Study of the combustion characteristics of endothermic fuel thermal decomposition products in a subsonic air flow

M S Stashkiv, L S Yanovsky and I V Shevchenko
National Research University “Moscow Power Engineering Institute”, 14 Krasnokazarmennaya street, Moscow, 111250, Russia

Abstract. The development of high-speed aircraft is directly related to the design of efficient cooling systems of the propulsion system. At high supersonic speeds, the aerodynamic heating of the air flow during braking is so great that the fuel becomes the only possible refrigerant on board. Currently, a large amount of research is devoted to the study of cooling systems using endothermic fuels with subsequent combustion of the products of their thermal degradation in the combustion chamber of an air-jet engine. The paper presents the results of experimental studies of products combustion of thermal destruction of aircraft endothermic fuel in a subsonic air flow.

The chemical regeneration by absorbing the heat of aerodynamic heating, as well as from the power plant (PP) by thermochemical degeneration of fuel in the cooling system of PP and aircraft (A) [1] is the most appropriate way to cool hypersonic aircraft (A) with the use of liquid hydrocarbon endothermic fuel. As a result of the processes of thermal decomposition of fuel, combustible components with higher heat of combustion and lower molecular weight compared to the original fuel are formed. These components can be used for the efficiency of the thermodynamic cycle of the aircraft power plant. Endothermic hydrocarbon fuels, the processes of thermochemical decomposition of which proceed with heat absorption, i.e. endothermic effect, are recognized as promising fuels for hypersonic A [2].

The paper presents results of experimental study of characteristics of combustion products of thermal decomposition of aircraft endothermic fuels of ET-1 in a subsonic air flow.

Evaluation of the characteristics of combustion in a subsonic flow of the products of thermal decomposition of the fuel was conducted in a small-size combustion chamber with a subsonic air flow. Such characteristics as combustion completeness, carbon deposition, and the patterns of change in some characteristics of combustion with the change of the degree of thermochemical conversion of the endothermic fuel of ET-1 have been investigated.

The rate of turbulent combustion of fuel process determines the size of the chamber and its specific calorific intensity in the GTE combustion chamber. This means that the completeness of fuel combustion with given geometric dimensions of the chamber, the pressure according to the composition of the fuel-air mixture, is determined by the time of its stay in the combustion chamber.

Experimental studies were carried out on a plant equipped with a reactor-gas generator of products of thermochemical conversion of fuel and an annular combustion chamber [3]. The fuel system consisted of a fuel tank connected by a main line to the combustion chamber, a fuel pump, filters and a fuel heater.

The reactor gas generator was made in the form of replaceable electrically heated tubes made of heat-resistant alloy. Thermocouples were installed on the outer surface of the reactor tubes, as well as on the inlet and outlet of the reactor. The water refrigerators and a fuel-gas separator were installed after the
reactor for sampling the products of thermal degradation of the fuel for chemical analysis. The starting fuel supply system consisted of a propane tank and a reducer. The instrumentation included flowmeters, temperature sensors, pressure gauges and differential pressure gauges.

The evaporative combustion chamber is the most adapted for such tests out of the known combustion chambers of gas turbine engines. The working process in it does not depend on the quality of the spray introduced into the evaporation tubes of the fuel and, consequently, on its physical characteristics such as density, viscosity, surface tension. This fact predetermined the choice of the combustion chamber of the evaporative type as an object of testing on endothermic fuel.

The combustion chamber diagram is shown in figure 1. It consists of a cylindrical heat pipe 4 with a cylindrical head placed in body 1. The cylindrical shape of the combustion chamber is chosen to eliminate the influence of the inlet diffuser on the combustion characteristics and simplify the technology of its manufacturing. The heat pipe is made of sheet steel EI 868 with a thickness of 1 mm. Its length is 293 mm, the diameter of the pipe is 90 mm, the relative length $l_2/d_2=3.25$.

The choice of this diameter is due to the fact that with its further reduction, difficulties arise in the organization of the working process, heat losses to the environment begin to significantly affect the thermal balance of the combustion chamber.

The head of the combustion chamber is equipped with eight air nozzles 6 for air supply and four evaporation tubes. Fuel through the fuel manifold 7 is supplied to the evaporation tube 5. Passing through tubes 5, the liquid fuel is heated and evaporated. Evaporation tubes 5 are curved, so the fuel in the gaseous state is ejected from the evaporation tubes towards the air entering the heat pipe; it improves the mixture process (figure 1).

**Figure 1.** Combustion chamber of evaporative type: 1-body; 2-cup; 3-spark plug; 4-heat pipe; 5-evaporative tube; 6-air nozzle; 7-fuel collector; 8 - pipe supply of starting fuel-gas

Combustion chamber of the starting fuel supply tube. Additionally, a removable weighed element was installed in the chamber in the combustion zone to assess the propensity of the fuel and its degradation products to carbon formation.

The following method of conducting experiments has been adopted. The removal of the volumetric flow rate of air at a fixed air excess factor is associated with the necessity to change the fuel consumption simultaneously with the change of the air consumption. Thus, it is practically impossible to have a constant degree of the fuel conversion at different modes of air consumption chamber operation.

Therefore, the degree of decomposition will interfere with the process as another active factor. In order to exclude the influence of this factor, tests on both liquid fuel ET-1 and its degradation products were carried out at a constant fuel consumption, that is, at a constant mode of operation of the reactor,
and therefore, a constant degree of thermal degradation of the fuel. The decomposition products were cooled in water refrigerators to the initial temperature of the fuel injected into the reactor before being fed into the combustion chamber, which would exclude the influence of temperature on the studied characteristics.

Thus, simultaneously with the change in air flow, the excess air coefficient $\alpha$ was proportionally being changed, so at each point the characteristics were compared at the same $\alpha$. Thus, the comparison conditions were methodically maintained correctly, and the comparison criteria—the coefficient of heat release and the failure mode—were maintained.

Figure 2 shows the dependence of the heat release coefficient $\eta_z$ on the mass air flow rate $G_B$ when burning liquid fuel ET-1 and cooled products of its decomposition (a degree of decomposition $Z = 0.25$).

The coefficient of excess air $\alpha$ at an air flow rate $G_V = 75 \times 10^3$ kg/s reached 30.

The determination of coefficient $\eta_z$ by results of tests was carried out taking into account the heat expended on the thermal decomposition of fuel.

Figure 2 shows that the combustion chamber when pre-gasified fuel is introduced into it has higher values of $\eta_z$ in the entire range of air flow $G_B$ and $\alpha$. It also provides better characteristics of flame failure, which indicates a higher chemical activity of thermal decomposition products compared to the original fuel.

The obtained results are in good agreement with the theoretical analysis [1]. Comparative calculations of thermal decomposition products combustion containing H2, CH4 and C4H10, as well as fuel of the initial composition, performed in the framework of the two-stage kinetic model of combustion, showed that in temperature range 930 - 1730°C oxidation of thermal decomposition products is always more intense than the oxidation of the initial fuel, especially in the region of lower temperatures.

Figure 2. The combustion chamber characteristics on air consumption for different degrees of thermal decomposition of fuel $Z$: 1- $Z = 0$; 2- $Z = 0.25$.

To assess the propensity of fuel to carbon formation, a removable element—a thin-walled glass—was installed in the chamber, which allowed to increase the accuracy in determining the amount of formed carbon due to its low weight and its location in the zone of increased carbon formation.

Preheating the fuel in the reactor was carried out to a temperature of 620°C to obtain a high degree of degradation with the formation of pyrogas. The tests were carried out in two versions: with the supply of thermal degradation products of fuel into the combustion chamber, as well as with pre-cooling in water refrigerators, in order to eliminate the influence of temperature on the studied characteristic. The results of the experiments are shown in figure 3, where $m/m_0$ is the ratio of the mass of carbon on the removable element during combustion of fuel products after the process of thermal degradation $m$ to the mass of carbon from the original fuel $m_0$. 
Figure 3. The influence of the degree of thermal decomposition of fuel on carbon formation in the subsonic combustion chamber: 1 - \( t_{\text{t}} = 100^\circ\text{C} \); 2 - \( t_{\text{t}} = 600^\circ\text{C} \)

Figure 3 shows that the amount of carbon decreases with an increase in the degree of thermal decomposition \( Z \). Moreover, with a maximum value of \( Z = 0.25 \), the mass of carbon deposits decreased in comparison with the original fuel by 10 times. In the pre-cooling mode of thermal destruction products, there is also a reduction in the mass of carbon deposits on the removable element, but the value of the reduction is 2-2.5 times less.

The obtained data indicates a significant reduction in carbon formation on the combustion chamber elements during preliminary thermal decomposition of fuel.

Preliminary thermal decomposition of fuel should contribute to an increase in the speed and completeness of combustion due to the formation of hydrogen in the composition of pyrogas. It is of practical importance for supersonic VRD operated with endothermic fuels. To assess the effect of thermal decomposition on the completeness of combustion, special tests were carried out, the results of which are shown in figure 4.

Figure 4. The influence of the fuel thermal decomposition degree \( Z \) on the combustion completeness \( \eta_c \): 1 - \( Z = 0 \); 2 - \( Z = 0.25 \).

It can be seen that at the same value of the excess air coefficient, the combustion completeness of the degradation products is higher than that of the original fuel. The most noticeable effect in the range of numbers \( \alpha = 2.5-5 \), where there was not a high completeness of fuel combustion. At \( \alpha > 5 \), due to the increase in the completeness of combustion, the effect is leveled. As the \( Z \) value increases, the combustion completeness increases.

The comparative studies of the characteristics of combustion products of thermal decomposition and the original endothermic fuel ET-1 in the air flow showed that the workflow in the subsonic combustion
chamber VRD could be improved by increasing the degree of pre-thermal degradation of fuel. Preliminary thermal decomposition of fuel improves combustion characteristics: increases the completeness of combustion, improves the stall characteristics of the chamber, reduces carbon formation.

References
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