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METHOD OF CALCULATING LIMITS OF STABILIZATION OF A FLAME OF INHOMOGENEOUS MIXTURES TRAVELING OVER A POORLY STREAMLINED BODY

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A method has been developed for calculating the range of stabilization of a flame of inhomogeneous mixtures with allowance for characteristics of the atomization, vaporization, and distribution of the fuel in the flow.

The empirically established fact that the range of stable combustion of inhomogeneous mixtures can be generalized using the excess air coefficient for the vapor-phase circulation zone [1] can serve as a starting point for deriving an equation to calculate the total excess-air coefficient α at the moment of flameout. The range of stabilization of the flame in the channel is actually evaluated from the total quantity α.

The total amount of fuel in the vapor phase which enters the circulation zone per unit of time is made up of the fuel vaporized in the flow in the section from the nozzle to the stabilizer and the fuel which diffuses into the circulation zone as a result of vaporization on the hot stabilizer:

$$g_{\mathrm{c.z}} = g_{\mathrm{n}} + g_{\mathrm{st}}. \tag{1}$$

Here

$$g_{\mathrm{n}} = c\varphi g_{\mathrm{f}} \frac{G_{\mathrm{c.z}}}{G}, \tag{2}$$

$$g_{\mathrm{st}} = g_{\mathrm{f}}(1-\varphi) m\theta_{\mathrm{tot}}. \tag{3}$$

Writing (1)-(3) in terms of the equivalent ratios, we obtain

$$\frac{\alpha}{\alpha_{\mathrm{c.z}}} = c\varphi + (1-\varphi) m\theta_{\mathrm{tot}} \frac{G}{G_{\mathrm{c.z}}}. \tag{4}$$

To determine the form of the exchange function, we need to know the exact amount of fuel deposited on the stabilizer and the amount then transferred from the surface of the stabilizer to the circulation zone. For this purpose, fuel was delivered directly onto the rear surface of the stabilizer, rather than added to the flow. This prevented the fuel from vaporizing in the flow before it reached the stabilizer. In this case then, the composition of the mixture in the circulation zone owes only to the vaporization of the liquid fuel on the

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stabilizer surface. Simple analysis shows that, given a uniform distribution of fuel delivered to the rear surface of the stabilizer, the exchange function, i.e., the proportion of fuel which is vaporized on the stabilizer and finds its way to the circulation zone, is equal to

$$\theta_{\mathrm{tot}} = \frac{\alpha_1}{\alpha_{\mathrm{hom}}} \frac{G_{\mathrm{c.z}}}{G}. \tag{5}$$

In experiments to determine α_1, kerosene was supplied to the top and bottom surfaces of a channeled stabilizer ($h = 40$ mm) through four and six holes with diameter 0.3 mm in a collector (tube with diameter 3 mm), as well as through two swirl injectors with 0.9-mm-diam. nozzles counter to the flow. The stabilizer was installed in a channel 120 × 114 mm. The ratio $\alpha_1/\alpha_{\mathrm{hom}}$, as the experiments showed, does not depend on the temperature and depends in qualitatively the same manner on velocity for all of the fuel-delivery methods (Fig. 1):

$$\alpha_1/\alpha_{\mathrm{hom}} = k\sqrt{W}. \tag{6}$$

The quantitative differences are connected with the conditions of diffusion of the vapor phase along the stabilizer from the hot sections of the circulation zone to the cold sections. These conditions are specific to the method of fuel delivery. The independence of $\alpha_1/\alpha_{\mathrm{hom}}$ on temperature is also explainable. The effect of preliminary vaporization is negligible when fuel is delivered directly onto the stabilizer, and the simultaneous expansion of the range of stable combustion with respect to α_1 and α_{hom} occurs in proportion to expansion of the range of stabilization of the flame. This latter expansion takes place as a result of the effect of temperature on purely kinetic characteristics.

The relation $\theta_{\mathrm{tot}} \sim \sqrt{W}$ has physical significance if we remember that vaporization of the liquid obeys the criterional equation $\mathrm{Nu} \sim \sqrt{\mathrm{Re}}$.

Allowing for (6) and substituting (5) into (4) yields

$$\alpha/\alpha_{\mathrm{c.z}} = c\varphi + (1-\varphi)\, mk\sqrt{W}. \tag{7}$$

The deposition coefficient was calculated by a method based on approximate relations from [3]. These relations were obtained for the flow of monodisperse, uniformly distributed drops about an axisymmetric stabilizer:

$$R = \frac{\gamma_{\mathrm{f}}}{8.15}\sqrt{\frac{W_0 d^3}{g\mu_{\mathrm{v}}\gamma_{\mathrm{v}}}}, \tag{8}$$

$$y_{\mathrm{fal}} = \frac{h}{2} - R + \sqrt{R^2 - \frac{h^2}{4}\operatorname{ctg}^2\frac{\beta}{2}}. \tag{9}$$

All of the drops with a trajectory with a height $y < y_{\mathrm{fal}}$ fall on the stabilizer.

We obtained a formula which is more general than the one in [3] for calculating the deposition coefficient of vaporized drops, distributed according to the Rosen-Rammler law, on a flat stabilizer

$$m = 1 - \exp\left[-0.693\left(\frac{d_{\mathrm{fal}}}{d_m}\right)^n\right] + \frac{n}{130 d_m^n}\int_{d_{\mathrm{fal}}}^{d_{\max}} d^{n-1}\exp\left[-0.693\left(\frac{d}{d_m}\right)^n\right]\arcsin\frac{y_{\mathrm{fal}}}{y}\, d(d). \tag{10}$$

The trajectory of vaporizing drops atomized by the swirl injector was calculated by the method of Erastov [4].

There were four steps in the determination of the range of stabilization of flames of inhomogeneous mixtures.

1. The characteristics of the burner (discharge coefficient, nozzle exit velocity, spray-cone angle, thickness of fuel shroud) were found by the method proposed in [5].

2. The characteristics of the spray (d_m, $d_{\max}$) were determined from the expression proposed by M. S. Volynskyi. Of eight relations examined, this formula gives the closest agreement to experimental values of d_m obtained by catching drops from a flow on smoked plates. The value of $d_{\max}$ was taken as $2d_m$, in accordance with [3, 6].

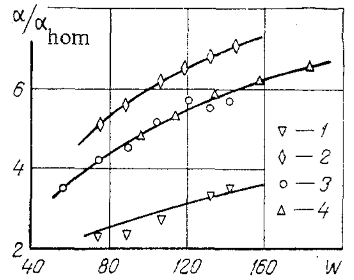

Fig. 1. Relative limits of stabilization of a flame with delivery of the fuel onto the front edge of the stabilizer: 1) delivery through the swirl injectors (T_0 = 573°K); 2) delivery through 4 holes (T_0 = 573°K); 3) delivery through 6 holes (T_0 = 573°K); 4) same (T_0 = 723°K).

3. The trajectory of the drops, the degree of vaporization of the fuel spray, and the deposition coefficient were calculated. The correctness of Erastov's method for determining drop path was confirmed by control measurements of the external contours of the fuel spray in the flow. The contour was determined with photographs. We assumed maximum-size drop trajectories in calculating the outer boundary of the spray. The 5-10% difference obtained between the calculated and empirical results may be considered tolerable. The degree of vaporization of the entire fuel spray, as recommended in [3, 4, 6], was assumed to be equal to the state of vaporization of drops of median diameter. The error in the calculation of φ here is no greater than 10%.

4. The value of α_{hom} at flameout of a homogeneous mixture under the conditions being considered was determined by the method in [7]. The initial data here were the flameout regimes obtained with variation of the degree of ballasting $g_{g.b}$, the initial temperature T_0, and the distance between the burner (nozzle) and stabilizer L_n in [8].

The qualitative and quantitative agreement between the theoretical and experimental flameout boundaries (Fig. 2) should be considered satisfactory for such a complex process as stabilization of a flame of inhomogeneous mixtures. The values of the constants c and k in [7] were constant for both the "lean" and "rich" boundaries.

It can be shown on the basis of the completed calculations which processes determine the complex configuration of the flameout characteristics of an inhomogeneous mixture in the "lean" region compared to the analogous curves for a homogeneous mixture. It follows from analysis of the results obtained that the observed contraction of the region of stable combustion with respect to the "lean" boundary which accompanies a reduction in velocity is due to a decrease in the deposition coefficient and a deterioration in heat transfer to the drops on the stabilizer surface, characterized by the factor $\sqrt{W}$. The strong dependence of m on W is due to two factors: the effect of velocity on the fineness of the spray and on the dimensions of the fuel spray as a whole. An increase in velocity promotes a reduction in mean drop size in the atomization spectrum and a reduction in the height of the trajectory of the drops. The simultaneous effect of these two factors leads to a marked contraction of the fuel spray, and, at high velocities ($W > 100$ m/sec), all of the remaining liquid fuel falls on the stabilizer ($m = 0.95$-0.98). Conversely, a decrease in W is accompanied by an increase in mean drop size and path height, so that part of the fuel misses the stabilizer. Thus, with W = 55-60 m/sec, the deposition coefficient $m = 0.5$-0.55.

After the value of m nearly reaches the limiting values 0.95-0.98, the process of drop deposition on the stabilizer ceases to be decisive as far as flame stabilization is concerned. An increase in the velocity and pressure of the fuel delivery at flameout is accompanied, as calculations have shown, by some increase in the degree of vaporization — thanks to the improved atomization of the spray. Together with a reduction in α_{hom}, this process begins to play the decisive role, and the flameout characteristic acquires its normal form: α decreases with an increase in velocity. Thus, the deposition and vaporization of drops on the stabilizer plays the leading role on those sections of the curve where α increases with velocity, while the path of the flameout boundary is determined by fuel vaporization in the flow and kinetic factors where α decreases.

The limits of flame stabilization seen with an increase in L_n are an example of a flameout boundary having sections with opposite changes in α with an increase in W (Fig. 2c). The

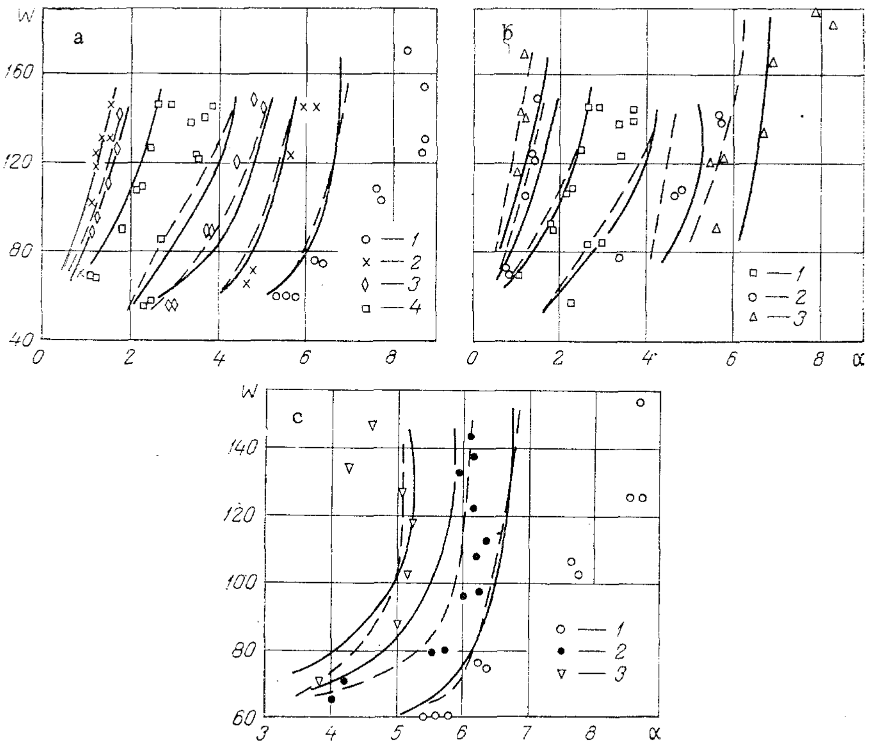

Fig. 2. Comparison of calculated and experimental flame stabilization ranges: a) T_0 = 573°K; L_n = 140 mm; 1) $g_{g.b}$ = 0; 2) 0.125; 3) 0.2; 4) 0.3; b) $g_{g.b}$ = 0.3; L_n = 140 mm; 1) T_0 = 573°K; 2) 723; 3) 843; c) $g_{g.b}$ = 0; T_0 = 573°K; 1) L_n = 140 mm; 2) 300; 3) 400. The solid and dashed curves, respectively, show calculations by the first and second methods.

rather indistinct character of the inflection on these curves is probably due to the imprecise determination of d_m and φ. In calculating the motion of vaporizing drops, there are several factors which obviously make the calculations less exact. The most important of these are neglect of the fractional vaporization of the fuel, the assumption of a constant temperature and velocity in the flow, and neglect of the interaction of the fuel spray as a whole with the slip flow.

It was established that the integral in Eq. (10) is negligibly small (10^{-3}-10^{-4}) if the size of the fuel spray ($2y_{max}$) is comparable to the height of the stabilizer. The value of the integral may affect the value of m at low flow velocities and small stabilizer dimensions. We may take a deposition coefficient m = 0.95-0.98 in determining the "lean" flameout boundary under high-velocity-flow conditions (W > 120 m/sec) for L_n 300 mm.

One of the main factors affecting the value of α is the size of the channel. The effect of channel size may be more conveniently expressed through shadowing of the tube by the stabilizer. Allowing for this, we may write

$$\frac{1-f}{1-f_0}\,\frac{\alpha}{\alpha_{hom}} = c\varphi + (1-\varphi)\,mk\sqrt{W}. \tag{11}$$

Equation (11) can be used to find the boundaries of flameout at values of fuel vaporization in the flow $\varphi < 0.6$. When $\varphi > 0.6$, the Rosen–Rammler drop-size distribution law is violated and the method requires corrections.

In an effort to cut down on the calculations necessary, a simpler method of computing the flameout range can be proposed. The essence of the method is neglecting drop vaporization when determining the deposition coefficient. The degree of vaporization of kerosene in a flow is determined from the empirical equation given in [1]. With a constant drop diameter, the initial system of differential equations is simplified, and a quadratic equation can be obtained for the time of drop motion up to an assigned station.

Comparison of the results of calculations performed by the first and second methods, shown in Fig. 2, illustrates that the difference in α is no more than 15%.

The methods developed here can be used for different variants of calculation of flame stabilization in once-through chambers. By assigning the desired range of stable combustion for the given conditions in an incoming flow, we can obtain:

a) the size of stabilizer required for a fixed value of L_n and known burner atomization characteristics;

b) the distance between burners of a given design and a stabilizer of a known size h;

c) characteristics of the atomization spectrum d_m and n for given L_n and h, which can then be used to select burner parameters.

NOTATION

α, $\alpha_{c.z}$, α_{hom}, α_1, excess air coefficients: total, in vapor-phase circulation zone, homogeneous mixtures, with delivery of fuel to stabilizer; g_f, $g_{c.z}$, g_n, g_{st}, fuel consumptions: total, vaporized in circulation zone, fuel portion vaporized in the slip flow which enters the circulation zone, vaporous fuel portion which enters circulation zone from front surface of stabilizer; φ, degree of vaporization in flow; c, coefficient of nonuniformity of distribution of vaporized fuel across flow; m, coefficient of fuel deposition on stabilizer; θ_{tot}, exchange function accounting for the percentage of vaporized fuel entering the circulation zone out of the total weight of fuel deposited on the stabilizer; G, $G_{c.z}$, air flow rates: total, through circulation zone; h, characteristic dimension of channeled stabilizer; W_0, W, velocity of flow in channel and at edge of stabilizer; k, proportionality factor dependent on method of fuel delivery to stabilizer; R, radius of curvature of path of drops flowing about the stabilizer; γ_0, γ_f, specific weights of gas and fuel, respectively; μ_v, viscosity of gas; $g = 9.81\ \text{m/sec}^2$; d, d_{max}, d_m, diameters of drops: running, maximum, and median, respectively; β, angle at vertex of stabilizer ($\beta = 60°$ in our experiments); y_{fal}, height of trajectory of drops of diameter d_{fal} which touch the rear edge of the stabilizer; n, constant of drop-size distribution; $g_{g.b}$, degree of air ballasting by first-stage combustion products; L_n, distance between burners and stabilizer; f_0, f, degree of shadowing of stabilizer channel in the given experiments ($f_0 = 0.35$) and in any comparable experiments.

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