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Fig. 1

Figure 1: Fig. 1

Abstract

Full Text

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ON THE THEORY OF TURBULENT COMBUSTION

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The authors of well-known theories of turbulent combustion, constructed on the basis of one or another variant of the use of the so-called “frontal model” (1–4), proceeded from the assumption that the front of a laminar or small-scale turbulent flame is preserved under any of its curvatures and fragmentations into separate burning elements. This assumption of the, as it were, indestructibility of the flame front is based on the theoretical proposition that an increase in the intensity of diffusive exchange in the flame front contributes to an increase in the velocity of its propagation in accordance with the relation $U_{\text{fl}} \sim \sqrt{\chi_{\text{m}}\overline{W}_{\text{p}}}$. With an unchanged mean reaction rate $\overline{W}_{\text{p}}$, directly proportional to the increase in U_{fl}, the width of the combustion zone δ_{fl} increases and, correspondingly, the temperature gradient in the flame front decreases (Fig. 1a). But for an unlimited volume occupied by combustion products, the indicated changes cannot alter the final combustion temperature (neglecting radiation losses) and accordingly cannot affect the mean characteristic reaction rate, the completeness of combustion, and the heat flux referred to unit mass of the burnt mixture.

Fig. 1

It was assumed that the action of small-scale turbulent diffusion (scales $l < \delta_{\text{fl}}$) is in this respect quite analogous to an increase in the coefficient of molecular diffusion and, consequently, is likewise incapable of influencing in any way the reaction rate and completeness of combustion, and accordingly can only contribute to an increase in the propagation velocity of the flame front. In doing so, however, it was overlooked that such a proposition is valid only so long as the volume occupied by the combustion products is large in comparison with the volume of the combustion zone and in all cases practically complete completion of combustion and attainment of the final adiabatic flame temperature T_{ad} are ensured.

If, however, one is dealing with the propagation of a flame from a separate tongue

Fig. 2

Figure 2: Fig. 2

or element of combustion products surrounded by a fresh combustible mixture, with the dimensions of such an element comparable to the width of the laminar-flame zone, then the situation proves to be essentially different. For limited dimensions of such an element, an increase in the rate of small-scale turbulent transport, leading to a broadening of the combustion zone and an increase in the flame velocity, may lead to the final temperature of the combustion products ...

burning will begin to decrease, and, correspondingly, the reaction rate and the specific heat flux will fall (Fig. 1b). Combustion will prove incomplete, and with a further increase in the rate of turbulent diffusion conditions may arise under which flame propagation becomes altogether impossible—extinction will occur.

The conditions for such extinction of an individual isolated lump or tongue of flame of finite dimensions, thrown by turbulent pulsation into a fresh mixture, are entirely analogous to the conditions for the blow-off of a stationary combustion regime in so-called homogeneous constant-volume reactors, considered theoretically by Ya. B. Zel' dovich (^{5}). As the combustion process in a bounded volume is intensified, owing to the entry into this volume per unit time of large amounts of fresh mixture, the temperature in it begins to decrease, since combustion does not have time to be completed within the time interval allotted for this purpose. This decrease in temperature leads to a slowing of the reaction, as a result of which, at a certain rate of supply of fresh mixture to the reactor, a further stationary combustion regime becomes impossible.

Fig. 2

The mean temperature T_p inside the reaction volume is determined by the balance between the rate of heat release and the heat expenditure for heating the fresh mixture. Blow-off of the stationary regime occurs when the temperature is lowered by an amount

$$T_{\text{ad}} - T_p \simeq \frac{RT_{\text{ad}}^2}{E}.$$

The absolute values G_{crit} corresponding to blow-off prove proportional to the maximum reaction rates in the front of a laminar flame, i.e., to the maximum of the function $e^{-E/RT_p}(T_{\text{ad}} - T_p)^n$. These theoretical ideas received good confirmation in works (^{6},^{7}).

Taking into account that, along with large-scale pulsations that distort the flame front or tear it into separate burning lumps of relatively large size $l \gg \delta_{\text{lam}}$, and with small-scale pulsations $l < \delta_{\text{lam}}$ that intensify transport processes in the front itself, every turbulent flow contains to one degree or another the whole spectrum of pulsations with intermediate scales, and that initially large pulsations are then fragmented into smaller ones, the indicated mechanism of extinction of individual burning lumps must be quite probable. The presence of flame extinction under conditions of intense turbulent exchange is confirmed by a whole series of experimental observations, in particular when jets of flame gases with high velocities are injected into a combustible mixture.

Although the indicated extinction can mainly occur in those cases when around the burning lumps there is an excess of fresh cold mixture, i.e., at the beginning of the turbulent-combustion zone, it is precisely under these conditions that it can exert a decisive influence on the rate of propagation of the leading boundary of the turbulent flame and on the conditions of its stabilization. This rate must be determined by the greater or lesser probability of extinction of individual lumps of combustion products, thrown by the fastest turbulent pulsations into the fresh mixture, i.e., by the possibility or impossibility of further flame propagation from such fast lumps.

Let us attempt to analyze quantitatively the conditions for extinction of a lump of combustion products with initial temperature T_{ad}, surrounded by the initial mixture with temperature T_0, using experimental data on the limits of combustion blow-off in a spherical reactor (^{6}). Thus, for example, for an isooctane–air mixture at an excess-air coefficient of

of air $\alpha = 1.43$, a pressure of 1 ata, and $T_0 = 400^\circ$K, blow-off occurred at a heat-release rate of 222 $\text{cal/cm}^3 \cdot \text{s}$, which corresponds to a fresh-mixture flow rate $V_{\text{crit}} = 640$ cm^3/s per 1 cm^3 of reaction volume.

Let us imagine that a mole of combustion products has the form of a cylinder with base area 1 cm^2 and height 0.25 cm. The fresh mixture enters through both bases with velocity V_0', while the combustion products are removed through the lateral surface of the cylinder (Fig. 2). In order to obtain extinction of such a mole, it is necessary to feed into it 160 cm^3/s of fresh mixture, i.e. $V_0' = 0.8$ m/s, which is only 1.8 times greater than the normal flame-propagation velocity U_l in the mixture under consideration; thus, even with a slight excess of the small-scale turbulent exchange over the molecular one, flame extinction should be expected.

In the case of a stoichiometric mixture, according to the data of the same authors, blow-off occurred at $V_{\text{crit}} = 2.1$ $\text{l/s} \cdot \text{cm}^3$, which under our conditions would correspond to the value $V_0' = 2.65$ m/s, already 3.3 times exceeding U_l at $\alpha = 1$ ($V_{\text{cr}} \sim W_{\max}$, whereas $U_l \sim \sqrt{W_{\max}}$); accordingly, the probability of extinction here should be considerably smaller.

The mechanism considered for the extinction of individual burning moles of finite size under the action of small-scale turbulent diffusion makes it possible to explain, in a very simple way, a whole series of features of turbulent combustion. Thus, for example, numerous experimental data show that, in full agreement with the theory of K. I. Shchelkin (^{2}), the propagation velocity of a turbulent flame (referred to the front boundaries of the combustion zone), as a rule, proves to be proportional to the root-mean-square value of the pulsation velocity $U_t \sim \overline{U}'$. In the self-modeling region this dependence correspondingly turns into $U_t \sim U_{\text{flow}}$ (^{8}). At the same time, however, experiment shows that, contrary to Shchelkin' s theoretical conclusions, the reaction-kinetic properties of the combustible mixture affect U_t at all, including the very highest, values of $\overline{U}'$, and there is no one-to-one relation between U_t and U_l.

A refinement of the dependence $U_t = f(\overline{U}', W_p)$ is given in (^{9}), where, over a wide range of variation of $\overline{U}'$ from zero to 8 m/s, ideal straight lines were obtained, corresponding to the formula

$$U_t = a\overline{U}' + b, \tag{1}$$

where $b \simeq U_l$, while the value of the angular coefficient a is the greater, the higher the combustion temperature T_{ad}, and, correspondingly, the reaction rate in the flame. However, changes in T_{ad} affect the value of a considerably more weakly than they affect U_l.

The indicated results prove to be fully understandable in light of the scheme, considered above, of extinction of individual moles of flame. Assuming—as has repeatedly been done by many investigators and appears most probable from the standpoint of the physics of the phenomenon—that the flame in a turbulent flow is carried forward into the fresh mixture with the velocity of the pulsations, we find, while remaining within the framework of the frontal model, an exhaustive explanation of the influence on U_t of the reaction-kinetic properties of the combustible mixture. In this case the indicated influence in many respects proves to be similar to the known dependences for homogeneous (volumetric) processes.

The higher the reaction rate in the flame zone, the less probable should be the extinction of individual burning moles thrown by the fastest large-scale pulsations into the fresh mixture; or, in other words, the more probable is the propagation of the front boundaries of the turbulent flame with the velocity of the fastest pulsations. Conversely, at a low reaction rate, ignition of the initial mixture proves possible

only by the main mass of pulsations having velocities close to the root-mean-square value.

Hence the value of the coefficient a in equation (1) may vary from $a \simeq 1$ (near the limits, evidently, it may be $a < 1$) to certain maximum values corresponding to the ratio $\frac{U'_{\max}}{\overline{U'}}$ in the given turbulent flow. In the case of normal pipe turbulence this ratio is 3.5–4 (^{10}); in the presence of turbulence-producing grids it may reach 6 (^{11}), in accordance with which the propagation velocity of a turbulent flame in rapidly burning mixtures, in particular at high pressures, may exceed

$\overline{U'}$ severalfold, as is in fact observed in practice. In this case there is no need to invoke autoturbulization to explain this phenomenon, as many investigators have attempted to do ([3,13,14]).

Although in our treatment of turbulent combustion we proceed from the frontal model (assuming in all cases the leading role of combustion at the interfaces between moles of fresh mixture and combustion products) and, correspondingly, from an identical reaction mechanism (both in laminar and in turbulent flames), in the light of the proposed scheme it is clear that the reaction rate should influence the propagation velocity of a turbulent flame only indirectly—through a change in the degree of probability of combustion extinction on the surface of individual fast moles. This explains the known ([9,12,14]) absence of an unambiguous relation between U_t and U_l. Whereas the laminar-flame velocity $U_\mathrm{l} \sim \sqrt{\varkappa_\mathrm{m} W_\mathrm{p}}$, the propagation velocity of a turbulent flame must be a more complex function not only of W_p, but also of the characteristics of the turbulent flow, taking into account the spectra of pulsation velocities and their scales.

The different influence of pressure on U_l and U_t also finds an explanation: in the first case it is weakly negative or zero, while in the second it is clearly pronounced and positive. The latter is connected with the influence of pressure both on the reaction rate and on the reduction of the width of the laminar flame-front zone, and, correspondingly, on the reduction of the sizes of burning moles, at which the extinguishing action of small-scale turbulent diffusion becomes possible.

The limits of stabilization of turbulent combustion by means of pilot flames, behind poorly streamlined bodies, and on gas jets receive quite simple explanations. The observed narrowing of the limits of flame blow-off on stabilizers when fine meshes are placed in front of them is explained by the greater probability of extinction of flame moles of relatively small size.

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