EXTINCTION OF OPPOSED-JET DIFFUSION FLAME

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We study the condition for extinction of a diffusion flame formed by two oppositely directed coaxial gas jets, one of which contains oxidizer and the other fuel. With increase of the rate of supply of matter into the reaction zone the heat flux from the reaction zone, which goes to heat the reagants being supplied, begins to exceed the amount of heat released in the chemical reaction zone. At some critical matter flux the high-temperature combustion regime becomes unrealizable. The reaction transitions into the other possible regime – low-temperature slow oxidation of the homogeneous mixture which is formed by diffusive mixing of the basic reacting components.

Potter and Butler [1] conducted experiments on the extinction of the diffusion flame formed by two oppositely directed coaxial gas jets, one of which contains oxidizer and the other fuel. For sufficiently high mass velocities of the approaching streams the diffusion flame extinguishes on the axis of symmetry. This is caused by the fact that with increase of the rate of supply of matter into the reaction zone the heat flux from the reaction zone, going to heat up the supplied reagants, begins to exceed the amount of heat released in the chemical reaction zone. Thus, at some critical matter flux the high-temperature combustion regime becomes unrealizable. The reaction transitions into the other possible reaction – low-temperature, slow oxidation of the homogeneous mixture which is formed by diffusive mixing of the basic reacting components. Spalding [2] found the critical condition which determines the jet velocity at which extinction of the diffusion flame takes place because of excessively intense supply of matter into the reaction zone. The calculation was made by numerical methods. The problem was posed with account for both thermodiffusional and hydrodynamic effects (velocity distribution in the colliding jets). In the following we present a simpler model for obtaining the effect described above, which actually excludes examination of the hydrodynamics of the oppositely directed jets. We introduce the following notations: x = coordinate measured along the jet axis (x = 0 corresponds to the point where the jets collide); y = coordinate measured along the direction orthogonal to the jet axis; u, v = gas velocity components; d = diameter of undisturbed part of jet; ρ = gas density; c_p = specific heat; D, $\varkappa$ = respectively the diffusion and thermal conduction coefficients; T = temperature, a, b = concentrations of the reacting components.

We assume that combustion takes place without heat loss to the surrounding medium and the jet surface is impermeable for matter, i.e., at the jet surface we have

$$\frac{dT}{dn}=0, \qquad \frac{da}{dn}=\frac{db}{dn}=0 \tag{1}$$

where n is the normal to the jet surface.

We take the velocity distribution in the colliding jets in the form

$$\rho u=\begin{cases}\rho_0 u_0 H(x), & |y|\leqslant d/2\\ 0, & |y|>d/2\end{cases}, \qquad \rho v=\begin{cases}2yu_0\rho_0\delta(x), & |y|\leqslant d/2\\ du_0\rho_0\delta(x), & |y|>d/2\end{cases} \tag{2}$$

Here H(x) = ±1 respectively for x < 0 and x > 0, δ(x) is the δ-function. If we take the velocity distribution from the hydrodynamic problem of colliding jets, then significant curvature of the streamlines will take place at a distance ~d from the point where the jets collide. The assumed scheme (2) can obviously serve as an approximation for the limiting case of a thin jet ($d \ll D/\rho_0 u_0$, $\varkappa/\rho_0 u_0 c_p$).

In the region $|y| \le d/2$ the diffusion and heat conduction equations take the form

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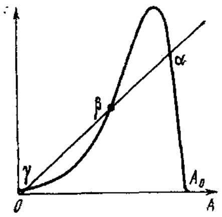

Fig. 1

$$c_p u_0 \rho_0 \left(H(x) \frac{\partial T}{\partial x} + 2y\delta(x) \frac{\partial T}{\partial y} \right) = \varkappa \Delta T + Qq$$

$$u_0\rho_0 \left(H(x) \frac{\partial T}{\partial x} + 2y\delta(x) \frac{\partial a}{\partial y} \right) = D\Delta a - q \quad u_0\rho_0 \left(H(x) \frac{\partial b}{\partial x} + 2y\delta(x) \frac{\partial b}{\partial y} \right) = D\Delta b - q \tag{3}$$

$$q = kab \exp(-E / RT) \tag{4}$$

Here q is the chemical reaction rate, Q the thermal effect of the reaction, k the pre-exponential factor, E the activation energy, R the gas constant.

For $|y| = d/2$ we have from the conditions (1)

$$\partial T / \partial y = 0, \qquad \partial a / \partial y = \partial b / \partial y = 0 \qquad (x \neq 0) \tag{5}$$

Although the velocity distribution depends on y (2), the structure of (3) and the boundary conditions (5) make it possible to seek temperature and concentration profiles which are independent of y. It is obvious that the result obtained below will also be independent of d. Thus the problem becomes one-dimensional. The system of diffusion and heat conduction equations takes the form

$$c_p u_0 \rho_0 H(x) \frac{dT}{dx} = \varkappa \frac{d^2T}{dx^2} + Qq, \quad u_0\rho_0 H(x) \frac{da}{dx} = D\frac{d^2a}{dx^2} - q, \quad u_0\rho_0 H(x) \frac{db}{dx} = D\frac{d^2b}{dx^2} - q \tag{6}$$

The boundary conditions (conditions in the approaching flow) are

$$T(\pm\infty) = T_0, \quad a(-\infty) = a_0, \quad a(+\infty) = b(-\infty) = 0, \quad b(+\infty) = b_0 \tag{7}$$

We shall examine the limiting case of reaction kinetics for which the width of the reaction zone is much less than that of the zone owing to transport effects. In this approximation we set

$$q = J\delta(x), \quad J = k \int_{-\infty}^{\infty} ab \exp(-E / RT) dx \tag{8}$$

For simplicity we consider only the case $a_0 = b_0$. Then by virture of symmetry $b(x) = a(-x)$. Thus, the reaction zone is considered a surface of discontinuity of heat and matter fluxes. Upon passage through $x = 0$ the temperature and concentration remain continuous

$$\begin{gathered} da / dx_+ - da / dx_- = J / D, \; a_+ = a_- \\ dT / dx_+ - dT / dx_- = -JQ / \varkappa, \; T_+ = T_- \end{gathered} \tag{9}$$

From (6), using (7) and (9), we have

$$\begin{aligned} T_\pm &= T_0 + A \exp(\mp c_p u_0 \rho_0 \, x / \varkappa) \\ a_- &= a_0 + B \exp(u_0 \rho_0 \, x / D) \\ a_+ &= (a_0 + B) \exp(-u_0 \rho_0 \, x / D) \end{aligned}$$

Hence, using (8) and (9), after simple transformations we obtain the relation for finding A

$$(u_0\rho_0)^2 A = F(A)$$

$$F(A) = kD \left(\frac{a_0 Qk}{2c_p} - A \right) \int_0^1 \left(a_0 - \frac{a_0}{2} z + \frac{Ac_p}{kQ} z \right) \exp(-E / RT^*) \, dz$$

$$T^* = T_0 + Az^{Dc_p/\varkappa}$$

The qualitative form of the function F(A) for the case $E/RT_0 \gg 1$ is shown in Fig. 1, where $A_0 = a_0 Qk/2c_p$.

The points α, β, γ correspond to the solution of (13). The point α corresponds to the high-temperature stable reaction regime which is realized for sufficiently small reactant input velocities. We see from Fig. 1 that extinction of the diffusion flame takes place at some high finite temperature.

The point β corresponds to the unstable combustion regime. The point γ corresponds to the low-temperature reaction regime. For sufficiently strong input of matter into the reaction zone the regime corresponding to the point γ is the only possible regime. We note that in the low-temperature oxidation regime the width of the reaction zone becomes comparable with the width of the zone owing to transport effects, and the approach based on the assumption of narrowness of the chemical reaction zone is no longer suitable for description of this regime.

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