MECHANISM OF TURBULENT FLAME STABILIZATION ON A BLUFF BODY

S.M. FROLOV, V.Ya. BASEVICH, and A.A. BELYAEV
N.Semenov Institute of Chemical Physics, Russian Academy of Sciences, Moscow, 117977 Russia

Results of detailed calculations of combustion in a wake behind a bluff body are presented and a flame stabilization criterion is formulated. According to this criterion, a flame is blown off from the flameholder at a Michelson number value less than unity, i.e., when the burning time of a particle moving along the limiting trajectory in the recirculation zone exceeds the time of particle journey to the turning point of the limiting trajectory. The calculated limiting velocity at which a stoichiometric methane-air flame is stabilized agrees satisfactorily with the available experimental data. It is shown that as the ratio of channel blockage by the flameholder changes, the range of stable combustion varies nonmonotonically, namely, there is an optimal flameholder size at which the best stabilization parameters are achieved. This result is also consistent with experimental observations.

(Received February 2, 1999)

1. INTRODUCTION

Flame stabilization in a turbulent flow by the aerodynamic recirculation technique is extensively used in practice, e.g., in engine devices of aircrafts [1,2], industrial burners, and so on. Nonetheless, the level of understanding of the phenomenon is still insufficient for applying the suggested theoretical and computer models to designing combustion chambers and for optimizing the design and operation parameters of engine devices.

The most important characteristic of a combustion chamber is the range of fuel-air mixture composition within which combustion is stable. Flame stabilization on bluff bodies of various shape and size was studied in numerous experimental works [3-15]. Stabilization limits were assessed at various velocities of the incident flow, its temperature, turbulence intensities at the combustion chamber inlet, pressure in the chamber, channel blockage
with the flameholder, fuel sort, flameholder temperature etc. A functional
correlation between the limiting ratio of the fuel and air flow rates \( \Phi \) in the
combustion chamber was ascertained. It is normally written as follows

\[
\frac{U}{p^\alpha H^\beta T^\gamma} = f(\Phi),
\]

where \( U \) is the flow velocity, \( p \) is the pressure, \( H \) is the representative
flameholder size, and \( T \) is the flow temperature. Various authors report
different exponent \( \alpha, \beta, \) and \( \gamma \) values. For example, exponent \( \alpha \) equals 0.95
in [6], exponent \( \beta \) varies from 0.45 to 1.0 in [8], and exponent \( \gamma \) assumes
a value equal to 1.7 in [6]. As follows from Eq.(1), a flame is more stable
at high flow pressures and temperatures, low flow velocities, and when
flameholders are of larger size (at a low blockage ratio in a combustor
equipped with a flameholder).

The available stabilization criteria are based on a comparison of the
representative times of chemical reactions and the mixture residence time
in the recirculation zone. The theoretical models of flame propagation in
turbulent flows either assume that the rate controlling step is mixing [16,17]
or use fairly simplified mechanisms of chemical reactions [18]. Models
suggested in [16-18] fail to explain many experimental observations.

At present problems on flame stabilization in a turbulent flow are
solved numerically integrating the equations of chemical hydrodynamics
(see, e.g., [19,20]). The approach is based on multi-dimensional
hydrodynamic equations, i.e., conservation equations for mass, momentum,
and energy, together with continuity equations for individual components of
the reacting medium. Time and space scales in a reacting turbulent flow are
extremely diverse, therefore when solving stabilization problems one has to
introduce additional model assumptions to describe coupling between
turbulence and combustion. Moreover there arises another fundamental
problem — formulation of the boundary conditions at the open combustor
ends (inlet and outlet). The computation region in practical calculations must
always be restricted. In doing so, of importance is to provide "transparen-
cy" of the conditional open boundaries to acoustic perturbations generated
in the combustion zone. As distinct from [19] where the "reflecting"
Dirichlet boundary conditions were used, in [20] a method for calculating
flame stabilization based on "non-reflecting" boundary conditions was
suggested. In [20], we employed a prescribed probability density function
(PDF) for the temperature in a turbulent flame and detailed fuel oxidation
kinetics.

The objective of the present work is to apply the method suggested in
[20] to investigation of the stabilization phenomenon based on the
fundamental equations of chemical hydrodynamics aimed at formulation of
the flame stability criterion.

2. FLAME STABILIZATION MECHANISM

Although the phenomenon of flame stabilization on bluff bodies has been extensively employed in practice, reactive flows around flameholders are still poorly understood. It is commonly recognized that in a reacting flow, likewise in isothermal flows, a recirculation zone with two symmetric domains of vortex motion of the combustion products is formed behind the flameholder [1,2]. The recirculation zone lengths \( L_{rc} \) behind plane and axisymmetric bodies are different. The \( L_{rc}H \) values measured in combustion chambers with plane flameholders of height \( H \) (V-shaped, cylindrical, prismatic, and other flameholders) vary between 3 and 6 [11], depending on the burner operation conditions. These ratios are significantly greater than the appropriate values in isothermal flows \( (L_{rc}/H \approx 1.5 - 2.0) \) [11, 1]). In combustors with axisymmetrical flameholders (disc, cone, cylinder, etc.) and low blockage ratios, \( L_{rc}/H \approx 2 \) [21] (which is close to values inherent in isothermal flows [21,22]) or \( L_{rc}/H \approx 2.5 - 4.0 \) [23] or even \( L_{rc}/H \approx 10 - 11 \) [15].

Dunskii [24] (cited by [2]) was probably the first to suggest a criterion of flame stabilization on a bluff body. The theory developed in [24] is based on a comparison of the characteristic residence time of the combustible mixture near the recirculation zone, \( t_r \), with the representative combustion time, \( t_c \). Assessing the residence time as \( t_r = H/U \) and the combustion time as \( t_c = a/\dot{u}_a^2 \) (\( a \) is the thermal diffusivity and \( \dot{u}_a \) is the laminar burning velocity), Dunskii concludes that at the blow-off limit

\[
\frac{t_r}{t_c} \approx \frac{H\dot{u}_a^2}{Ua} = \text{const} = \text{Mi},
\]

where \( \text{Mi} \) is the Michelson number near equal to unity. Although criterion (2) is based on the concept of laminar mixture burning in the vicinity of a flameholder, it fits quite satisfactorily the available experimental data [1,2]. This presumably stems from the fact that the errors occasioned in evaluating \( t_r \) and \( t_c \) are compensated for, because for \( t \), a relation \( t \approx L_{rc}/U \) would be more appropriate.

Criterion (2) can be written as follows

\[
\frac{U}{H} = C\frac{\dot{u}_a^2}{a} = f(\Phi),
\]
where $C$ is a constant value. Equation (3) is consistent with the empirical equation (1) in predicting the effect of the flow velocity and flameholder size on the blow-off combustion limit at a fixed $\Phi$ value.

![Diagram](image)

**FIGURE 1.** To the mechanism of flame stabilization on a bluff body: (1) flameholder, (2) recirculation zone, (3) mixing layer, (4) trajectory of a gas particle, (5) ignition point, (6) trajectory turn point.

Stabilization criteria similar to Eq.(3) or involving the Michelson number (2) were derived later in [4,7,25] (see [2]). However, these criteria do not reflect the effect of many governing parameters on the flame stability. Nonetheless, relations similar to Eq.(2) characterize the essence of the combustion stabilization on a bluff body. We believe that the essence of this phenomenon reduces to the following (see Fig.1).

In the flameholder vicinity the newly supplied fresh mixture interacts with the combustion products filling the recirculation zone 2. This interaction is concentrated in the turbulent mixing layer 3 near the outer boundary of the recirculation zone where the fresh mixture mixes with the combustion products. Combustion is stabilized due to continuous ignition of the fresh mixture supplied to a certain domain in the mixing layer and to injection of some fraction of the combustion products formed in the recirculation zone by reverse flows. If we travel along streamline 4 which is the trajectory of an imaginary gas particle, the ignition point 5 can be specified by time $t$, lapsed after the particle enters the mixing layer. If accidentally ignition of the newly supplied mixture is either premature or delayed, the balance between the outflow of the combustion products from the recirculation zone and their inflow in it is not violated provided inflowing gas contains only products of complete combustion. Whenever the ignition time exceeds its critical value, the balance is violated and the recirculation zone no longer warrants stable combustion. The critical ignition delay is controlled by time $t$, within which our imaginary particle
approaches the turning point 6 in the trajectory. Thus, combustion stability is provided at \( t_r / \tau_c = \text{Mi} \geq 1 \).

According to the above-discussed flame stabilization mechanism, time \( t_c \) specifies the instant of mixture ignition in the layer where the fresh mixture mixes with the combustion products. Estimating time \( t_c \) presents difficulty, therefore to validate the aforesaid mechanism, we performed detailed numerical calculations of stabilization of a flame on bluff V-shaped bodies of various size and its blow-off from the flameholder. To this end, we used formulation of the problem described in [20] and partially reproduced in the next section.

3. FORMULATION OF THE PROBLEM

Instantaneous values of the dependent variables are written as a sum of the ensemble-averages and fluctuations. After averaging the set of equations governing a turbulent flow of a reactive gaseous mixture reads:

\[
\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial}{\partial x_j} \left( \bar{\rho} \bar{u}_j \right) = 0, \tag{4}
\]

\[
\frac{\partial}{\partial t} \left( \bar{\rho} \bar{u}_j \right) + \frac{\partial}{\partial x_j} \left( \bar{\rho} \bar{u}_j \bar{u}_j + p \bar{u}_j \right) - \bar{\tau}_{ij} + \frac{\partial p}{\partial x_i} - \rho g \frac{x_i}{u_d} = 0, \tag{5}
\]

\[
\frac{\partial}{\partial t} \left( \bar{\rho} h \right) + \frac{\partial}{\partial x_j} \left( \bar{\rho} \bar{u}_j h + \bar{\rho} u_j \bar{h} \right) - \frac{\partial}{\partial x_j} \left( \frac{\lambda}{C_p} \frac{\partial \bar{h}}{\partial x_j} \right) - \frac{\partial \bar{p}}{\partial x_i} = 0, \tag{6}
\]

\[
\frac{\partial}{\partial t} \left( \bar{\rho} m_a \right) + \frac{\partial}{\partial x_j} \left( \bar{\rho} u_j m_a + \bar{u}_j \bar{m}_a \right) - \frac{\partial}{\partial x_j} \left( D \frac{\partial \bar{m}_a}{\partial x_j} \right) = \rho \bar{\tau}_a, \tag{7}
\]

\[
h = c_p T + \frac{1}{2} u_i^2 + \sum_{a=1}^{n} m_a H_a,
\]

where \( \rho \) is the density, \( t \) is time, \( x_j \) is the Cartesian coordinate, \( u_i \) is particle velocity projection on coordinate \( x_j \), \( p \) is the pressure, \( g \) is the gravitational acceleration, \( \bar{\tau}_{ij} \) is the tensor of viscous stresses, \( h \) is the total enthalpy, \( m \) is the mass concentration of reagent \( \alpha \), \( H_a \) is the heat of its formation, and \( \bar{\tau}_a \) is the rate of component \( \alpha \) formation or consumption. Prime labels fluctuations and bars and overline means averaging. The terms specifying fluctuations of the density, molecular diffusion coefficient, and molecular
viscosity are disregarded.

The set of equations (4)-(7) should be supplemented by relations for the variables describing turbulent transport and the average chemical reaction rate in the turbulent flow. To calculate turbulent transport, we used the \( k - \varepsilon \) model of turbulence [26-20];

\[
\frac{\partial (\bar{\rho}k)}{\partial t} + \frac{\partial (\bar{\rho} \bar{u}_i k)}{\partial x_i} = \frac{\partial}{\partial x_j} \left( \mu_t \frac{\partial k}{\partial x_j} \right) + \mu_\text{eff} \frac{\partial \bar{u}_i}{\partial x_j} \left( \frac{2}{3} \frac{\partial \bar{u}_m}{\partial x_m} + \bar{p} k \right) - \frac{\bar{p}}{\rho} \varepsilon \frac{k}{\varepsilon},
\]

(8)

\[
\frac{\partial (\bar{\rho} \varepsilon)}{\partial t} + \frac{\partial (\bar{\rho} \bar{u}_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_j} \left( \mu_\text{eff} \frac{\partial \varepsilon}{\partial x_j} \right) + \frac{c_1 \mu_\text{eff}}{c_2} \frac{\partial \bar{u}_i}{\partial x_j} \left( \frac{2}{3} \frac{\partial \bar{u}_m}{\partial x_m} + \bar{p} k \right) - \frac{\bar{p} \varepsilon^2}{\kappa} + \frac{C_3 \bar{p} \varepsilon}{k} \frac{\partial \bar{u}_m}{\partial x_m},
\]

(9)

where \( k \) is the turbulent kinetic energy, \( k = \sum_i \frac{u_i^2}{2} \), \( \varepsilon \) is the dissipation of the turbulent kinetic energy, \( \varepsilon = C_v \rho k^{3/2} / l \) (\( l \) is the integral turbulence scale), \( G_t \) is the rate of turbulence generation (by [27]), and the components of tangential stresses are expressed through the average strain rate \( \frac{\partial \bar{u}_m}{\partial x_m} \).

[27]. The effective viscosity \( \mu_\text{eff} \) in Eqs.(8) and (9) is a sum of the turbulent and molecular viscosities: \( \mu_\text{eff} = \mu_t + \mu \). Turbulent transport of scalar quantities was modeled using the hypothesis of similarity between scalar and vector fields. The empirical constants appearing in the \( k - \varepsilon \) model were assigned the standard values (see, e.g., [20]).

The average reaction rate was calculated by a statistical model based on a prescribed one-point bimodal PDF of the temperature in the turbulent flame front [20]. The average heat release rate \( S \) implicitly appearing in Eq.(6) and quantity \( \dot{r}_a \) in Eq.(7) were calculated by formulas

\[
S = \sum_{\tau} \int_{\tau_0}^{\tau_\infty} D_a W_a(T) P(T, \bar{T}) dT,
\]

(10)

\[
\dot{r}_a = \sum_{\tau_0} \int_{\tau_0}^{\tau_\infty} [W_{1a}(T) - W_{2a}(T)m_a] P(T, \bar{T}) dT,
\]
FIGURE 2. Model probability density functions for the temperature specified by Eqs. (11) (a) and (12) (b) at various values of the average temperature $\overline{T}$ at the flame front: 293 K (curves 1), 600 K (2), 1200 (3), 1800 (4), 2054 (5).
where $W_a$ and $D_a$ are the rate of concentration variation and heat of component $\alpha$ decomposition into atoms, respectively, $W_{1a}$ and $W_{2a}$ are the rates of formation and consumption of component $\alpha$ in all chemical reactions, respectively, $T_0$ and $T_\infty$ are the initial and combustion

temperatures, respectively, and $P(T, \bar{T})$ is the temperature PDF at the
turbulent flame front depending on the instantaneous local temperature $T$
and average $\bar{T}$ temperature. We suppose that $W_a$, $W_{1a}$, and $W_{2a}$ in a
turbulent flame are the same as in a laminar flame, so that calculations of $S$
and $\dot{r}_{\alpha}$ were preceded by calculations of the appropriate laminar flame,
the calculated $W_a$, $W_{1a}$, and $W_{2a}$ values were tabulated.

Two PDF forms were used:

\[
\tilde{P}(T, \bar{T}) = \begin{cases} 
\frac{T - \bar{T}}{T_e - T_0} & \text{at } T = T_0, \\
\frac{T_\infty - T_0}{T_\infty - T_e} & \text{at } T = T_\infty, \\
P_r(T, \bar{T}) & \text{at } T_0 + \Delta < T < T_e - \Delta 
\end{cases}
\]  

(11)

\[
\tilde{P}(T, \bar{T}) = \begin{cases} 
1.0 & \text{at } T = T_0, \\
\frac{T - T_0}{T_e - T_0} & \text{at } T = T_\infty, \\
P_r(T, \bar{T}) & \text{at } T_0 + \Delta < T < T_e - \Delta, 
\end{cases}
\]  

(12)

\[ P(T, \bar{T}) = \tilde{P}(T, \bar{T})/\int_{T_0}^{\bar{T}} P(T, \bar{T}) dT. \]

It is seen that the two PDF forms are two-parametric. The PDF value at
intermediate temperatures $T_0 + \Delta < T < T_e - \Delta$ was assumed constant and
equal to $P_r(T, \bar{T})$. The PDF distribution "thickness" at the ends of
temperature interval $\Delta$ and constant $P_r(T, \bar{T})$ were chosen so that
calculations of propagation of a plane turbulent flame in a closed vessel
yielded a burning velocity observed in experiment (see [20]). The
probability density functions specified by Eqs. (11) and (12) and used in this work are plotted in Figs. 2, a and b, respectively. The probability density function given by Eq. (12) was used, after normalizing, in calculations of flows with high turbulence intensities, in order to take into account a finite probability density of non-reacting mixture portions (reaction extinguishment) even at $\bar{T} = T_c$. One of the most important benefits of the adopted combustion model is an opportunity of using kinetic mechanisms of hydro-

\[ a \]

\[ b \]

\[ c \]

\[ d \]

\[ e \]

FIGURE 3. Temperature fields calculated for combustion of a stoichiometric methane-air mixture in a combustion chamber with a V-shaped flameholder 0.1 m in height and divergence angle of 60°. Ten isotherms cover a temperature range between $T_0$ and $T_e$ and are spaced at equal intervals. The combustion chamber is 1 m long and 0.2 m wide. The initial mixture parameters are: $p_0 = 0.1$ MPa, $T_0 = 293$ K, $l_p = 4$ mm, the intensity of turbulence $u'_L = 2\%$. The incoming flow velocity $u_0 = 40$ m/s (a), 50 m/s (b), 60 m/s (c), 70 m/s (d), 80 m/s (e).
carbon oxidation of an arbitrary complexity.

There is another fundamental problem arising in solving the problem of flame stabilization in a turbulent flow, namely, formulation of correct boundary conditions at the open channel ends. The fact is that the computational region is always restricted so that transparency of the conditional to acoustic perturbations generated in the combustion zone must be warranted. Formulation of this problem and its solution were discussed at length in [20]. Following [20] we write the boundary condition at the computational-region exit in the form:

$$p_x' c_0 (1 + M) p_x = \frac{c_0^2 (1 + M)}{2} \int_0^x p_y (0, \tau) d\tau,$$  \hspace{1cm} (13)

where subscripts $t$, $x$, and $y y$ signify differentiation with respect to time, longitudinal coordinate and double differentiation with respect to the transverse coordinate, respectively, $c_0$ is the acoustic velocity in the unperturbed flow, and $M$ is the Mach number of the unperturbed flow. Unlike the often used Dirichlet and von Neumann conditions, Eq.(13) is non-local in space and time and provides transparency of an open boundary of the computational region to pressure perturbations coming from the computational region.

Similarly, at the inlet section of the computational region the non-reflecting conditions read [20]

$$p_x' c_0 (1 - M) p_x = \frac{c_0^2 (1 - M)}{2} \int_0^x p_y (0, \tau) d\tau, \hspace{1cm} \rho_x' \ln \frac{p_x}{p_0} = \rho_0' \ln \frac{p_x}{p_0},$$  \hspace{1cm} (14)

where $\gamma$ is the ratio of specific heats. In practical calculations it suffices to use Eq.(13) at the outlet section while at the inlet section, the standard boundary conditions, i.e., to prescribe the flow velocity (rate) and temperature.

In numerical computations, the set of equations (4)-(9) together with additional relations, initial and boundary conditions were solved by the method of control volumes using a scheme with two-stage pressure correction. All the dependent variables were calculated at the center of a control volume. The facets of control volumes are coincident with the computational grid lines. The computational grid is curvilinear and non-orthogonal.
4. CALCULATION RESULTS

Figures 3-5 show the calculated temperature distributions in a premixed stoichiometric methane-air mixture burning in a channel with a plane V-shaped flameholder. The angle at the flameholder apex is 60°. The channel

![Diagram](image)

**FIGURE 4.** Temperature fields calculated for combustion of a stoichiometric methane-air mixture in a combustion chamber with a V-shaped flameholder. The chamber is 0.1 m in height and divergence angle of 60°. Ten isotherms cover a temperature range between $T_0$ and $T_e$ and are spaced at equal intervals. The combustion chamber is 1 m long and 0.2 m wide. The initial mixture parameters are: $p_0 = 0.1$ MPa, $T_0 = 293$ K, $l_0 = 4$ mm, the intensity of turbulence $u'_{50} = 2\%$. The incoming flow velocity $u_m = 20$ m/s (a), 30 m/s (b), 40 m/s (c), 50 m/s (d), 60 m/s (e), 70 m/s (f), 80 m/s (g).
is 1 m long and 0.2 m wide. The flameholder is located 0.24 m downstream of the inlet channel section. The flameholder height \( H \) in Figs.3-5 equals 0.1, 0.05, and 0.02 m, respectively. In all cases, the initial mixture parameters are: \( p_0 = 0.1 \) MPa, \( T_0 = 293 \) K, \( l_0 = 4 \) mm, and turbulence intensity \( u'_0 = 2\% \). Isotherms in Figs.3-5 are plotted so that the \( T_0 - T_r \) interval is divided into 10 equal portions.

In calculations, we used the flame symmetry property studied in [20]: the bottom boundary in Figs.3-5 is the plane of symmetry. The combustible mixture flows from left to right (along the \( x \) axis). The inlet boundary conditions are: \( u_x = u_{in}, \ u_y = 0, \ T = T_0, \ \phi = 1, \ l_x = l_0, \) and \( u' = u'_0, \) where \( u_{in} \) is the velocity of the incoming flow. At the outlet we used boundary condition (13) for the pressure and von Neumann conditions for other variables. At the rigid wall (the topmost channel boundary), we used the non-permeability condition for velocity and temperature constancy condition, \( T_x = T_0. \) The method of wall functions [28] was applied to other variables.

The rates \( S \) and \( \hat{r}_a \) (see Eq.(10)) in a turbulent flame were calculated with regard for the detailed mechanism of chemical oxidation reactions of \( C_1-C_2 \) hydrocarbons suggested in [29]. The mechanism comprises 280 elementary steps and 35 species. Prior to simulating turbulent combustion, we calculated a propagating one-dimensional laminar flame. The results of the latter calculations for temperature dependences of \( W_a, \ W_{in}, \) and \( W_{in} \) in the appropriate laminar flame front (see Eq.(10)) were tabulated. In calculating a turbulent flame at any prescribed temperature \( \overline{T} \), the average energy release rate and \( \hat{r}_a \) were assessed using the \( W_a, \ W_{in}, \) and \( W_{in} \) values taken from the tables and temperature PDF (Eq.(12)) at \( P_f(\overline{T}, T) = 2 \times 10^{-3} \) and \( \Delta = 250 \) K.

Mixture ignition was modeled by presetting in the initial distribution of the parameters within the computational region a zone filled with the products of complete combustion of a stoichiometric methane-air mixture. This zone surrounded the flameholder and served as a reliable ignition source for an incoming fresh mixture.

The temperature fields illustrated in Figs.3-5 correspond to the following velocities of the incoming flow at about 50 ms after the ignition:

- Fig.3 - \( u_{in} = 40 \) m/s (a), 30 ms (b), 60 ms (c), 70 m/s (d), and 80 m/s (e);
- Fig.4 - \( u_{in} = 20 \) m/s (a), 30 ms (b), 40 ms (c), 50 m/s (d), 60 m/s (e), 70 (f), and 80 m/s (g);
MECHANISM OF STABILIZATION

Fig.5 — $u_m = 20$ m/s (a), 30 m/s (b), 40 m/s (c), 50 m/s (d), and 60 m/s (e).

![Images of temperature fields](image)

FIGURE 5. Temperature fields calculated for combustion of a stoichiometric methane-air mixture in a combustion chamber with a V-shaped flameholder 0.1 m in height and divergence angle of 60°. Ten isotherms cover a temperature range between $T_0$ and $T$, and are spaced at equal intervals. The combustion chamber is 1 m long and 0.2 m wide. The initial mixture parameters are: $p_0 = 0.1$ MPa, $T_0 = 293$ K, $l_0 = 4$ mm, the intensity of turbulence $u'_0 = 2\%$. The incoming flow velocity $u_m = 20$ m/s (a), 30 m/s (b), 40 m/s (c), 50 m/s (d), 60 m/s (e).

The temperature fields displayed in Figs.3,a,b; 4,a-d; and 5,a,b pertain to stable combustion, while the residual flame in Figs.3,c-e; 4,e-g; and 5,c-e fades away with time. An example illustrating evolution of the combustion process with a flame blown-off from a flameholder 0.02 m high at $u_m = 60$ m/s is shown in Fig.6.

To understand why the flame evolution changes abruptly with increasing velocity of the incoming flow above some critical value, we
analyze Fig.7 that shows five calculated trajectories of averaged particle motion in the vicinity of a V-shaped flameholder for stable mixture burning. Three of the five trajectories exhibit turning points at which the average flow reverses its direction. There is a limiting trajectory (indicated by the

arrow in Fig.7) that separates trajectories with and without turning points.

FIGURE 6. Flame blow-off from a V-shaped flameholder 0.02 m in height and with a 60° angle at the apex. The incoming flow velocity is $u_u = 60$ m/s. Isotherms are evenly spaced at intervals equal to 1/10 of the $T_b - T_f$ range. The combustion chamber length is 1 m and width, 0.2 m. The initial mixture parameters are: $p_0 = 0.1$ MPa, $T_b = 293$ K, $l_0 = 4$ mm, and turbulence intensity $u' = 2\%$. The topmost frame corresponds to time of 8.1 ms after ignition.
An analysis of numerous calculations demonstrates that the turning point of the limiting trajectory is most important for stable combustion on a flameholder. The following conclusion can be drawn from an analysis of variations of the average temperature along the limiting trajectory. Combustion is always stable whenever the temperature attains a value, 

\( \bar{T}_e \) close to \( T_e \), \( \bar{T}_e = 0.95T_e \). If \( \bar{T}_e = \bar{T}_s \) is attained after the trajectory turns toward the zone of reverse currents, the flame is always unstable. In the latter case, even if temperature \( \bar{T}_e \) is attained in direct vicinity of the turning point, but downstream of it, the flame is inevitably blown off from the flameholder, though the blow-off process is oscillatory exhibiting several back and forth flame displacements and pressure fluctuations.

![Image of calculated gas particle trajectories](image)

**FIGURE 7.** Calculated gas particle trajectories in a combustion chamber with a V-shaped flameholder (solid lines) and lines of a constant reduced residence time \( t/t_e = \text{const} \) (dashed curves). The residence time \( t_e \), is defined as a time it takes for a gas particle to travel along the limiting trajectory to the turning point (indicated by arrow). The conditions of computations are the same as in Fig.3.b.

The observed flame behavior can be described quantitatively using representative times \( t_e \) and \( t_e \), introduced by Dunski. In the flame stabilization mechanism considered residence time \( t_e \) is unequivocally defined as a time within which an imaginary gas particle entered the mixing layer approaches the turning point in the limiting trajectory. The dashed lines in Fig.7 corresponding to condition \( t/t_e = \text{const} \) illustrate the flow pattern behind the flameholder. Gas particles entering the zone behind the flameholder are seen to lag far behind gas particles in the free flow. Reaction time \( t_e \) is uniquely defined as a time it takes for a gas particle travelling along the limiting trajectory to be preheated to a temperature \( \bar{T}_e = 0.95T_e \). Then the combustion stability criterion assumes the following form

\[
\frac{t_e}{t_e} = \text{Mi} \geq 1,
\]

(15)
TABLE 1. Combustion Times \( t_r \), Residence Times \( t_e \), and Michelson Number \( M_i \) Calculated for Combustion of a Stoichiometric Methane-Air Mixture in a Combustion Chamber with a V-shaped Flameholder of Height \( H \) and 60° Angle at the Apex at a Incoming Flow Velocity \( u_m \). Also Listed are the Maximum Local Velocities of the Incoming Flow \( u_m \) in Flameholder Vicinity

<table>
<thead>
<tr>
<th>( H, \text{ m} )</th>
<th>( u_{li}, \text{ m/s} )</th>
<th>( u_{m}, \text{ m/s} )</th>
<th>( t_r, \text{ ms} )</th>
<th>( t_e, \text{ ms} )</th>
<th>( M_i )</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>40</td>
<td>85</td>
<td>4.4</td>
<td>8.4</td>
<td>1.9</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>106</td>
<td>6.4</td>
<td>7.6</td>
<td>1.2</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>130</td>
<td>6.0</td>
<td>6.4</td>
<td>0.8</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>28</td>
<td>3.5</td>
<td>11.2</td>
<td>3.2</td>
<td>+</td>
</tr>
<tr>
<td>0.05</td>
<td>40</td>
<td>57</td>
<td>4.4</td>
<td>8.8</td>
<td>2.0</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>72</td>
<td>5.6</td>
<td>7.2</td>
<td>1.3</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>87</td>
<td>7.6</td>
<td>6.0</td>
<td>0.8</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>23</td>
<td>4.4</td>
<td>88.</td>
<td>2.0</td>
<td>+</td>
</tr>
<tr>
<td>0.02</td>
<td>30</td>
<td>35</td>
<td>4.6</td>
<td>5.6</td>
<td>1.2</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>47</td>
<td>6.4</td>
<td>4.8</td>
<td>0.75</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: Symbols + and - signify stable burning and blow-off, respectively.

Table 1 lists the \( t_r \), \( t_e \), and \( M_i \) values calculated for the flows shown in Figs. 3-5. Times \( t_r \) and \( t_e \) were calculated by the average-velocity field 50 ms after ignition, whatever the combustion mode — stable or unstable. In addition to the incoming flow velocity we also list in the table the maximum velocities at the flameholder section (the narrowest combustion chamber section). In contrast to combustion in a free flow where the characteristic velocity is \( u_{m} \), combustion stability is controlled by velocity \( u_{m} \).

It follows from the table that the Michelson number value equal to unity separates solutions with stable and unstable combustion. The limiting incoming flow velocity \( u_{m} (M_i = 1) \) can be evaluated from intersection of the \( t_r(u_m) \) and \( t_e(u_m) \) curves (see Fig. 8). As seen from Fig. 8, the limiting velocity for a V-shaped flameholder of height \( H = 0.05 \) m is greater than the appropriate velocity for a flameholder with \( H = 0.1 \) m. This is attributed to a significant increase in the maximum velocity \( u_{m} \) at higher blockage ratios and is consistent with experimental observations [1]. Thus, the range of stable combustion changes nonmonotonically as the channel blockage ratio varies, namely, there is an optimal flameholder size at which the flame is most stable.

By and large, the calculated values of \( u_{m} = 40-100 \text{ m/s} \) agree with the experimental \( u_{m} \) values at which combustion of a stoichiometric methane-air
mixture is stabilized (50-60 m/s for a cylindrical flameholder at a 0.3 channel blockage ratio [14]). It is worth noting that calculations with PDF given by Eq.(11) yield, with other things being equal, a limiting incoming flow velocity of 65 m/s in a combustion chamber with a V-shaped flameholder with a 60° apex angle and 0.02 m in height.

\[ t_r, t_c, \text{ ms} \]

\[ u_{in}, \text{ m/s} \]

**FIGURE 8.** Determination of the limiting incoming flow velocity $u_{in}$ at which a stoichiometric methane-air mixture burns stably on V-shaped flameholders with a 60° angle at the apex and of height equal to 0.1 m (curves 1), 0.05 m (2), and 0.02 (3). The solid lines correspond to the calculated residence time $t_r$ and dashed lines, to the combustion time $t_c$. Curves 1-3 are calculated under the conditions identical to those in Figs.3-5, respectively.

The oscillatory regime of flame blow-off at subcritical Michelson numbers $M_i < 1$ is illustrated in Figs.9 and 10. Figure 9 shows evolution of the combustion process on a V-shaped flame holder with a 60° apex angle and 0.03 m high. The time interval between frames is 2 ms. After ignition, the combustion zone splits into two flame fronts: immediately behind the bluff body (base wake flame) and in a far wake zone (II). The base wake flame periodically traverses the zone of reverse currents and merges with the flame in the far wake. However a thin flame neck formed is periodically cut by the accelerating fresh mixture flow. In the final run, the far-wake flame is carried away by the flow, while the residual flame 1 gradually fades away. The oscillation frequency ranges between 120 and 160 Hz.

Figure 10 displays another situation observed at subcritical Michelson numbers. As in the case shown in Fig.9, the combustion zone formed after
FIGURE 9. Calculated dynamics of combustion stabilized on a V-shaped flameholder with a 60° apex angle and 0.03 m in height. The isotherms are evenly spaced at intervals equal to 1/10 of the $T_0 - T_e$ interval. The combustion chamber length and width are 1 m and 0.2 m, respectively. The initial mixture parameters are: $p_0 = 0.1$ MPa, $T_0 = 293$ K, $l_n = 4$ mm, turbulence intensity $u'_n = 2\%$, and the incoming flow velocity $u_m = 50$ m/s. Time intervals between the frames are 2 ms.
FIGURE 10. Calculated dynamics of combustion stabilized on a V-shaped flameholder with a 60° apex angle and 0.05 m in height. The isotherms are evenly spaced at intervals equal to 1/10 of the $T_0 - T_r$ interval. The combustion chamber length and width are 1 m and 0.2 m, respectively. The initial mixture parameters are: $p_0 = 0.1$ MPa, $T_0 = 293$ K, $l_0 = 4$ mm, turbulence intensity $u'_0 = 2\%$, and the incoming flow velocity $u_0 = 80$ m/s. Time instants: 4.1 ms (a), 6.1 ms (b), 8.1 ms (c), 10.1 ms (d), 18.1 ms (e), 28.1 ms (f).

Ignition is represented by a base wake flame and far wake flame. As distinct from the case illustrated in Fig.9, Fig.10 shows a third, intermediate, flame. This latter flame after being formed merges with the far wake flame. Several events of intermediate-flame formation and merging of flames are observed. The base wake flame is incapable of passing over the zone of reverse currents and gradually fades away. In the final run, combustion is blown off.
5. CONCLUSIONS

The use of the combustion model [20] based on a prescribed one-point
temperature probability density function in a turbulent flame, detailed
kinetic mechanism of fuel oxidation, and non-reflecting boundary conditions
at the open ends of a combustion chamber enabled us to numerically
simulate combustion in the wake behind a bluff body and to formulate a
flame stabilization criterion. According to this criterion, a flame is blown
off from the flameholder at Michelson numbers less than unity, whenever
the burning time of a gas particle travelling along the limiting trajectory in
the recirculation zone exceeds the time it takes for the particle to approach
the turning point of the limiting trajectory. The limiting stabilization velocity
calculated for a stoichiometric methane-air mixture fit satisfactorily the
available experimental data. The range of stable mixture combustion is
shown to change nonmonotonically with the ratio of channel blockage by the
flameholder. There exists an optimal flameholder size at which combustion
is most stable. This result is consistent with experimental observations.

The work was implemented within the Federal program "Governmental
Support of Integration of Higher Education and Fundamental Science in
1997-2000" founded by the President (project K-0176) and was also
supported by the Russian Foundation for Basic Research (project 99-03-
32261a). FIRE computer code (AVL LIST GmbH, Austria) was used in
calculations.

REFERENCES

1. B.V.Raushenbakh., S.A.Belyi, I.V.Bespakov, et al., Fizicheskie Osnovy
Rabocheho Protessa v Kamerakh Sgoraniya Vozduhno-Reaktivnykh
Dvigateley (Physical Fundamentals of the Operation Process in Combustion
2. S.M.Iliashenko and A.V.Talantov, Teoriya i Raschet Pryamolochnykh Kamer
Sgoraniya (Theory and Calculations of Ramjet Combustion Chambers)
(Mashinostroenie, Moscow, 1964).
3. G.C.Williams, H.C.Hottel, and A.C.Scurlock, Proc. 3d Sympos. on
Combustion, Flame, and Explosion Phenomena (Williams and Wilkins,
Combustion, Flame, and Explosion Phenomena (Williams and Wilkins,
5. H.M.Nicholson and J.P.Field, Proc. 3d Sympos. on Combustion, Flame, and
Explosion Phenomena (Williams and Wilkins, Baltimore, 1949), p.44.
York, 1980).