Mechanisms of Flame Stabilization in a Ramjet Burner

S.M. Frolov, V.Ya. Basevich, A.A. Belyaev
N. N. Semenov Institute of Chemical Physics
4, Kosigin Str., Moscow, 117977 Russia

The knowledge of physical mechanisms of flame stabilization at bluff-body flame holders is necessary for elaborating efficient means to control combustion in ramjet burners. For understanding the mechanisms of flame stabilization, detailed computations of premixed and non-premixed turbulent combustion were performed. Fluid particle tracing techniques were used to study the histories of temperature and species concentrations in notional fluid particles, and to estimate characteristic residence and reaction times in the recirculating flow. Based on these studies, quantitative criteria of flame stability were formulated. The criteria provide sound grounds for applying various means for passive and active combustion control.

Introduction

The flow patterns around bluff bodies in combustible flows are still not understood completely. What is definitely known is the existence of a recirculation zone in the immediate wake of the flame holder which takes the form of a pair of eddies, similar to isothermal flows. The length of the recirculation zone differs for 2D and axisymmetric bluff bodies.

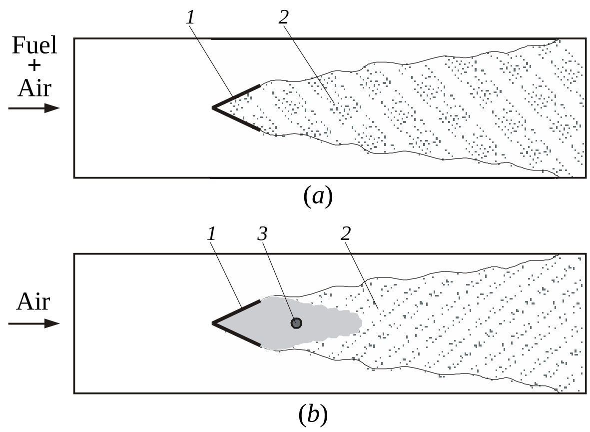
Bluff body flame stabilization in non-premixed and partially premixed gaseous systems is complicated by mixing of fuel and oxidizer. In addition to the aspects mentioned above, a necessity of controlling fuel distribution in the burner becomes an important factor in maintaining stable combustion in the overall fuel–air ratio range desired. Flame stabilization in partially premixed methane-air and propane–air mixtures was studied.[1,2] A number of publications are available on flame stabilization in non-premixed gaseous systems.[3,4] Flames of fuel sprays were considered in application to specific combustor designs. In the latter case, additional complications dealing with spray atomization, volatility, and fuel droplet migration come into play.

There is obviously the need in further studies of the mechanisms governing flame stability, in particular, in confined flows with premixed and non-premixed combustion. The objective of this research is a thorough analysis of flame behavior near stability limits, applying the computational approaches developed earlier.[5–8]

Formulation

Figures 1*a,b* show typical burners with flame holder. Mathematically, the compressible turbulent reactive flow in the burner is assumed to be governed by the Favre averaged conservation equations of mass, species continuity, momentum and energy, supplemented with the averaged thermal and calorific equations of state for chemical species. A standard $k-\varepsilon$ model was employed as a turbulence closure. For modeling mean reaction rates, a presumed probability density function (PDF) method,[8] as well as the joint velocity–scalar PDF method[6,7] were applied. In the latter case, only equation for ε was solved to provide the turbulence time scale.

Figure 1 Typical burners with flame holder. (*a*) premixed combustion, (*b*) non-premixed combustion. *1* — flame holder,



2 — combustion products, *3* — fuel injection core

A set of initial conditions included the specification of velocity, pressure, temperature (T_0), turbulence parameters, and species concentrations in the computational domain. Ignition was simulated by enveloping the flame holder by hot combustion products at temperature T_c, to avoid generation of intense ignition-induced pressure disturbances. Temperature T_c

Approved for public release; distribution is unlimited.

is the adiabatic flame temperature for the mixture of equivalence ratio Φ. No-slip, constant temperature boundary conditions at rigid walls were adopted. At the burner inlet, constant velocity (u_{in}), temperature, turbulence parameters and species concentrations were specified. Non-reflecting pressure boundary conditions[8] were applied at the burner outlet that ensured transparency to pressure disturbances generated inside the computational domain.

Combustion of gaseous methane in air was considered. Detailed, systematically reduced, and overall reaction mechanisms of methane oxidation were used.

Computationally, the set of governing equations was solved by the finite volume method on generalized boundary-fitted curvilinear non-orthogonal computational grids, applying FIRE solvers, developed by AVL LIST GmbH, Austria.

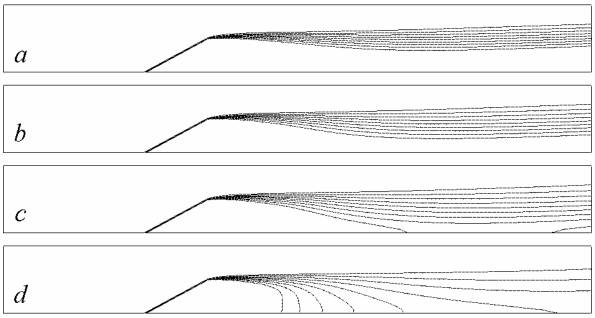


Figure 2 Predicted temperature fields during combustion of premixed stoichiometric methane – air mixture in a burner with flame holder: t = 50 ms, u_{in} = 40 m/s (*a*), 50 (*b*), 60 (*c*), and 80 (*d*)

Stability of Premixed Flames

Figure 2 shows the predicted temperature fields during combustion of premixed stoichiometric methane–air mixture at normal conditions and different inlet velocity u_{in}. A burner is 1 m long and 0.2 m wide. A flame holder is a V-gutter with apex angle 60° and height $H = 10$ cm. Only upper half of a burner is considered due to symmetry properties of the arising flames.[8] Isotherms correspond to uniform division of the whole temperature interval from T_0 to T_c to 10 sections. Combustion is stable at $u_{in} < 50$ m/s. The residual flame arising at $u_{in} > 60$ m/s decays in a long run. At $50 < u_{in} < 60$ m/s, the abrupt change in flame evolution occurs: the flame loses stability and blows off.

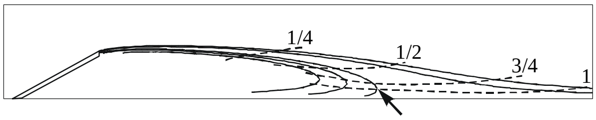


Figure 3 Calculated trajectories of the averaged motion of notional particles in the vicinity of the flame holder

In order to understand the reasons of the abrupt changes in flame evolution when the approach stream velocity increases above a certain critical value, consider Fig. 3. Figure 3 shows five calculated trajectories of the averaged motion of notional fluid particles in the vicinity of the flame holder, for the case of stable combustion. The recirculation zone is seen behind the flame holder. Three of the five trajectories have turning points where the averaged flow changes to the opposite its direction. There exists the limiting trajectory (shown by arrow) which separates the trajectories with and without turning points. The analysis revealed that the turning point at the limiting trajectory is of significant importance for flame stability. When following the mean temperature evolution along the limiting trajectory, it was observed that the flame was stable if temperature attained the value T_* close to T_c (eventually $T = 0.95T_c$) before reaching the turning point. If temperature T_* was attained after passing the turning point at the limiting trajectory, the flame was unstable. In the latter case, even if T_* was attained very close to but after the turning point, the flame inevitably blew off though exhibiting a few violent longitudinal oscillations.

Thus, the mechanism of premixed flame stabilization is seen as follows. In the vicinity of flame holder, the fresh fuel–air mixture interacts with combustion products (and, in general, with residual fuel (at $\Phi > 1$) or air (at $\Phi < 1$)) filling the recirculation zone. This interaction occurs in a turbulent mixing layer at the outer border of the recirculation zone, where mixing takes place. Combustion stability is achieved due to continuous ignition of the mixture in a certain location in the mixing layer and due to continuous feeding of the recirculation zone by the hot combustion products. When tracing a notional particle, its ignition can be characterized with time t_c after particle entered the mixing layer. Occasional delay or advance in particle ignition does not violate the energy balance in the recirculation zone unless the products of incomplete combustion enter the recirculation zone. If t_c exceeds a certain critical value, the energy balance is violated and the recirculation zone fails to support stable combustion. The critical delay in particle ignition is determined by time t_r required for the particle to reach the turning point at the limiting trajectory. Shown in Fig. 3 by dashed curves are the curves $t/t_r = const$, which illustrate the flow field behind the bluff body.

Quantitatively, the stability criterion for premixed flames is written as

$$\mathrm{Mi} = \frac{t_r}{t_c} > 1 \qquad (1)$$

where Mi is the Mikhelson number and t_c is defined as the time taken for the fluid particle to attain temperature T_*. Table 1 summarizes the data for t_r, t_c, and Mi for three V-gutters of different height H : 10 cm (No.1), 5 cm (No.2), and 2 cm (No.3). The calculated values of maximum flow velocity in the narrowest cross section of the burner, u_m, are also presented. As follows from Table 1, the Mikhelson number of unity separates the solutions with stabilized and unstable flames. The Mikhelson number for the V-gutter No.2 is larger than that for No.1 and No.3, other conditions being equal. This is the indication of the non-monotonic dependence of the limiting approach stream velocity on the size of the flame holder.[9] Table 2 compares the calculated t_r, t_c, u_m, and Mi data for the flame holders of similar size (5 cm) but different shape: V-gutter (No.1), plate (No.2), and rod (No.3). The open-edge V-gutter appears to exhibit the widest stability limits in the burner under consideration. Its stability limits are wider than those for the plate and rod, that agrees with experimental data.[9]

The comparison of predicted and measured[2,10] limiting approach stream velocities for the rod flame holder is presented in Fig. 4 as a function of the equivalence ratio. The calculations were performed by using the presumed PDF method.[8] In these calculations, the probability density of intermediate temperatures P_T in the turbulent flame brush and 'widths' of PDF modes at the ends of the temperature interval were fixed throughout the whole range of the equivalence ratios, except for the lower and upper flammability limits. At approaching the limits, the presumed PDF had to be corrected in order to fit the experimental data.

Table 1 Predicted combustion time t_c, residence time t_r, and the Mikhelson number Mi in a ramjet burner with flame holder of height H at various inlet velocities. Signs "+" and "–" correspond to stable combustion and flame blow-off, respectively

No.	H m	u_{in} m/s	u_m m/s	t_c ms	T_r ms	Mi	Stab-ility
1	0,1	40	85	4.4	8.4	1.9	+
		50	106	6.4	7.6	1.2	+
		60	130	8.0	6.4	0.8	–
2	0,05	20	28	3.5	11.2	3.2	+
		40	57	4.4	8.8	2.0	+
		50	72	5.6	7.2	1.3	+
		60	87	7.6	6.0	0.8	–
3	0,02	20	23	4.4	8.8	2.0	+
		30	35	4.6	5.6	1.2	+
		40	47	6.4	4.8	0.75	–

Table 2 Predicted values of t_c, t_r, and Mi in a ramjet burner with flame holder (V-gutter (No.1), plate (No.2), and rod (No.3)) of 5 cm height depending on the inlet velocity. Signs "+" and "–" correspond to stable combustion and flame blow-off, respectively

No.	u_{in} m/s	u_m m/s	t_c ms	t_r ms	Mi	Stab-ility
1	20	28	3.5	11.2	3.2	+
	40	57	4.4	8.8	2.0	+
	50	72	5.6	7.2	1.3	+
	60	87	7.6	6.0	0.8	–
2	20	29	4.5	10.9	2.4	+
	30	44	5.1	8.8	1.7	+
	40	58	6.3	8.0	1.3	+
	50	72	11.2	7.0	0.6	–
3	20	32	6.1	10.2	1.7	+
	30	49	7.2	6.3	0.9	–

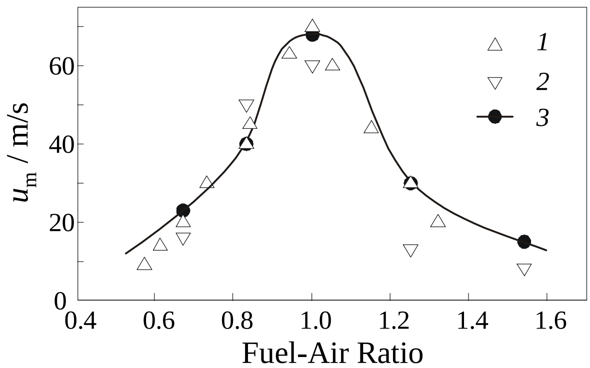


Figure 4 Comparison of predicted (*3*) and measured[2,10] (*1*, *2*) limiting approach stream velocities depending on the fuel–air ratio

Stability of Non-Premixed Flames

In simulations of non-premixed flames, fuel injection was modeled by a source term in the fuel conservation equation. The source term was taken zero everywhere in the computational domain except for the injection core (see Fig. 1*b*). Injection-induced momentum and energy deposition to the flow was neglected. Mean reaction rate was calculated by the presumed PDF method[8] as a function of local values of mean temperature and equivalence ratio. Detailed reaction mechanism of methane oxidation was used for calculations of reaction rates in laminar flames of various compositions. The values of equivalence ratio at the lower and upper flammability limits for methane were taken $\Phi_l = 0.67$ and $\Phi_u = 1.54$, respectively. The mean reaction rates at $\Phi > \Phi_u$ and $\Phi < \Phi_l$ were linearly extrapolated to zero.

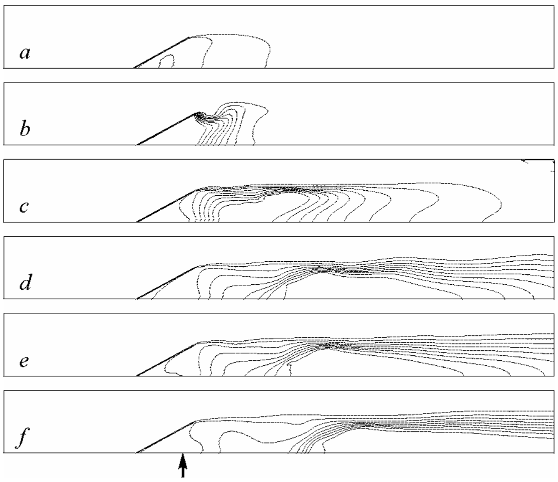


Figure 5 Predicted temperature fields during non-premixed combustion of methane-air mixture in a burner with flame holder. Temperature fields correspond to t > 70 ms after ignition and u_{in} = 10 m/s. Arrow shows a position of fuel injection core. (*a*) $m_g = 2$ mg/s, (*b*) 15, (*c*) 20, (*d*) 50, (*e*) 100, (*f*) 200

Figure 5 shows predicted temperature fields for the case when the fuel injection core is positioned inside the bluff-body, at a distance $x_{jc} = 8$ cm from the apex. In this example, $u_{in} = 10$ m/s and the mass flow rate of fuel injection m_g varies from 2 mg/s to 200 mg/s. A burner is 1 m long and 0.2 m wide. A flame holder is a V-gutter with apex angle 60^o and height $H = 10$ cm. Isotherms correspond to uniform division of the whole temperature interval from T_0 to $T_{c,st}$ to 10 sections. Here $T_{c,st}$ is the adiabatic combustion temperature for the stoichiometric methane–air mixture.

At low m_g, in the long run mixture composition is beyond the flammability limits everywhere in the computational domain, and combustion does not occur (Fig. 5*a*). Increase in m_g results in fuel ignition inside a V-gutter and stable positioning of the combustion zone at the edge of the stagnation region behind the body (Fig. 5*b*). Further increase in m_g results in the displacement of the combustion zone downstream from the body and in spreading the flame area (see Figs. 5*c*–*f*).

The flame in Fig. 5*f* is at the stability margin. The high-temperature region is located downstream from the recirculation zone. Nevertheless, a notional particle travelling along the limiting trajectory still ignites before the turning point. The particle becomes flammable ($\Phi < \Phi_u$) just before reaching the turning point and the particle mean temperature at the ignition site (about 1600 K) is close to the corresponding combustion temperature.

When the fuel injection core is positioned far behind the recirculation zone (e.g., at a distance of 50 cm from the body apex), flame blows off.

In the case when the fuel injection core is positioned outside the bluff body but still inside the recirculation zone, the flame behavior is similar to that shown in Fig. 5. In a series of numerical tests with $x_{jc} = 26$ cm, $u_{in} = 15$ m/s, the mass flow rate of fuel injection m_g varied from 10 mg/s to 150 mg/s. Similar to Fig. 5*a*, at low m_g values, m_g < 20 mg/s, mixture composition was beyond the flammability limits everywhere in the computational domain, and combustion did not occur. At m_g = 50 mg/s, the flame arose and stabilized at the edge of the V-gutter and the fuel jet core. Further increase in m_g resulted in elongating the flame zone downstream from the body. At m_g lager than approximately 80 mg/s, flame separation into two combustion zones occurred. The first zone was positioned in the nearest wake behind the body, while the second was located downstream from the fuel injection site. The second flame exhibited irregular longitudinal oscillations. Finally, at m_g = 150 mg/s, the flame blew off.

Figure 6 shows the history of integrated mixture fraction (solid curve) and fuel mass (dashed curve) in the burner at m_g = 30 mg/s, $u_{in} = 15$ m/s, and

$x_{jc} = 26$ cm. For a relatively long time, fuel is accumulated in the recirculation zone and only a part of it burns. When the flow is stabilized (at $t > 25$ ms), a large amount of unreacted fuel still exists in the burner. At this stage, there is a balance between fuel supply and its diffusion through the mixing layer at the edge of the recirculation zone. The difference between the solid and dashed curves is the measure for the amount of fuel burned. This difference is slightly less than m_g, which is the indication that some unburned fuel leaves the burner through the outlet.

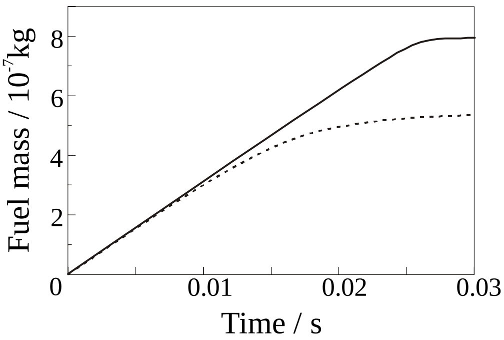


Figure 6 The predicted history of mixture fraction (solid curve) and fuel mass (dashed curve) in the burner at $m_g = 30$ mg/s, $u_{in} = 15$ m/s, and $x_{jc} = 26$ cm

The mechanism of non-premixed flame stabilization is seen very similar to that relevant to the premixed combustion. As far as the injection core is positioned inside the recirculation zone behind the flame holder and the fuel mass flow rate m_g is sufficient to support combustion (i.e. to provide $\Phi_l < \Phi < \Phi_u$), the mechanism is treated as follows. In the recirculation zone, the accumulated fuel is mixed with high-enthalpy combustion products entering the zone at the rear end. In the vicinity of flame holder, the fresh air mixes with preheated fuel and the combustion products from the recirculation zone. Combustion stability is achieved due to continuous ignition of the mixture in a certain location in the mixing layer, and due to continuous feeding of the recirculation zone by the combustion products. Thus, as compared to the premixed flame, an additional condition for flame stability arises, that is the necessity for the mixing process to ensure the mixture in the mixing layer to be within the flammability limits, when approaching the end of the recirculation zone. In the simplest case of mixing controlled ignition, $t_c = t_m$, where t_m is the characteristic mixing time in the mixing layer. Quantitatively, the stability criterion for non-premixed flames is similar to Eq. (1).

Figure 7 shows a comparison of predicted and measured[4] limiting approach stream velocities for bluff-body stabilized combustion of non-premixed methane-air mixture as a function of fuel mass flow rate. In experiments,[4] a 3D flow pattern took place since methane was injected from the lateral wall of a burner, transversely to the flow. A burner had a rectangular cross section, and an open-edge V-gutter served as a flame holder. In a model, a 2D formulation was applied with the shape of the flame holder, fuel injection site, and the burner blockage ratio (B.R. = 0.5) kept similar to those in experiments.[4] The agreement between the predicted and measured results in Fig. 7 is encouraging. The predicted limiting values of u_{in} differ from the corresponding measured values by a factor of 2, at most. Calculations predict a rich limit of flame stability that was not observed experimentally.

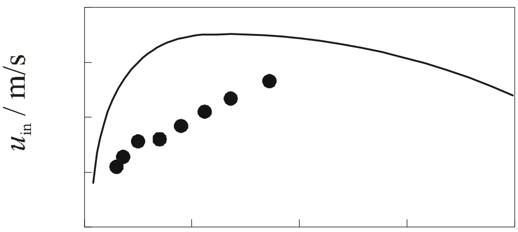


Figure 7 The comparison of predicted and measured[4] limiting approach stream velocities for bluff-body stabilized combustion of methane as a function of fuel mass flow rate

Combustion Control Strategies

The stability criterion (1) provides sound grounds for applying various means for passive and active combustion control. Clearly, increase in t_r and decrease in t_c values results in improvement of flame stability.

The value of t_r can be increased by means of decreasing the flow velocity at the edge of the flame holder. First, this can be achieved by changing the shape of the bluff body, e.g. replacing a rod by plate or V-gutter (see Table 2). Second, this can be achieved by displacing the velocity maximum away from the body. For premixed flames, the latter approach was successfully demonstrated,[8] and various means for displacing the velocity maximum were considered. Third, this can be achieved by proper relative positioning of several flame holders.[11] It was shown[11] that there exists an optimum distance between flame holders, which ensures the highest combustion stability at variable operating conditions.

The value of t_c can be decreased by means of promoting combustion. Both in premixed and non-premixed bluff-body stabilized flames, one of the most important processes controlling combustion is mixing. For premixed flames, it is mixing between the fresh fuel–air mixture and combustion products filling the recirculation zone. For non-premixed flames, it is mixing of air with fuel and combustion products. Keeping in mind that the approach stream turbulence deteriorates combustion stability, at least for premixed flames,[12] the prospective approach is to arrange the enhanced turbulent mixing/entrainment in the mixing layer at the border of the recirculation zone, without effecting transport processes in the free stream. Experiments[12] demonstrated that the use of turbulence enhancing elements at the edge of the V-gutter intensified combustion significantly. Combustion can be promoted by chemical additives and active centers,[7] partial premixing,[1,2] secondary injection of combustion products,[8] irradiation of the mixture, etc.

Conclusion

Detailed computations of premixed and non-premixed turbulent combustion in burners with flame holders were performed to understand the mechanism of confined flame stabilization. Apart from sophisticated computational techniques, fluid particle tracing techniques were extensively used to follow the histories of temperature and species concentrations in notional fluid particles, and to estimate characteristic residence and reaction times in the flow. Based on these studies, the criteria of flame stability were formulated which provide sound grounds for applying various means for passive and active combustion control. Qualitatively, these criteria are similar to heuristic relationships known earlier, however here they were substantiated quantitatively. In future, it is intended to spread the analysis to transonic and supersonic flows and to combustion of fuel sprays.

References

[1]Fettig, F., Choudhuru, A. P. R., and Wilhelm, R. H. *Proc. 7th Symp. (Intern.) on Combustion.* London: Butterworth Sci. Publ., 1959, 621.

[2]Filippi, F., and Fabbrovich-Mazza. L. *Proc. 8th Symp. (Intern.) on Combustion.* Baltimore: The Williams and Wilkins Co. 1962, 256.

[3]Chen R.-H., Driscoll, J. F., Kelly, J., Namazian, M., and Schefer, R. W. *Comb. Sci. Techn.* 1990, 71, 197.

[4]El-Atroush, A. A., Litwin, T., and Wolanski, P. *Archivum Combustionis.* 1996, 16(3–4), 243.

[5]Frolov, S. M., Basevich, V. Ya., Neuhaus, M. G., et al. *Proc. 8th ONR Propulsion Meeting* (G. D. Roy and F. A. Williams, Eds.). San Diego: Univ. of Calif., 1995, 27.

[6]Frolov, S. M., Basevich, V. Ya., Neuhaus, M. G., et al. *Proc. 9th ONR Propulsion Meeting* (G. D. Roy and K. Kailasanath, Eds.). Washington, DC: Naval Research Lab., 1996, 305.

[7]Frolov, S. M., Basevich, V. Ya., Belyaev, A. A., et al. *Proc. 10th ONR Propulsion Meeting*. Monterey: Naval Postgrad. Sch., 1997, 38.

[8]Frolov, S. M., Basevich, V. Ya., Belyaev, A. A., et al. *Proc. 11th ONR Propulsion Meeting* (G. D. Roy and A. Krothapalli, Eds.). Tallahassee: Florida State Univ., 1998, 9.

[9]Raushenbakh, B. V., Belyi, S. A., Bespalov, I. V., Borodachev, V. Ya., Volynskii, M. S., and Prudnikov, A. G. *Physical Fundamentals of the Operation Process in Ramjets.* Moscow, Mashinostroenie, 1964.

[10]Basevich, V. Ya., and Kogarko, S. M. *Sov. J. Phys. Combustion and Explosion.* 1972, 8(4), 582.

[11]Frolov, S. M., Basevich, V. Ya., Belyaev, A. A., et al. In: *Chemical Propulsion* (G. D. Roy, Ed.) Taylor & Francis, Washington, DC, 1999 (in press).

[12]Solntsev, V. P. In: *Flame Stabilization and the Development of Combustion in Turbulent Flow* (G. M. Gorbunov, Ed.), Moscow, Oborongiz, 1961, 75.