COMPUTER-ASSISTED REFINEMENT OF GTE COMBUSTION CHAMBERS

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Abstract. According to the studies of processes that occur in the complex products such as the aircraft engines, a significant share of time is spent at designing for operational development and refinement of engines and their separate units and assemblies. In this process, the refinement of combustion chambers (whose calculations are a very cumbersome procedure that needs a large volume of studies at both laboratory and test-bed conditions) is of special importance. Use of computer programs that realize the mathematical models of both the design and confirmatory calculations significantly facilitates the realization of processes of design and refinement and makes it possible to reduce considerably their cost.

At refining the combustion chambers (CCs), the basic requirement is to provide their high reliability, efficiency, and reduction of NO_x emissions.

As is known, it is necessary to create in this case good conditions for proper mixing of air and fuel as well as to improve the process of fuel burn-out; the distribution of gas temperature throughout the length of flame tube (FT) in the zone of combustion must have the maximum permissible values (no more than 2000K); the time period of combustion products' stay in the high-temperature area must be minimal.

The required distribution of gas temperatures can be obtained by supplying the necessary quantities of secondary air to the flame tube flow duct. In this paper, we consider an algorithm for calculating the required CC characteristics using as the base the computer-assisted system of engine refinement whose use allows reducing the volume of developmental work. The system uses the one-dimensional simulation of intra-chamber processes such as fuel atomization, vaporization, mixing, and burnout throughout the entire FT length.

In the course of the computer-assisted refinement of engines, it is necessary to determine the optimal distribution of air throughout the flame tube length; the value of this distribution must provide high efficiency of combustion and operational reliability with the quantities of fuel toxic components being minimal.

1. In the initial stage of calculations, a CC configuration is being formed; it can be obtained by using as the base the average statistical data and hydraulic calculations. It can be obtained also by using the prototype provides the possibility for:

– configuring of FT external and internal shells;

– FT opening;

– distribution of the openings' relative areas.

2. Proceeding from the prescribed geometry and balance equations for air, fuel, and combustion products, it is possible to find the distribution of local blend compositions throughout the FT length:

$$\alpha_i = G_{air}/(G_{ti}L_0).$$

3. Knowing the initial values of heat content in the mixture of air, fuel, and products of combustion, it is possible to determine the mean temperature of gases:

$$T_{\text{c.p.}i} = \frac{c_{p\text{c.p.}} T_{p\text{c.p.}i-1} G_{\text{c.p.}i-1} + c_{p\text{air}} T_{\text{air}i} \Delta G_{\text{air}i} + \eta G_{fi} z Hu}{c_{p\text{c.p.}} G_{\text{c.p.}i}},$$

where $c_{c.p..p.}$, c_{pair} are the heat capacities of gas and air at the corresponding sections; $T_{\text{c.p.}}$, T_{air} are the temperatures of gas and air, respectively; G_t is the fuel flowrate; $G_{\text{c.p.}}$, G_{air} are the flowrates of combustion products and air; Hu is the calorific value of fuel; η is the combustion efficiency in the exhaust.

4. In order to determine the local blend compositions, it is necessary to know the quantity of secondary air that is fed to the combustion zone examined. For this, we determine the fraction of air in the gas flow by using mixing coefficients in the following manner:

$$G_{\text{air}i} = G_{\text{air}\Sigma} \bar{F}_{\text{fr.}} (1 + m_{\text{p}i} + m_{\text{act}i}).$$

Here, $m_{\text{p}i}(x,r) = A \dfrac{T_{\text{c}} W_0}{T_0 W_{\text{c}}} \dfrac{1}{k} \dfrac{\exp K \left(1 + \dfrac{r^2}{R^2_{\text{r.f.r.}}}\right)}{I_0 \left(2K \dfrac{r}{R_{\text{r.f.r.}}}\right)} \dfrac{F_i}{F_\Sigma}$; $k = \dfrac{R_{\text{r.f.r.}}}{B \left(1 + \text{tg}^2\varphi\right)^{0,5} (x + \Delta x)}$;

I_0 is the Bessel null-order function; A and B are the constant coefficients that can be determined by using the experimental data derived in the course of CC prototype tests:

$$m_{\text{act}i} = \frac{h_i(x) d_0 n_0 \cos\varphi}{R^2_{\text{r.f.r.}}};$$

h_i is the depth of cross jet penetration into the flow.

5. When solving the equation for mixing, it is also possible to determine the maximum permissible nonuniformity of temperature fields at CC outlet:

$$\Theta = 1 - \bar{F}_{\text{fr.}} \left(1 + A_1 0 \frac{T_{\text{c}} W_0}{T_0 W_c} \frac{F_i}{F_{m_i} K} \frac{e^{K\left(1 + \frac{r^2}{R^2_{\text{r.f.r.}}}\right)}}{I_0\left(2K \frac{r}{R_{\text{r.f.r.}}}\right)} + \sum_{i=1}^{k} A_2 \frac{d_{0i} n_{0i} h_{0i} \cos\varphi_i}{F_{mi}} \right) \left(1 + \frac{1}{L_0 \alpha_{\text{fr.}}}\right),$$

where α_h is the mixture composition behind the flame tube head; h_{oi} is the depth of the jet penetration into the flow; F_m is the FT area at the i-th section; d_{oi}, n_{oi} are correspondingly the diameter and number of openings in the i-th row; k is the number of opening rows; $K = (R^2_{\text{r.f.r.}} W_{\text{o}})/(D_{\text{f}} l_{\text{comp}})$ is the non-dimensional complex.

The empirical coefficients A_1 and A_2 can be found by using either the experimental data on either CC prototype blow-downs or the data on tests of first CC models newly developed. On having the constant coefficients determined, it is possible to reveal influence exerted by one or the other of the design parameters, such as: $\bar{F}_{\text{fr}}$ – a degree of FT head opening; d_{oi}, n_{oi} – the openings' diameter and number; $F_{mi}, l_к$ – frontal area and FT length as well as operating parameters of temperature T_g and gas velocity W_g, degree of fuel vaporization z, air-to-fuel ratio behind the FT head α_h, and coefficient of turbulent diffusion D_t.

6. Making use of the theory of surface turbulent combustion of the averaged "volume" of mixture, it is possible to derive the relation that determines the local efficiency of fuel combustion:

$$\eta = \frac{3U_{m0}^3}{W'^3}\left\{\frac{1}{3}\left[1-\exp\left(-\frac{3\Delta x\varepsilon}{l_i}\right)\right]-\right.$$
$$\left.-\frac{U_{norm}}{U_{m0}}\left[1-\exp\left(-\frac{2\Delta x\varepsilon}{l_i}\right)\right]+\frac{U_{norm}^2}{U_{m0}^2}\left[\left(1-\exp\left(-\frac{\Delta x\varepsilon}{l_i}\right)\right)\right]\right\}.$$

where W' is the rate of flow pulsations; $W' = \varepsilon W$, where ε is the turbulence intensity.

The above-given relation makes it possible to determine the combustion efficiency of the average volume of mixture that has the size to be proportional to the turbulence scale l_i and air-to-fuel ratio α_I, covers the distance Δx at the flow velocity W, and burns for this time period at the turbulent rate $U_{m0} = U_{norm} + W'$, where U_{norm} is the normal rate of combustion.

7. Determination of toxic substance emissions.

As the basic dependence for determination of NO_x emission, the Zeldovich's equation is used:

$$\frac{d\mathrm{NO}}{d\tau} = \frac{5\cdot 10^{11}}{\sqrt{\mathrm{O}_2}}\exp\left(-\frac{86000}{RT_c}\right)\left[\mathrm{O}_2\mathrm{N}_2\frac{64}{3}\exp\left(-\frac{43000}{RT_c}\right)-(\mathrm{NO})^2\right],$$

where O_2, N_2, and NO are the concentrations of gas mixture components;τ is time; T_c is the temperature in the zone of reaction.

The instantaneous values of concentrations O_2, N_2, and $T_г$ can be determined by using the well-known techniques for calculating compositions of the thermodynamically equilibrium products of combustion.

The calculations to be made with use of this differential equation make it possible to determine the emission thermal NO_x streams of in the post-flame zone (the streams appearing as a result of the straight-chain reaction between nitrogen and free oxygen in air).

8. The herein-presented procedure of the computer-assisted refinement was used successfully at development of the combustion chamber for one of the domestic engines. As it was noted above, the basic aim of these calculations was the reduction of NO_x emission and increase of CC reliability by using the models described.

The preliminary analysis of working processes in the combustion chambers showed that it is necessary to lower the temperature of gas in the zone of combustion (by redistribution of secondary air); as a result, the quantity of NO_x ejections will be decreased. Proceeding from this fact, we introduced the corresponding changes in the process of distribution of secondary air (by closing the mixers' branch pipes and redistributing this area to two rows of openings arranged in FT frontal part.

As applied to these variants of FT configuration, the calculations showed that redistribution of secondary air makes it possible to attain significant changes in FT characteristics. Figure 1 presents some graphs illustrating the variations of gas temperature, combustion efficiency, and NO_x emission throughout the entire FT length.

As it follows from the analysis of the so-obtained design curves, the redistribution of secondary air results, due to additional air delivery to the zone of combustion, in lowering the gas temperature in this zone.

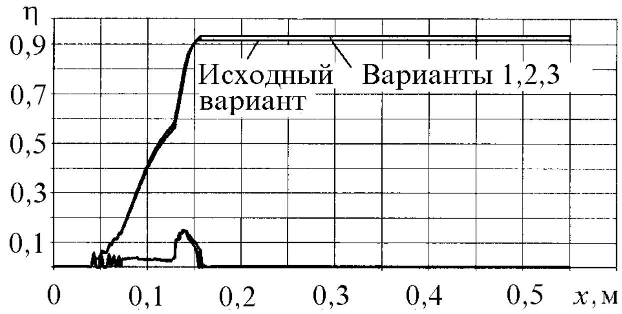
a

Variants 2,3

Variant 1

Initial variant

m

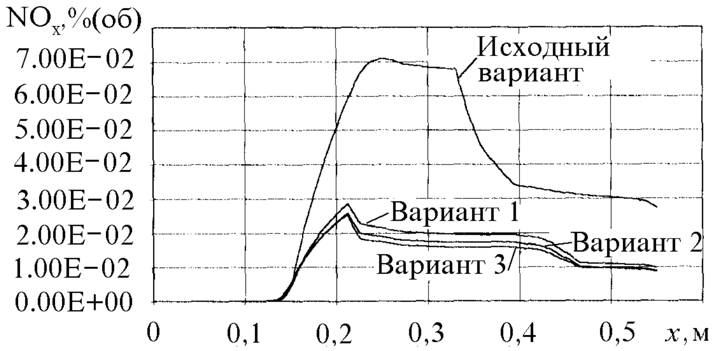


b

Initial variant

Variants 1,2,3

m



c

Initial variant

Variant 1

Variant 2

Variant 3

(v) m

Fig.1. Distribution of parameters (*a* – gas temperature; *b* – combustion efficiency; *c*– NO_x concentrations) along the CC duct at α_{comp} = 5,6; T_{comp}^* = 610 K; P_{comp}^* = 1,0 MPa

As it follows from these graphs, combustion efficiency in this case insignificantly diminishes (as compared with the initial variant). A reduction in the maximum permissible gas temperature and length of high-temperature zone makes it possible to lower the NO_x concentration from 0,02 up to 0,01% of the total volume of exhaust gases.

This redistribution of secondary air will also make it possible to reduce the overall level of temperature stress concentrations in FT walls; as a result, the reliability of CC operation significantly increases.

As is seen from the above-given results, the herein-suggested procedure of computer-assisted FT refinement makes it possible to predict effectively any variations in FT configuration and, at the same time, reduce significantly the scope of rather expensive experimental studies.

The essence of the computer-assisted refinement technique is in that a number of changes are introduced to CC configuration with the aim of obtaining the values of parameters required; after that, the calculations aimed at determining its new characteristics are carried out. Based on the so-obtained data, the CC configuration is then corrected. As a result, an experimental model is constructed and tested.

The test data are compared with those specified in technical specifications. In cases of disagreement between the so-obtained characteristics to these specifications, the CC configuration will be recalculated again by introducing some additional changes until the optimal solution is found. After that, the working diagrammatic sketch is drawn up.