The analysis of the level of emission characteristics depending on the aerosol structure

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Abstract. An attempt to combine the main verified recommendations for the organization of low-emission combustion of fuels (in relation to three main components of standardized harmful substances SN, NOx, and CO2) into one of the crucial modern problems implemented. The paper is devoted to the search for some general trends in the formation of emission characteristics based on the accumulated experience such as computational and experimental results obtained in CIAM.

1. Introduction
In modern realities, the levels of harmful substances emissions produced by heat engines are of the utmost importance. Numerous documents (including ICAO) are constantly tightening up such requirements and introducing new components for standardization [1]. Developers and researchers face new tasks to reduce the content of harmful substances in engine exhaust gases. This is especially important for engines and facilities operating on liquid fuels, where the issues of crushing and evaporation of the liquid phase fuse into the mixing problems of the fuel-air components [2].

This paper is devoted to the search for some general trends in the formation of emission characteristics based on the accumulated experience.

One of the longest studied emission components is smoke levels [3]. It is well known that in order to reduce the smoke in the exhaust gases, it is necessary to deplete the air-fuel mixture at the head of the combustion chamber. In further considerations, there are two opinions. The first is that it is sufficient to lower the temperature at the head of the combustion chamber (due to the depletion of the mixture with fuel) and provide an increased volume of air (above stoichiometry) participating in combustion [4]. The second is that it is necessary (in the ideal case) to crush the fuel into a finely dispersed uniform aerosol, surround each droplet with the amount of air necessary for its unhindered evaporation, exclude interaction with neighboring droplets, and ensure uniform combustion of such mixture in a thin flame front without the overheated clusters formation.

For experimental verification of the effectiveness of the proposed approaches, experimental studies are carried out at the CIAM facilities [5].

2. Results and discussion
2.1. Experimental data
Three combustion chambers with different degree of mixture enrichment in the head are experimentally investigated. Geometry for option 1 is a simple centrifugal nozzle without air swirler. For option 2, we choose the same nozzle but having additional air jets at the head which are necessary...
to deplete the mixture. Option 3 is represented by the centrifugal nozzle adapted for use in conjunction with an external air swirler.

Each chamber is tested in 4 main modes. In author’s opinion, the most interesting part is the comparison of structures in the general mode with the following parameters: ambient air pressure of 0.5 MPa; \( T_e = 600 \) K; and \( \alpha_{CC} = 3 \). Percentage of air in the head part is different for each option: it is 7% for Option 1, 14% for the Option 2 and 18% for Option 3. The measured smoke level \( SN \) is 60, 40 and 11 units, respectively.

Table 1 shows the results of experimental studies for the third option of the combustion chamber.

Table 1 summarizes information from the studies of harmful substances emission in the exhaust gases for the full-size experimental combustion chamber with the sampling combs installed both along the nozzle axis and in the middle between the nozzles. The column "Alfa" contains the values of the ratio of fuel consumption, multiplied by the stoichiometric coefficient, to the mass air flow rate, set by the test rig adjustments. As a result, the emission indices of the main pollutants, the completeness of fuel combustion and the smoke number are given.

The parameter setting error does not exceed 1.5%. The sample is representative.

| Mode | Measurement place      | \( T_{CC} \), K | \( P_{CC} \), kPa | \( \alpha \) | \( \eta_\epsilon \), \% | CO, ppm | \( C_3H_8 \), ppm | EiNOx, g/kg | SN |
|------|-----------------------|-----------------|-------------------|-------------|-----------------|---------|------------------|--------------|----|
| 1    | CC along the nozzles  | 350             | 200              | 7.0         | 98              | 880     | 190              | 2.3          | 2.5 |
|      | CC between the nozzles| 350             | 200              | 6.9         | 97.8            | 730     | 189              | 2.3          | 2.0 |
| 2    | CC along the nozzles  | 440             | 350              | 5.6         | 99.5            | 277     | 25               | 3.0          | 6.6 |
|      | CC between the nozzles| 440             | 350              | 5.4         | 99.4            | 280     | 34               | 3.3          | 5.5 |
| 3    | CC along the nozzles  | 470             | 430              | 4.6         | 99.8            | 170     | 4.1              | 3.8          | 7.2 |
|      | CC between the nozzles| 470             | 430              | 4.5         | 99.7            | 180     | 24.5             | 3.8          | 10.1|
| 4    | CC along the nozzles  | 500             | 500              | 3.6         | 99.8            | 110     | 2                | 4.1          | 10  |
|      | CC between the nozzles| 500             | 500              | 3.6         | 99.8            | 132     | 8                | 4.3          | 11.2|

The combustion efficiency reaches 99.5% in modes 2–4. There is no significant shortfall in the combustion efficiency in the mode of 5% power. In mode 1, a combustion efficiency of 97.9% was obtained. Such a high value is a very good indicator for the mode with such low set parameters.

The CO emissions determined in mode 4 are 1110 ppm and 132 ppm. Such values are significantly less than the current requirements of the order of 250 ppm.

The EiNOx emission index in mode 4 is 4.1–4.3 g / kg t.

SN satisfies the requirement: \( SN \leq 50 \) in all investigated modes with a huge margin.

Returning to the discussion of all three options, it is noted that a 2-fold change in the air flow rate from option 1 to option 2 reduces the smoke number, but only by a third. A further slight increase in air consumption up to 2.5 times from option 1 to option 3 and the organization of improved fuel air mixing allow reducing \( SN \) 6 times. Hence, it is obvious that the simple air addition to the CC head, while leading to the expected reduction in smoke production, does not exploit all the potential advantages of using mixtures with a high degree of homogenization. Consequently, the mixing quality of the components plays a significant role. Thus, it is necessary to dilute the flow of fuel droplets with air, i.e. increase the distance between the droplets so that the required volume of air around each of them is provided for its unhindered and complete evaporation. In this case, the volume of gas should not prevent the complete combustion of the fuel and the propagation of the flame over the described mixture clusters.

2.2. Discussing NOx emission

The component of harmful substances emission, being, probably, of the greatest interest to the scientific community, is NOx. Meeting current and planned standards with the help of existing CC of
standard layouts is becoming impossible [6]. The anticipated increase in the thermodynamic parameters of the new engines requires more scientific research. Below is the reasoning that illustrates the complexity of the task to reduce NOx. Examining, for example, the averaged parameters (during takeoff) of some engines in operation that meet the 2008 standards (CAEP6) it may be noticed that the temperature at the outlet of the combustion chamber \(T_4\) is 1650 K and the pressure before the combustion chamber \(P_1\) is 2.5 MPa. Analyzing the ICAO databank and modern developments for promising engines, we may assume an increase in \(T_4\) to the level of 1900–2100 K and in \(P_1\) to the level of 4.5–5.5 MPa. It is known from the experience that the multiple pressure increase entails a change in the production of nitrogen oxides by a power of 0.5, therefore, when passing from one engine generation to another, we will get only a 1.6-times increase in NOx emissions due to the pressure increase. Additionally, a change in temperature even by 300K will increase NOx emissions approximately 7-10 times. Multiplying these values and taking into account the tightening of standards, it is found that when using the existing 4th generation engine technology in the aircraft engine industry, it will be necessary to reduce NOx emissions 15–20 times for engines to be commissioned in 2030. Therefore, more than fifteen years ago, the interest in studying methods to reduce harmful substances emissions from aircraft engines increased many times around the world. At the same time the number of works in this field is still increasing.

The most interesting dependence in this section is the dependence of NOx production on the fineness of fuel droplets crushing and their distribution inside the air flow. A number of computational studies have been carried out with varying the fuel droplets diameter or injection points. It is necessary clarify immediately that a much larger amount of research is needed to derive general parametric dependencies. This is due to the fact that emission depends on many factors such as residence time, mixing quality, operating modes, design features, etc. Today it is impossible to give unambiguous recommendations for reducing all emission components for the all types of combustion chambers (such as RQL, LPP, LDI, etc.). It is possible to give only general recommendations based on work experience or particular examples of emission changes for specific structures. For example, for LPP combustion chambers with residence times of up to 10 ms, fuel droplets should have an average Sauter diameter of about 10–25 µm for the take-off mode (at “cold” conditions). With such diameters, it is possible to distribute the fuel over the main stream thickness, "pull" the fuel into the reverse flow zones and ensure its rapid evaporation for complete combustion within the allotted time. When switching to less heat-stressed regimes, the average Sauter droplet size can increase. However, in the modes of ground launch and low power mode it should not exceed the value of 50 microns, but rather tend to 35 microns. At such values, sufficient combustion efficiency should be ensured. Rapid evaporation, good mixing with air and combustion of a mixture with properties close to homogeneous can be ensured.

Complex 3D studies of the influence of the initial distribution of fuel droplets behind the external nozzle of the two-circuit frontal device on the air flow and the NOx emission index at the exit from the combustion chamber have been carried out. In the first variant, at the initial moment, the droplets move along the generatrix of a truncated cone, with an initial diameter of 50 mm. The axis coincides in direction with the \(x\) coordinate. The angle between the generatrix of the cone and its axis is \(\alpha = 0^\circ\). Initial axial velocity is 10 m/s, initial SMD size is 30 microns. As the size distribution law, the Rosin-Ramler equation is used.

The field of the excess ratio of the reduced fuel in the gas phase is shown in Fig. 1a. Red crosses correspond to the maximum concentration of the liquid phase of the fuel, at a distance of 30 mm from the nozzle end (±50 mm from the nozzle axis), obtained in the tests. The figure shows that the maximum concentration of the fuel liquid phase, in this version of the calculation, is much closer to the axis of the nozzle.

The flow of NOx mass through the cross-section at the outlet from the combustion chamber in this version corresponds to the emission index at the outlet from the combustion chamber – 22.98 g/kg (for NO2 – 35.24 g/kg).

The gas stagnation temperature field is shown in Fig. 1b
Figure 1. Coefficient of excess of recovered fuel in the gas phase (a) and gas stagnation temperature (b).

In the second version, all parameters remained, only the angle between the generatrix of the cone and its axis changed to $\alpha = 45^\circ$.

The flow of NOx mass through the cross-section at the outlet from the CC in this version even slightly increased and corresponded to the emission index at the outlet from the CC – 24.39 g/kg (in terms of NO2 – 37.4 g/kg). This was due to an increase in the transverse area of the high-temperature combustion zone caused by a decrease in the flame compression by the fuel jets.

In the third version, all parameters remained the same, only the angle between the generatrix of the cone and its axis changed to $\alpha = 55^\circ$.

The flow of NOx mass through the cross-section at the outlet from the CC in this version significantly decreased and corresponded to the emission index at the outlet from the CC – 15.26 g/kg (in terms of NO2 – 23.4 g/kg).

In the fourth version, all parameters remained, and only the angle between the generatrix of the cone and its axis changed to $\alpha = 65^\circ$.

The field of the excess ratio of the reduced fuel in the gas phase is shown in Fig. 2a. Red crosses correspond to the maximum concentration of the fuel liquid phase, obtained in the test for the distance of 30 mm from the nozzle end (±50 mm from the nozzle axis). The figure shows that the maximum concentration of the liquid phase of the fuel, which, in this version of the calculation, coincides with the test results.

The flow of NOx mass through the cross-section at the outlet from the CC in this version corresponds to the emission index at the outlet from the CC – 13.9 g/kg (in terms of NO2 – 21.31 g/kg).

The gas stagnation temperature field is shown in Fig. 2b.
In the complex of performed calculations, the influence of the initial distribution of fuel droplets behind the external nozzle of the two-circuit frontal device on the air flow and the NOx emission index at the outlet from the combustion chamber has been investigated. It is shown that with an increase in the opening angle of the external fuel flame over 45°, i.e., with a decrease in its interaction with the central rich stabilization zone, the total NOx emission decreases.

A comparison of the NOx production depending on the place of fuel injection was also made (Fig. 3). Fuel droplets were fed through the fuel holes in the internal and middle swirlers of the burners. In option 1, the fuel moved along the outer surface of the central tube, and in option 2 it separated from the intermediate nozzle surface.

![Figure 3. Fuel concentration (a) and gas temperature (b).](image)

In option 2, the fuel from the intermediate nozzle surface fell on the outlet nozzle surface, flowing along it, which led to the absence of effective secondary crushing. In option 1, the fuel also flowed along the tube surface, but was effectively crushed from it by two gas streams. This led to a 33% reduction in NOx emissions in option 1. The calculated results were confirmed by experimental data. Thus, it is necessary to exclude the deposition of fuel on the wall.

At the end of the section devoted to NOx emissions, an obvious conclusion can be made: it is necessary to distribute the liquid fuel over the largest possible area in the initial section and improve the characteristics of the liquid phase dispersion.

2.3. Discussing the CO2 emission

The third component requiring close attention is CO2. The most indicative here may be the program for the creation of a new multi-fuel (hybrid) aircraft and its engine (the 7th European program - AHEAD (Advanced Hybrid Engines for Aircraft development)) [7]. Reducing CO2 emissions was envisioned through the development of a hybrid multi-fuel engine that would run on liquefied natural gas, LH2 (liquid hydrogen) or conventional biofuels. As part of the work, researchers made a forecast about an almost 2 times increase in CO2 emissions from aircraft engines by 2050, without the introduction of special measures. Another way of development is using alternative fuels, new technologies and materials which should reduce the total effect of CO2 production by 50% of the current level.

This approach of using more and more alternative fuels in the aviation industry to offset CO2 emissions seems to be the only correct one.

At CIAM, research is underway for transferring aircraft engines to alternative types of fuel. In particular, for testing in an aircraft combustion chamber, a number of liquid biofuel samples have been analyzed and the most preferable one has been selected [8]. Combustion chamber fire tests on standard fuel show an acceptable performance. However, with regard to biofuels, it was revealed that its use worsens the stability of combustion and decreases the combustion efficiency in comparison with kerosene. For the use of biofuels in gas turbine engines, a number of measures are recommended to modernize traditional combustion chambers. The main ones are optimization of the fuel injection system to reduce the dispersion of droplets of fuel-air aerosol and the creation of a sufficiently
intensive and extended reverse flow zones due to the system of swirlers. Preliminary results allow us to assume with great confidence that measures to improve atomization in the combustion chambers will provide acceptable starting characteristics, combustion stability and combustion efficiency when switching to alternative fuels for aircraft engines, but this issue requires further research.

In 2017, another component was added to the ICAO standards, i.e., non-volatile particles (NvPM) [1]. However, the nowadays knowledge of their formation features does not allow formulating unambiguous recommendations for reducing emissions of this component. Today, at the first stage, we would recommend using the same approaches as for reducing the smoke amount.

Conclusions

In this paper author have made an attempt to bring together the main verified recommendations for the organization of low-emission combustion of fuels (in relation to the three main components of standardized harmful substances SN, NOx, CO2). Restrictions on the way of implementing these recommendations may be the requirements for the combustion chamber to ensure stable combustion in a wide range of conditions, high combustion efficiency in all operating modes, safety of flights on new types of fuel, etc. As often happens in technical problems, an optimal solution may be found by means of a compromise.

References

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