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

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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 $q_f$.

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

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

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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. Traditionally, for performance modeling of air-breathing engines, the enthalpy of the working fluid is calculated as a function of 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 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 was 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 it 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 \( c_p \) 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 \( c_p \). 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 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 \( h(T, p, q_f) \) [4–16]. Therefore, for models where \( q_f \) is calculated using \( h(T, p, q_f) \), 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 \( c_p \) 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 \( c_R(T, p) \) 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 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 by \( h(T, p, q_f) \) 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 dependences \( c_R(T, p) \) 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 \( c_R \) values obtained experimentally. These \( c_R \) 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 \( c_R = f(H, M_0) \) 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 \( L_0 \) 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

\[
\begin{align*}
C + O_2 & = CO_2; \\
H + \frac{1}{2} O_2 & = \frac{1}{2} H_2O; \\
S + O_2 & = SO_2,
\end{align*}
\]

and by

\[
L_0 = \left( \frac{g_a}{\mu_a} + \frac{1}{4} \frac{g_m}{\mu_m} \right) \frac{g_{o_2}}{g_{o_2}} \tag{3}
\]

where \( g_a \) – mass fraction of the component; \( \mu \), kg/kmol – molar mass of the component.

The chemical combustion reaction of kerosene of the conditional formula \( C_{12}H_{22}S \), with an excess of oxidant \( \lambda \) can be represented by equation (4).

\[
C_{12}H_{22}S + \lambda \left( \frac{a + \frac{b}{4} + c}{x_{o_2}} \right) = 
\]

\[
\begin{align*}
&\left( \frac{x_{N_2}}{x_{o_2}} \right) N_2 + \frac{x_{o_2}}{x_{o_2}} O_2 + \frac{x_{o_2}}{x_{o_2}} Ar + \\
&+ \frac{x_{CO_2}}{x_{o_2}} CO_2 + \frac{x_{H_2O}}{x_{o_2}} H_2O \\
&= a + \lambda \left( \frac{a + \frac{b}{4} + c}{x_{o_2}} \right) CO_2 + \\
&+ \left( \frac{b}{2} + \lambda \left( \frac{a + \frac{b}{4} + c}{x_{o_2}} \right) \right) H_2O + c \ SO_2 + \\
&\left( \lambda - 1 \right) \left( \frac{a + \frac{b}{4} + c}{x_{o_2}} \right) O_2 + \lambda \left( \frac{x_{N_2}}{x_{o_2}} \right) \left( \frac{a + \frac{b}{4} + c}{x_{o_2}} \right) Ar. \tag{4}
\end{align*}
\]

Denoting

\[
\chi = \lambda \left( \frac{a + \frac{b}{4} + c}{x_{o_2}} \right),
\]

rewrite equation (4) as
The energy conservation law for this reaction is as follows

\[ \Delta H = 0 \]

Equation (6) is an expression of the mass conservation law.

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

\[ q_f = \frac{H_u}{\eta_f} \]

considering [14]

\[ h'_i = h''_i, \]

equation (12) after transformations takes the following form

\[ q_f = \frac{H_u}{\eta_f - 1} \]

According to equation (13), \( q_f \) is determined using the iterative procedure.

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

\[ h'_i = \frac{\Delta h_i}{c_{p,m}} (T'_i - T_0) = \frac{1}{p_0 - p_i} \int_{T_0}^{T'_i} c_{p,m}(T,p) \text{d}T \]

where \( c_{p,m} \), 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 \( T'_i \) or inlet temperature \( T'_m \) 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

\[ p_i = \sum_{j=1}^{n} x_j p_{m,j}, \]

where \( x_j \) – molar fraction, \( p_{m,j} \) – 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

\[ c_{p,m} = \sum_{j=1}^{n} x_j c_{p,m,j}, \]

The equations \( c_{p,m} = f(T,p) \) for the main components of air and combustion products for hydrocarbon fuels, which are united throughout the specified pressure and temperature range (nitrogen \( \rho = 0.1...200 \text{ bar}, T = 150...2870 \) K; oxygen: \( \rho = 1...200 \text{ bar}, T = 210...2870 \) K; argon: \( \rho = 1...200 \text{ bar}, T = 190...1300 \) K; water vapor: \( \rho = 0.1...200 \text{ bar}, T = 700...2600 \) K; carbon dioxide: \( \rho = 1...200 \text{ bar}, T = 390...2600 \) K) are obtained in [29], based on the results of [23]. The specific heat capacity averaged both by pressure and temperature can be obtained by integrating \( c_{p,m} = f(T,p) \) 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

\[ c_{p,n} = \frac{1}{T_2 - T_1} \left[ \sum_{i=1}^{n} f_i (T_{2,i} - T_{1,i}) \right] + \frac{\alpha}{T_2 - T_1} \left( \frac{p_2 + p_1}{2} - 1 \right) \times \sum_{i=1}^{n} f_i \left( T_{2,i}^{\beta-1} - T_{1,i}^{\beta-1} \right) \]

where \( f_i, \alpha, \beta \) – 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

\[ c_{p,a} = \frac{1}{T_2 - T_1} \left[ \sum_{i=1}^{n} f_i + \left( \frac{p_2 + p_1}{2} \right) \right] \left( T_{2,i}^{p-1} - T_{1,i}^{p-1} \right), \]

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 \( c_{p,a} = c_{p}^0 = 0.52043 \frac{kJ}{KgK} \) [29].

For carbon dioxide and water vapor

\[ c_{p,c} = \frac{1}{T_2 - T_1} \left[ \sum_{j=1}^{n} \frac{h_{ij}}{p_j - p_i} \right] \left( T_{2,j}^{p-1} - T_{1,j}^{p-1} \right), \]

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 $T=273...1000$ K and for carbon dioxide – $p=0...20$ bar, $T=273...1800$ K. Tensor coefficients are presented in Tables 1, 2, respectively.

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

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

(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.

| Sector combus tor operating conditions [26] | Com bustor inlet | Average outlet temperature, K | Combustion efficiency, % | Fuel flow (aviation kerosene, g/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 99.8 345.1 |                              |                          |                                   |
| 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 |                              |                          |                                   |

### Table 1

| Coefficients $h_{ij}$ of equation (20) for H$_2$O
|---|---|---|---|---|---|
| $j$ | $i$ | 0 | 1 | 2 | 3 |
| 0   | 2.7896E+00 | -9.5510E-03 | 3.7834E-05 | -7.4897E-08 | 8.2591E-11 |
| 1   | 2.5589E+01 | -1.9772E-01 | 7.1427E-04 | -1.3603E-06 | 1.4392E-09 |
| 2   | 3.6395E-01 | -3.2489E-03 | 1.1904E-05 | -2.2910E-08 | 2.4436E-11 |
| 3   | 3.6385E-01 | -3.2489E-03 | 1.1904E-05 | -2.2910E-08 | 2.4436E-11 |

### Table 2

| Coefficients $h_{ij}$ of equation (20) for CO$_2$
|---|---|---|---|
| $j$ | $i$ | 0 | 1 |
| 0   | 4.90071E-01 | 1.45536E-03 |
| 1   | 1.23678E-02 | -3.65356E-05 |
| 2   | 5.36017E-04 | -1.85784E-06 |

### Table 3

| 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 $c_{pa}(T, p, q_f)$, 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 $h(T, q_f)$.

### Table 4

| Component | Molar fraction $n_i$ | Mass fraction $g_i$ |
|-----------|---------------------|---------------------|
| Carbon C  | 0.328641            | 0.852045            |
| Hydrogen H| 0.670170            | 0.145955            |
| Sulfur S  | 0.000289            | 0.002000            |

### Table 5

| 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$_2$O           | 0.015824            | 0.009901            |

Note: $p_{atm}=101,325$ Pa; $t_{atm}=27^\circ$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

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

(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 shows that the average relative calculation error:

– using the values of enthalpies \( h(T, q_f) \) [32] is \( \delta q_f = 14\ldots29\% \);

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

\[
h(T) = h_i(T_i) + \int_{T_i}^{T} c_p(T, p) dT = h_i(T_i) + c_{pa} \cdot (T - T_i),
\]

is \( \delta q_f = 5\ldots11\% \);

– using the enthalpies calculated by the temperature and pressure averaged specific heat \( c_{pa} \), according to the formula (15) is \( \delta q_f = 0\ldots4.3\% \).

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 \( \delta q_f = 0\ldots4.3\% \) 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 \( h(T, q_i) \), 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\%.
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 ($T$, $p$) 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 ($\delta q_f=0...5\%$). With the dissociation taken into account by the simplified method (integrating $c_p$ over temperature at constant pressure), $\delta q_f=5...11\%$.

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 allows to increase 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 $\delta q_f$ 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%.

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