CRITERIAL DESCRIPTION OF FLAME GEOMETRY FOR A HOMOGENEOUS MIXTURE

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Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, Vol. 7, No. 4, pp. 145–149, 1966

An analysis of the process of combustion and generalization of the experimental material on flame propagation in various types of combustion equipment using the theory of similarity would considerably facilitate the application of data accumulated in practice to the design and development of combustion systems.

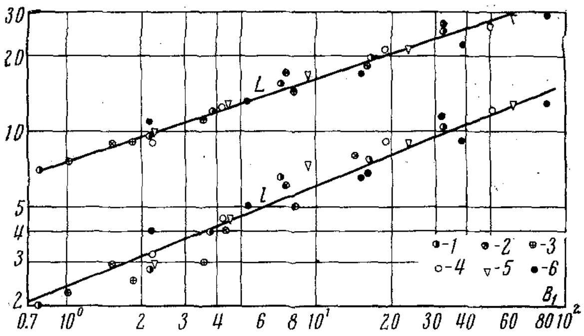

Fig. 1. Length of flame in tunnel burner according to the data of V. I. Andreev [4]; fuel—town gas; for α = 1.1, T_0 = 20–600° C; experimental points: 1) u = 50; 2) u = 100; 3) u = 25 m/sec; for T_0 = 20–600° C; u_0 = 50 m/sec; 4) α = 1.2; 5) α = 1.3; 6) α = 1.4.

In spite of the complexity of the combustion process, which excludes the possibility of precise modeling, in most cases it is sufficient to use a limited number of similarity criteria to obtain a description of individual aspects of the process accurate enough for practical purposes. Examples of this are generalizations of the data on blow-off and flashback—the extreme cases of flame propagation [1–3], etc.

Spalding has shown that for these cases the similarity criteria, and even (at large Péclet numbers N_{Pe}) the form of the criterial relation, can be obtained from an analysis of the energy equation [2].

Obviously, even for cases intermediate between blow-off and flashback, the similarity criteria can be obtained in the same way.

1. Similarity criteria of the combustion process. We will analyze the energy equation

$$(a_T + a)\frac{\partial^2 T}{\partial x_i^2} - u\frac{\partial T}{\partial x_i} + \Phi = 0. \qquad (1.1)$$

In accordance with the dimensionality of the terms of this equation, the term allowing for the presence of heat sources should represent the temperature increase at a given point in space due to the chemical reaction in unit time.

If the reaction time is τ_p, and the temperature increase due to total combustion is $(T_1 - T_0)$, then

$$\Phi \sim \frac{T_1 - T_0}{\tau_p}, \quad \text{or} \quad \Phi = A\frac{T_1 - T_0}{a} u_n^2 \left(\tau_p \sim \frac{a}{u_n^2},\ A = \text{const}\right).$$

Here τ_p is the reaction time, a is the thermal diffusivity (m^2/sec), and the turbulent transfer coefficient $a_T = u'\lambda$.

Then Eq. (1.1) can be written in the following dimensionless form:

$$\left(\frac{u'\lambda}{u_0 d} + \frac{1}{N_{Pe}}\right)\frac{\partial^2\psi}{\partial X_i^2} - U\frac{\partial\psi}{\partial X_i} + A\frac{u_n^2 d}{u_0 a} = 0,$$

$$X_i = \frac{x}{d}, \quad U = \frac{u}{u_0}, \quad \psi = \frac{T - T_0}{T_1 - T_0}, \quad \frac{u'\lambda}{u_0 d} = \varepsilon\Lambda. \qquad (1.2)$$

For a given geometrical system the product of the degree of turbulence and the relative scale of turbulence λ may be assumed constant.

Therefore, in the general case when ψ = const

$$X_i = f(N_{Pe} B,\ \varepsilon\Lambda) \qquad \left(B = \frac{u_0 a}{u_n^2 d}\right). \qquad (1.3)$$

At large Péclet numbers molecular transfer can be neglected. We then have

$$X_i = f(B, \varepsilon\Lambda). \qquad (1.4)$$

Then, if it is a matter of generalizing data obtained on the same equipment, B is the only generalizing criterion. However, if the turbulence parameters are varied, for example, by exchanging turbulence generators, then relation (1.4) should apply.

Analogously, in the general case

$$\psi = f(N_{Pe}, B, \varepsilon\Lambda) \qquad (1.5)$$

while at large Péclet numbers

$$\psi = f(B, \varepsilon\Lambda). \qquad (1.6)$$

Thus, for describing the flame of a homogeneous mixture in a given geometrical system two, and in a developed turbulent flow one criterion will suffice, since a change in the turbulence parameters may be treated as a consequence of a change in geometry. As the temperature varies strongly during combustion, neglecting the change in thermal diffusivity may lead to serious errors.

Since $a = a_0(T/T_0^{1.8})$, taking the arithmetic mean temperature as the characteristic value, we obtain

$$a = a_0\left(\frac{\theta_0 + 1}{2}\right)^{1.8}.$$

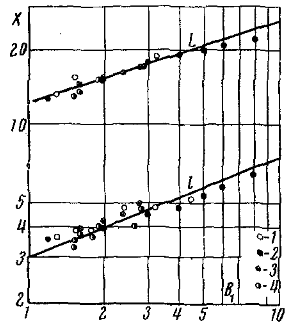

Fig. 2. Length of flame in straight-through combustion chamber. Experimental data of [6]. Fuel—gasoline. Experimental points: 1) α = 1.4, T_0 = = 200–400° C, u_0 = 90–65 m/sec 2)—α = 1.4, T_0 = 200° C, u_0 = 40–160 m/sec; 3)—α = 1.4, T_0 = 400° C, u_0 = = 60–140 m/sec 4)—α = 1.1–1.7, T_0 = = 400° C, u_0 = 96.

Here $\theta_0 = T_1/T_0$; therefore it is convenient to take the characteristic parameters at the initial temperature of the mixture; as criteria we will take

$$N_{Pe1} = \frac{N_{Pe0}}{(\theta_0 + 1)^{1.8}},$$

$$B_1 = B_0(\theta_0 + 1)^{1.8}\left(N_{Pe0} = \frac{u_0 d}{a_0},\ B_0 = \frac{u_0 a_0}{u_n^2 d}\right).$$

The ignition of a homogeneous mixture is usually arranged so that the mixture flows into a space filled with combustion products. The jets may have various cross sections and be differently oriented with respect to the direction of flow of the main stream.

The relative dimensions of the jet and the space into which it flows, and the shape and direction of the jet are the geometrical factors influencing the form of relations (1.3)-(1.6). Therefore, as mentioned above, these relations in their specific form are valid only for geometrically similar systems.

For the geometrical system in question (combustion chamber type) the characteristic of most practical importance is the length of the flame measured from the jet orifice to a point with a given degree of completeness of combustion, in particular, the points where $\psi = 0$ and $\psi = 1$.

The first case corresponds to the length of the "cold" part of the flame l, the second to the total length of the flame L. It is especially important to know the relation for the total length of the flame, since this is usually the basis for selecting the longitudinal dimension of the combustion chamber.

2. Experimental data on flame length for different systems. 1. The experimental data of V. I. Andreev [4] were obtained on a tunnel burner with a crater diameter of 18 mm and a tunnel diameter of about 50 mm.

The experiments were conducted with town gas whose basic component is methane. Therefore, in analyzing Andreev's data, values of the normal velocities were taken from experimental data obtained for methane-air mixtures [5].

The results of the analysis are presented in Fig. 1; values of L and l were taken from burnup curves.

2. The experimental data of [6] on the flame length in a straight-through combustion chamber with V-sahped stabilizers are presented in Fig. 2. The transverse dimension of the stabilizer was 40 mm, the distance between stabilizers d = 40 mm. The fuel was gasoline. Values of the normal velocities were taken from the data of N. N. Inozemtsev (see Fig. 2).

The length l was calculated from $l = (1/2)\,\mathrm{tg}\varphi$, where φ is the mean angle of inclination of the leading edge of the flame with respect to the direction of flow.

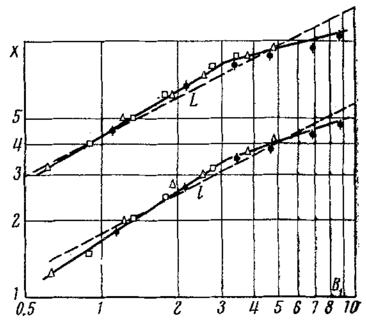

Fig. 3. Length of flame in a burning mixture of town gas and air according to the data of L. S. Kozachenko; T_0 = const, u_0 = const, u_0 = 3.1-24 m/sec; experimental points for gas concentration: 1-7%; 2-8% 3-9%.

The total length was taken as the sum $L = l + l_*$, where l_* is the length of the combustion zone from the point with $\psi = 0$ to the point with $\psi = 0.9$ along the jet axis.

The results of the analysis are presented in Fig. 2.

3. The data of L. S. Kozachenko* for town gas and air mixtures burning in an open flame are presented in Fig. 3.

The jet had a square section (40 × 40 mm). At the nozzle outlet it was confined on two sides by walls, and on the other two ignited with a hydrogen flame. The values of the normal velocities were assumed to be the same as in paragraph 1 above.

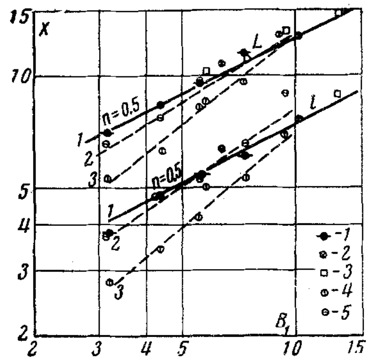

Fig. 4. Length of flame in burning gasoline-air mixtures according to the data of L. S. Kozachenko: T_0 = const, u_0 = = 33-76 m/sec; 1) $\alpha = 0.8$; 2) $\alpha = 1.0$; 3) $\alpha = 1.2$; 4) turbulence grid d = 2 mm; 5) d = 5 mm.

4. On the same apparatus Kozachenko conducted experiments with gasoline-air mixtures. The results are presented in Fig. 4, curves 1.

Curves 2 and 3 relate to cases where the turbulence of the jet was changed by introducing turbulence grids with rod diameters of 2 and 5 mm, respectively.

Values of the normal velocities were taken from the same source.

In Kozachenko's experiments the flame lengths were determined by analyzing schlieren photographs of the flame "section."

An examination of Figs. 1-4 suggests the following conclusions.

a) The experimental data on flame lengths, determined as the distance from the jet orifice to a point on the jet axis with a given degree of completeness of combustion, may be satisfactorily generalized by means of the criterion

$$B_1 = \frac{u_0 a_0}{u_n^2 d} (\theta_0 + 1)^{1.8}.$$

The criterial relation has the form

$$X = c\, B_1^n. \qquad (2.1)$$

b) The values of the coefficient c and the exponent n in (2.1) depend on the geometry of the system in which combustion takes place.

c) Values of the exponent n for a given system geometry are somewhat different for different ψ.

d) A quantitative comparison of relations of type (2.1) for the flame length is possible only if they are determined in the same way or if it is certain that the distances are determined to points with the same value of ψ.

With the help of an expression of type (2.1) it is possible to trace the effect of different parameters on the flame length. As an example, we will consider the effect of pressure on flame length. Obviously, other things being equal, $B_1 \sim p^{2k-1}$. Since $a \sim p^{-1}$, $u_n \sim p^{-k}$,

$$L \sim p^{(2k-1)n}. \qquad (2.2)$$

Thus, for example, in a burning mixture of gasoline and air

$$L \sim p^{-0.5n}$$

since in this case k = 0.25 [7]. However, when methane burns in the pressure range p > 5 atm, we have L = const, since in this case k = = 0.5; at p < 5 atm we have $L \sim p^{-0.5n}$, since k = 0.25 [7].

*Data taken from L. S. Kozachenko's doctoral dissertation, Institute of Physical Chemistry AS USSR, 1954.

Thus, the effect of pressure on flame length will vary with the system geometry, the degree of turbulence of the flow, and the degree of dependence of the normal velocity u_n on pressure. Clearly, the more confined the space and the lower the level of turbulence, the less the effect of pressure on flame length.

If a change in pressure is accompanied by a change in the other parameters, for example, so that the Reynolds number R = const, then

$$B \sim p^{(2k-1)}, \; L \sim p^{2n(k-1)}. \qquad (2.3)$$

The effect of pressure on flame length was investiaged by V. S. Pelevin [8] for a gasoline-air mixture burning at $p \leq 1$ atm.

The burning conditions were similar to those in Kozachenko's experiments except that Pelevin used a circular jet.

In the first series of experiments the condition R = const was satisfied, which, accordance with (2.3), gives $L \sim p^{-1.5n}$.

In the second series a constant velocity u_0 = const was maintained. In this case, in accordance with (2.2), we have $L \sim p^{-0.5n}$.

These two relations correspond to those obtained by V. S. Pelevin if n = 0.5, which corresponds to the slope of the curves obtained in analyzing Kozachenko's data.

An expression of type (2.1) can also be used to solve another important practical problem: finding the maximum possible flame length in a given system.

Obviously, the maximum flane length corresponds to pre-blow-off conditions. If blow-off occurs at sufficiently large values of N_{Pe}, which is usually the case in practice, then B_1 = const, since blow-off is described by the relation [1-3]

$$\frac{u_0 D}{a} = c_1 \left(\frac{u_n D}{a}\right)^2,$$

where D is the diameter of the stabilizer.

For a given geometry d/D = const and hence $B_1 = c_1 d/D$. The blow-off values of B_1 for a tunnel burner, taken from [9], are 130–160.

In this case the maximum flame length is 40 times the jet dimension (Fig. 1). The flame length at the other extreme of propagation—flashback—can be similarly found. In conclusion, it should be noted that the blow-off and flashback characteristics must also depend on $\varepsilon\Lambda$.

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30 January 1965 Novosibirsk