## AIRCRAFT AND ROCKET ENGINE
## DESIGN AND DEVELOPMENT

# Investigation of the Flame Stabilization Mechanism in Phase-Inhomogeneous Air–Fuel Mixtures

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**Abstract**—The mechanism of flame stabilization in phase-inhomogeneous air–fuel mixtures is considered. A method is proposed for refining the thermal theory of flame stabilization by taking into account the heat consumed for heating and evaporation liquid fuel in the ignition zone. An analytical dependence is obtained for the calculation of flaming out curves during the steady combustion of two-phase mixtures. Analysis of the experimental data shows their compliance with the laws of the calculated dependence.

At present, the mechanism of flame stabilization in a stream using separated flows is regarded as well studied and numerous theories in this area allow obtaining sufficiently accurate methods for calculating the flame separation boundaries. However, the variety of factors influencing the process of flame stabilization, especially in burning of inhomogeneous mixtures, requires additional study of the flame stabilization mechanism, since in practice, models obtained analytically on the basis of physical models of the process are widely used [1–5].

The additional information about this phenomenon was provided with the advent of new technologies for modeling the gas-dynamic and thermodynamic processes based on the use of high-power computers [6–8].

One of the best known models is the thermal model of flame stabilization.

In terms of the flame stabilization thermal theory, continuous ignition of the mixture in the circulation zone is possible only if the required amount of heat is supplied to a unit of volume of the mixture capable to burn. When a two-phase mixture ignites, part of the heat of the recirculation mixing zone (RMZ) is additionally spent on heating and evaporating the liquid fuel, therefore, the minimum required amount of heat is the sum of the heat spent on heating $q_h$, evaporation $q_{ev}$ of liquid droplets, and heating the resulting vapor–air mixture to the ignition temperature $q_i$:

$$Q_r = q_h + q_{ev} + q_i.$$

To estimate the minimum amount of heat required to ignite the two-phase mixture during contact with hot gases from the recirculation mixing zone, we consider the heat exchange process in the boundary layer of the front part of the RMZ. Here, the fresh mixture receives heat for heating and evaporating the droplets and heating of the resulting vapor–air mixture to the ignition temperature.

Figure 1 presents the pattern of the flame propagation in the mixing layer of the fresh mixture and hot gases. Here *A* is the ignition point; *1*—the swirler; *2*—the boundary of the RMZ; *3*, *4*—the forward and recirculation flows; *5*—the flame propagation in the mixing layer.
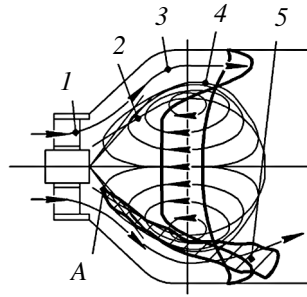
**Fig. 1.**

The heat amount required to heat the liquid fuel passing through the boundary layer to the temperature of equilibrium evaporation is

$$q_h = G_{fl}c_{pl}\left(T_e - T_{l0}\right),$$

where $c_{pl}$ is the heat capacity of the liquid fuel; $\left(T_e - T_{l0}\right)$ is the difference between the temperature of equilibrium evaporation and the initial temperature of the fuel.

Here the flow rate of liquid fuel through the layer under consideration is determined by the formula

$$G_{fl} = \frac{G_a}{L_0 \alpha_{bl}},$$

where $\alpha_{bl}$ is the composition of the fresh mixture in the boundary layer of RMZ ignition.

Air flowrate $G_a$ through this layer can be defined as

$$G_a \approx \pi D_z \delta_d \rho_w W.$$

If we assume that a layer of droplets is involved in the heating, which is close to the RMZ boundary, then the average diameter of the droplets in the mixture $\delta_d$ can be taken as the thickness of the layer of the liquid fuel heating:

$$\delta_d \approx d_{d0}.$$

Then the amount of heat required for heating the liquid fuel is determined by the following formula:

$$q_h \sim \frac{d_{d0}\pi D_z \rho_w W}{L_0 \alpha_{bl}} c_{pl}\left(T_e - T_{l0}\right).$$

Similarly, we can find the amount of heat needed to evaporate the fuel:

$$q_{ev} \sim \frac{d_{d0}\pi D_z \rho_w W}{L_0 \alpha_{bl}} H_{ev}z,$$

where: $H_{ev}$ is the heat of evaporation; $z$ is the degree of fuel evaporation for the characteristic time of the mixture residence in the circulation zone.

The amount of heat per unit of time required for ignition of the resulting vapor–air mixture increases with an increase in the mixture flow rate $G_m$ and the difference between the ignition temperature and the initial temperature $\left(T_i - T_m\right)$:

$$q_i \sim G_m c_p \left(T_i - T_m\right).$$

Here the vapor–air mixture flow rate can be determined from the equation

$$G_m = \pi D_z \delta_t W \rho w,$$

where $W$, $\rho$ are the speed and density of the mixture; $\delta_t$ is the thickness of a layer of the vapor–air mixture heating to the ignition temperature $T_i$.

The thickness $\delta_t$ is expressed by the following dependence according to [1]:

$$\delta_t = \frac{\lambda}{\rho c_p U_n} = \frac{a_m}{U_n}.$$

Then

$$q_i \sim \pi D_z \rho_w W a_m \frac{\lambda}{U_n}(T_i - T_m).$$

To calculate the amount of heat $Q_z$ transmitted per unit of time from the RMZ to the cold two-phase mixture to heat it to the temperature $T_i$, the heat transfer equation is used in [1]:

$$Q_z = \pi D_z l \chi (T_z - T_m),$$

where $\chi$ is the heat transfer coefficient; $T_z$ is the temperature of the gases in the RMZ.

From the condition of geometric similarity it follows that $l \sim D_z$, where $D_z$ is the characteristic size of the recirculation mixing zone (its diameter).

Using the empirical dependence $\mathrm{Nu} = \mathrm{Re}^{0.5}$, we can obtain

$$Q_z = \left[ \left( \frac{WD_z}{\nu} \right)^{0.5} \frac{\lambda}{D_z} \right] D_z^2 \pi (T_z - T_m).$$

Critical conditions for flame-out occur when $Q_z = Q_r$. After substituting the corresponding values of heat and simplifying transformations of this equality, we can obtain an expression for calculating the boundaries of the steady combustion of the two-phase mixture:

$$\sqrt{\frac{D_z}{W}} = B_1 \frac{a_m^{0.5}(T_i - T_m)}{U_n(T_z - T_m)} + B_2 \frac{d_{d0}\left[ c_{pl}(T_e - T_{l0}) + H_{ev}z \right]}{\alpha_{bl} L_0 a_m^{0.5} c_p(T_z - T_m)},$$

where $T_m$ is the initial temperature of the mixture; $T_z$ is the temperature reached in the RMZ; $d_{d0}$ is the initial diameter of the droplets in the mixture entering the circulation zone; $B_1, B_2$ are the experimental coefficients; $T_i, U_n$ are the ignition temperature and the normal rate of flame propagation. They correspond to mixture compositions favorable for ignition in the local zones of the RMZ boundary layer ($\alpha_{bl} \approx 1$).

In practical calculations, the temperature $T_z$ of combustion in the RMZ can be determined from the approximate dependence (at $\alpha_z > 1$)

$$T_z = T_m + \frac{H_u \eta_z}{c_p(1 + \alpha_z L_0)},$$

where $H_u$ is the lower heating value of the fuel; $\eta_z$ is the combustion efficiency.

The initial average diameter of a drop in a mixture $d_{d0}$ is determined using the Weber criterion.

The found equation reflects the main regularities of change in the limiting characteristic of the steady combustion boundaries for a two-phase mixture and it is convenient for using in qualitative analysis process. In combustion of a homogeneous mixture ($d_{d0} = 0$), this ratio transforms into the well-known Williams model [4]. From this dependence, it follows that in combustion of a two-phase mixture,

the maximum attainable rate of flame-out is less than in combustion of a homogeneous mixture (the right-hand side of this ratio has a two-member form). The maximum possible range of steady combustion in lean two-phase mixtures is wider than in homogeneous ones, since in local zones of a fresh two-phase mixture, there are compositions close to stoichiometric ones ($\alpha_{bl} \approx 1$), due to which the earlier ignition takes place by high-temperature combustion products from the RMZ.

Figure 2 shows the flaming out curves of steady combustion as dependencies of the flow speed $W$ on the total composition of the mixture in the combustion chamber $\alpha_\Sigma$ at flame-out for different mixing schemes. Here ——— —feeding the homogeneous mixture into the combustion chamber; • —fuel supply using a fuel–air atomizer; ◊, × —combustion of a fuel that is inhomogeneous in composition and phase. It is clear that with increasing the degree of inhomogeneity of the mixture, the flame-out limits shift to the area of greater $\alpha_\Sigma$ values, i.e. lean mixtures with simultaneous reducing the maximal achievable flow speeds, which corresponds to conclusions obtained in theoretical consideration of the flame stabilization mechanism in two-phase mixtures.
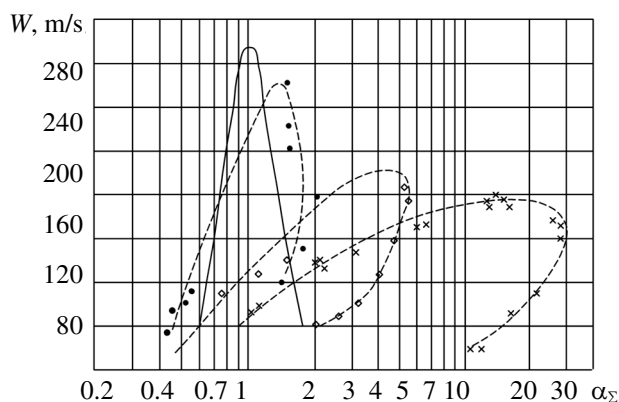


**Fig. 2.**

Thus, the dependences obtained for flame stabilization allow us to consider the phase inhomogeneity influence on the flaming out curves behavior and also to analyze the influence of various factors on the flame stabilization process in heterogeneous mixtures.

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