociation of hydrocarbonic fuel combustionproductson parameters of working process perspective gas-turbineengines. Modern problems of science and education, 1. Available at: https://www.science-education.ru/pdf/2012/1/15.pdf

3. Abdelwahid, M. B., Cherkasov, A. N., Fedorov, R. M., Fedechkin, C. S. (2014). Numerical investigation of erosion effect on altitude-speed characteristics of a turbojet engine. Vestnik UGATU, 18 (3), 16–22. Available at: http://journal.ugatu.ac.ru/index.php/Vestnik/article/view/1758/1637

4. Walsh, P. P., Fletcher, P. (2004). Gas Turbine Performance. Blackwell Science Ltd. doi: https://doi.org/10.1002/9780470774533

5. Rahman, M. M., Ibrahim, T. K., Abdalla, A. N. (2011). Thermodynamic performance analysis of gas-turbine power-plant. International Journal of the physical Science, 6 (14), 3539–3550. Available at: https://www.researchgate.net/publication/233532668_Thermodynamic_performance_analysis_of_gas_turbine_power_plant

6. Oyedepo, S. O., Kilanko, O. (2014). Thermodynamic Analysis of a Gas Turbine Power Plant Modelled with an Evaporative Cooler. International Journal of Thermodynamics, 17 (1). doi: https://doi.org/10.5541/ijot.480

7. Kotowicz, J., Job, M., Brzęczek, M., Nawrat, K., Mędrych, J. (2016). The methodology of the gas turbine efficiency calculation. Archives of Thermodynamics, 37 (4), 19–35. doi: 0https://doi.org/10.1515/aoter-2016-0025

8. Andrei, I.-C., Rotaru, C., Fadgyas, M.-C., Stroe, G., Leonida, Niculescu, M. (2017). Numerical investigation of turbojet engine thrust correlated with the combustion chamber's parameters. Scientific Research and Education In The Air Force, 19 (1), 23–34. https://doi.org/10.19062/2247-3173.2017.19.1.2

9. Qi, L., Zhao, N., Wang, Z., Yang, J., Zheng, H. (2018). Pressure Gain Characteristic of Continuously Rotating Detonation Combustion and its Influence on Gas Turbine Cycle Performance. IEEE Access, 6, 70236–70247. doi: https://doi.org/10.1109/access.2018.2880994

10. Hashmi, M. B., Lemma, T. A., Abdul Karim, Z. A. (2019). Investigation of the Combined Effect of Variable Inlet Guide Vane Drift, Fouling, and Inlet Air Cooling on Gas Turbine Performance. Entropy, 21 (12), 1186. doi: https://doi.org/10.3390/e21121186

11. Udeh, G. T., Udeh, P. O. (2019). Comparative thermo-economic analysis of multi-fuel fired gas turbine power plant. Renewable Energy, 133, 295–306. doi: https://doi.org/10.1016/j.renene.2018.10.036

12. Dobromirescu, C., Vilag, V. (2019). Energy conversion and efficiency in turboshaft engines. E3S Web of Conferences, 85, 01001. doi: https://doi.org/10.1051/e3sconf/20198501001

13. Kofman, V. (2016). Methodology of experimental and estemated determination of performance indicators of the main gte combustion chambers based on the results of their autonomous tests on the chamber stands. Perm National Research Polytechnic University Aerospace Engineering Bulletin, 46, 6–39. doi: https://doi.org/10.15593/2224-9982/2016.46.01

14. Il'ichev, Ya. T. (1975). Termodinamicheskiy raschet vozdushno-reaktivnyh dvigateley. Moscow: Tsentral'niy institut aviatsionnogo motorostroeniya, 126.

15. Kuznetsov, V. I., Shpakovsky, D. D. (2020). Methodology for estimating the specific fuel consumption of a two-circuit turbojet engine. Journal of «Almaz – Antey» Air and Defence Corporation, 2, 93–102. doi: https://doi.org/10.38013/2542-0542-2020-2-93-102

16. Rivkin, S. L. (1987). Termodinamicheskie svoystva gazov. Moscow: Energoatomizdat, 288.

17. Kishalov, A. E., Markina, K. V. (2017). Research and prediction of thermal gas parameters flow combustion chambers of aviation GTE. Vestnik voronezhskogo gosudarstvennogo tehnicheskogo universiteta, 13 (1), 60–68.

18. Kyprianidis, K. G., Sethi, V., Ogaji, S. O. T., Pilidis, P., Singh, R., Kalfas, A. I. (2009). Thermo-Fluid Modelling for Gas Turbines – Part I: Theoretical Foundation and Uncertainty Analysis. Volume 4: Cycle Innovations; Industrial and Cogeneration; Manufacturing Materials and Metallurgy; Marine. doi: https://doi.org/10.1115/gt2009-60092

19. Gazzetta Junior, H., Bringhenti, C., Barbosa, J. R., Tomita, J. T. (2017). Real-Time Gas Turbine Model for Performance Simulations. Journal of Aerospace Technology and Management, 9 (3), 346–356. doi: https://doi.org/10.5028/jatm.v9i3.693

20. NIST Reference Fluid Thermodynamic and Transport Properties Database (REFPROP): Version 10. Available at: https://www.nist.gov/srd/refprop

21. Li, H., Huang, H., Xu, G., Wen, J., Wu, H. (2017). Performance analysis of a novel compact air-air heat exchanger for aircraft gas turbine engine using LMTD method. Applied Thermal Engineering, 116, 445–455. doi: https://doi.org/10.1016/j.applthermaleng.2017.01.003

22. Klein, S. A. (2015). Engineering Equation Solver (EES). F-Chart Software. Madison, WI.

23. Boldyrev, O. I. (2012). Metodika rascheta ravnovesnogo sostoyaniya gomogennoy smesi produktov sgoraniya uglevodorodnogo topliva v kamerah sgoraniya GTD. Vestnik Ufimskogo gosudarstvennogo aviatsionnogo tehnicheskogo universiteta, 16 (2 (47)), 106–112. Available at: http://journal.ugatu.ac.ru/index.php/Vestnik/article/view/701/535

24. Dolmatov, D. A. (2011). Management of air hydrocarbon flames by short arc. Visnyk dvyhunobuduvannia, 2, 41–51.

25. Ambrozhevich, M. V., Shevchenko, M. A. (2019). Analytical determination of isobaric heat capacity of air and combustion gases with influence of pressure and effect of thermal dissociation. Aerospace technic and technology, 1 (153), 4–17. doi: https://doi.org/10.32620/aktt.2019.1.01

26. Dodds, W., Ekstedt, E., Bahr, D. (1983). Methanol combustion in a CF6l-80A engine combustor. 19th Joint Propulsion Conference. doi: https://doi.org/10.2514/6.1983-1138

27. Dodds, W., Ekstedt, E., Bahr, D., Fear, J. (1982). NASA/General Electric broad-specification fuels combustion technology program - Phase I results and status. 18th Joint Propulsion Conference. doi: https://doi.org/10.2514/6.1982-1089

28. Dvigatel' D-436-148. Rukovodstvo po tehnicheskoy ekspluatatsii. Available at: https://www.studmed.ru/dvigatel-d-436-148-rukovodstvo-po-tehnicheskoy-ekspluatacii_d8160eb83ce.html

29. Ambrozhevich, M. V., Shevchenko, M. A. (2019). Equations of average isobaric heat capacity of air and combustion gases with influence of pressure and effect of thermal dissociation. Aerospace Technic and Technology, 2, 18–29. doi: https://doi.org/10.32620/aktt.2019.2.02

30. Glushko, V. P. (Ed.) (1978). Termodinamicheskie svoystva individual'nyh veschestv. Vol. 1, Kn. 2. Moscow: «Nauka», 328.

31. ASTM D1655-20d. Standard Specification for Aviation Turbine Fuels (2020). ASTM International, West Conshohocken, PA. doi: https://doi.org/10.1520/d1655

32. Druzhinin, L. N., Shvets, L. I., Malinina, N. S. (1983). Metod i podprogramma rascheta termodinamicheskih parametrov vozduha i produktov sgoraniya uglevodorodnyh topliv. Rukovodyaschiy tehn. material aviatsionnoy tehniki. RTM 1677–83. Dvigateli aviatsionnye i gazoturbinnye. Moscow, 68.

33. Demenchonok, V. P., Druzhinin, L. N., Parhomov, A. L. et. al.; Shlyahtenko, S. M., Sosunova, V. A. (Eds.) (1979). Teoriya dvuhkonturnyh turboreaktivnyh dvigateley. Moscow: Mashinostroenie, 432.

34. Druzhinin, L. N., Shvets, L. I., Lanshin, A. I. (1979). Matematicheskoe modelirovanie GTD na sovremennyh EVM pri issledovanii parametrov i harakteristik aviatsionnyh dvigateley. Moscow: Trudy TSIAM, 45.