AUTOTURBULIZATING REGIMES OF GASEOUS SPHERICAL FLAMES

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A spherically propagating flame is a unique object for experimental and theoretical study of the phenomena of spontaneous instability and autoturbulization of flames. It is experimentally established that the propagation of a spherical flame results in the limiting self-similar turbulization mode.

$$\Delta R = R - R_1 = At^n = a(\sigma u_n)^{2n-1}\, t^n / k^{n-1}, \quad u_t / u_n = dR/(\sigma u_n dt) = na^{1/n}(\Delta R \sigma u_n / k)^{(n-1)/n} \quad (1)$$

Here, R_1 is the distance to the virtual source, which appears in (1) because the self-similar mode described by this formula is realized when some radius R_1 is attained, rather than since the moment of ignition ($t = 0$); u_t(m/s) is the apparent rate of turbulent combustion; $t(s)$ is the time; k(m^2/s) is the thermal diffusivity of the mixture; (is the degree of thermal expansion of the gas during combustion; and a and n are empirical constants. According to [1-5], the values of n are different for different mixtures and experimental conditions and are in the range of $1.25 \le n \le 1.5$. For the limiting mode with $n = 3/2$, we obtain $a \cong 2 \times 10^{-3}$ (within the scatter in the experimental values of $A \cong 2 \times 10^{-3}\ \sigma^2 u_n^2 / k^{1/2}$ ($m/s^{3/2}$). Fig. 1 gives the summary experimental data [1-4] illustrating the temporal evolution of visible self-similar turbulent flames in homogeneous stoichiometric and enriched hydrogen - air mixtures, where combustion was initiated by "soft" spark ignition.

The limiting self-similar mode of propagation has remarkable properties of self-organization and stability to externally induced perturbations, as attested by experiments with spherical flames passing in turbulizers (punched hard spherical shells) [1,6]: a flame accelerated in a turbulizer then decelerates such that, after some time, the self-similar mode is restored.

A spherical flame, as a volume filled with hot light combustion products, experiences the effect of the Archimed forces and floats up. To simplify the experiment, the flame propagation is sometimes recorded by the position of the upper edge of the flame, and the result is interpreted as the time dependence of the flame radius. For long times, such a dependence usually has the form $\Delta h \sim t2$, that is, corresponds in fact to the law describing a floating up burning sphere. Qualitatively, the effect of the volume filled with the initial hot mixture, the apparent rate of its normal combustion, and the buoyancy of the combustion products on the possibility of experimentally observing the limiting self-similar mode of propagation of a spherical turbulent flame may be estimated proceeding from the condition of equality of the combustion time and the time necessary for the development of convective motion. Zones I - III on the plane $\{R, u_b\}$ (Fig 2) correspond to the laminar, transient, and limiting modes of self-similar turbulent flame. (Line $2'$ is the result of joining the asymptotics

(2) and (3) in the intermediate region of slight acceleration of the flame that lost its stability.) In zone IV, the gravity effect gives rise to convective motion, ascent, and deformation of the combustion site. Based on the analysis of various sets of values of the initial radius R_0 and the normal apparent velocity u_b of the mixture in Fig. 2, one can predict a possible scenario of the spherical flame behavior: the normal burnout of the mixture (I), the ascent of the laminar source (the transition from I to IV at $u_b \le u_A$); partial autoturbulization of the spherical flame (II); transient mode (II) with subsequent ascent of the combustion site (the transition from II to IV through line AB); autoturbulization, the limiting self-similar mode, and the site ascent (II →III→ IV through curve *2*); and, finally, the developed turbulent mode of spherical flame (II→ III). Note that, for mixtures characterized by low combustion rates ($u_b < u_B$), no limiting autoturbulization of the spherical flame with the radius R ($t^{3/2}$ can be attained for any experimental scale. This is confirmed by experiments [7].

The effect of the flame ascent (region IV) not only presents difficulties for the interpretation of experiments with spherical flames, but also affects the development of instability and autoturbulization. After photographing slowly burning flames in mixtures with almost limiting component concentrations, Karpov [8] established that the flame ascent and the formation of ambient flows past the burning sphere hinder the development of perturbations (caused by the instability of the flame front) on the upper part of the sphere. The perturbations drift to the lower part of the burning site, and its top remains smooth and unperturbed. This process of "balding" of the flame is defined by the flow velocity gradient *G*, or, more exactly, by its dimensionless value $Kr = Gk/u_n^2$ (Karlovitch criterion) that characterizes the flame "stretch" in the vicinity of the stagnation point of the flow (the so-called stretch effect). Using the requirement $Kr > Kr_*$ and estimating the gradient G at $G \propto gt/R$, we derive the condition of flame "balding" at the early stage of the development of laminar flame instability ($R = u_b\ t$) in the form $gk/\sigma u_n^3 \ge Kr_*$ valid for slowly burning mixtures. From the physical standpoint, this means that, at $u_b \le (gk\sigma^2/Kr_*)^{1/3}$, neither the development of instability, nor the autoturbulization and self-acceleration of the laminar spherical front are possible, because of the stabilizing stretch-effect.

The results of theoretical investigations that are directly concerned with the process of autoturbulization of spherical flames and treatment of experimental data reduce to the following. In discussing the experimental data, Gostintsev et al. [9], who investigated the limiting self-similar mode of propagation of spherical flames and their fractal dimensions, proposed a model referred to as "cascade model". This model employs the concepts of the development of instability on a spherically propagating laminar flame (an increase of the perturbation wavelength along with an increase of the flame size) and treats the successive emergence of small-scale perturbations on the previously formed and stabilized large-scale wrinkles. Such a process enables one to obtain the structure of combustion surface of the fractal type. However, the model proposed in [9] is rather qualitative, and the fractal dimension remains indeterminate.

The concepts of fractal dimension of the flame front surface have recently come to be used to characterize turbulent combustion. In so doing, the rate of turbulent combustion as a flow-rate characteristic is treated as laminar combustion at the rate u_n on the front surface wrinkled to such an extent that its dimension D_3 becomes fractal (fractional) in a certain range of three-dimensional scale of perturbations. This concept, which dates back to the ideas of Damkoehler and Shchelkin, appears to be justified within the framework of the so-called "surface" mechanism of combustion, when a locally laminar wrinkled flame remains continuous or almost continuous in the mathematical sense.

According to the theory of fractals [10], the ratio between the surfaces of developed turbulent (broken laminar), S_l and normal smooth laminar, S_n , spherical flames is $S_l/S_n = u_l/u_n = (\lambda_i/\lambda_0)^{(2-D_3)}$ - (2) ,where u_l is the rate of turbulent combustion, and λ_i and λ_0 denote the inner cutoff and external cutoff three-dimensional scales of perturbations inside which the self-similar fractal behavior described by (2) is observed. It is assumed in [11,12] that the order of magnitude of λ_i is defined by the microscale of Kolmogorov's turbulence $\lambda_i \cong \eta \sim (\nu^3/\varepsilon)^{1/4}$, where ν (m/s) is the molecular viscosity, and ε (m^2/s^3) is the dissipation rate of turbulent energy per unit mass of the medium. However, Ioshida et al. [13] indicate that the measured values of λ_i are much higher than q and do not correlate with any scale of turbulence in the mixture. At the same time, it is generally recognized that λ_0 is proportional to the overall scale of motion.

On comparing relations (2) with the self-similar regularities of spherical flame propagation, found in [1,14,15], one can see that, at fairly large distances ($R >> R_1$) from the center, the fractal dimension D_3 of the branched surface of laminar flame front in the turbulent combustion mode is uniquely defined by the exponent n in the time law of radius growth R(t) and is equal to $D_3=(3n-1)/n$. For spherical flames, the outer limit λ_0 of the scale of perturbations, within which the fractal self-similarity is preserved, is $\lambda_0 \sim R$, and the inner limit is proportional to the laminar front thickness, $\lambda_i \sim k/u_n$. According to the data of [1,9], the values of n for autoturbulized flames vary in the range from 1.25 to 1.5, and $D_3 = 2.2 – 2.33$. The fractal dimension of flame in the limiting self-similar mode is $D_3=7/3$.

Note the correlation between the fractal dimension of spherical flames in the autoturbulization mode and the fractal dimension of flames measured using direct (with the aid of laser methods) observations of the evolution of wrinkled front during combustion in the field of forced turbulence with controlled intensity (value of the pulsation rate u'). Fig. 1 gives the experimental data $\{D_3, u'/u_n\}$ obtained under different conditions for a stationary turbulent flame in a Bunsen burner [12,13] and for a spherical flame propagating from a spark in internal combustion engines [11]. In the case of high intensity of turbulence, the fractal dimension of flames agrees with the values measured under conditions of turbulent transport of passive impurities ($D_3 = 2.3 – 2.4$ for turbulent jets [16], and $D_3 = 2.37$ for thunderclouds [17]). The foregoing results indicate that autoturbulized spherical flames with n = 1.25 – 1.5 correspond to the intensity of self-generated turbulence of $u'/u_n= 1 – 10$. For close-to-limiting modes (n = 3/2, $D_3=7/3$), the turbulence intensity $u'>>u_n$, the geometric characteristics of the flame front cease to depend on the rate of normal combustion, and the front proper appears as a strongly wrinkled interface between a fresh mixture and combustion products (isothermal or isoconcentrate surface) in a highly turbulized medium.

The fractalization of flame is observed in the calculation results [18], with the dimension of the line that describes the front of cylindrical symmetry tending to $D_2=4/3$ (Fig. 2). In the spherical case for isotropic turbulence, this would correspond to the dimension $D_2=D_2+1=$ 7/3, which likewise agrees with the experimental results for the mode of autoturbulization of spherical flames.

Gostintsev et al. [9] gave their attention to the fact that the limiting mode of autoturbulization $R \sim t^{3/2}$ may be compared with the regularities and relations used for traditional description of a turbulent Kolmogorov medium. Namely, the value of the rate of dissipation of turbulent energy ε (m^2/s^3), which defines the energy distribution over three-dimensional scales of pulsations in the inertia region of turbulence, may be estimated, as usual, in terms of the external scale and characteristic external velocity, that is, for a spherical flame in terms of its radius R and propagation rate d_1R in the form of $\varepsilon\sim (d_1R)^3/R$. On the other hand, the dissipation rate in the viscous region is expressed uniquely in terms of a priori preassigned quantities, namely, the normal rate of combustion u_n and the temperature diffusivity κ, in the form of $\varepsilon\sim u_n^4/\kappa$. Hence it follows immediately that $R\sim t^{3/2}$. (In so doing, the size of Kolmogorov's microscale of turbulence $\eta\sim(\nu^3/\varepsilon)^{1/4}$ is proportional to the thickness of laminar flame front $\eta\sim(\kappa/u_n)Pr^{3/4}$, where $Pr = \nu/\kappa$.)

The dependence of R on t may also be derived proceeding from the following. The effective coefficient of turbulent diffusion D_T in isotropic turbulent medium is proportional to the dissipation rate c and to the scale of R as $D_T\sim\varepsilon^{1/3}R^{4/3}$. Then, assuming that the radius R increases in time by the law of transport of the scalar quantity $R\sim (D_Tt)^{1/2}$, we derive $R\sim\varepsilon^{1/2}t^{3/2}$.

Taylor's instability may be treated as the cause of turbulization, and the rate of dissipation of turbulent energy may be estimated in terms of acceleration and flame radius $\varepsilon\sim(R(d_{tt}^2R)^3)^{1/2}$. According to the experimental data, this quantity in the limiting mode of turbulization is a constant quantity $\varepsilon\sim u_n^4/\kappa$. The latter consideration is especially important, because the concepts of developed turbulence suggest its origination on a large scale and the transition of turbulent energy to a smaller scale up to dissipation. The development of spontaneous instability does not lead to the growth of perturbations on the scale of the order of the flame radius, but leads mainly to the growth on a scale somewhat larger than κ/u_n. Therefore, one can assume Taylor's instability as the source of turbulization, at least in the energy-related meaning of this word. Note that, on the scale of the autoturbulization radius and of the visible rate of its propagation at the stage of limiting turbulization, the local rate u_n of propagation of the flame front and its width κ/u_n are negligibly small. Therefore, it may be assumed that, on the overall flame scale, Taylor's instability and turbulization occur in the same manner as in an inert medium. In so doing, the role of combustion and spontaneous instability remains very important and reduces to the following two aspects.

First, the spontaneous instability in its nonlinear manifestation leads to acceleration of flame to a degree ensuring the development of Taylor's instability. (The estimation by the experimental data of the Grashof number $Gr\sim R^3d_{tt}^2R/\nu$ for acceleration of flame in the neighborhood of the transition of combustion to the limiting mode of autoturbulization at the Reynolds number values of the order of 10^5 gives the value of $\sim10^{12}$.) The main singularities of the initial stage of flame acceleration apparently correspond qualitatively to the results of [1]. The combustion further maintains the accelerated flame propagation in the mode of autoturbulization.

Second, the role of combustion consists in setting up a constant and fixed (on a certain scale of three-dimensional perturbations) level of dissipation of turbulent energy. The experimentally demonstrated constancy of the dissipation rate $\varepsilon\sim u_n^4/\kappa$ in the limiting mode of autoturbulization appears to be quite natural, because the spontaneous instability gives rise to the strongest hydrodynamic perturbations on a scale proportional to the flame front width κ/u_n; on the other hand, the processes of laminar transport start showing up on this scale.

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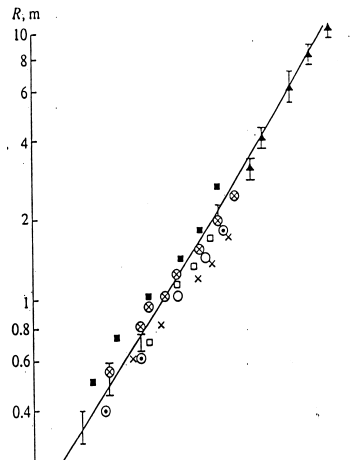

Fig. 1 Dependence R(t) for hydrogen-air flames propagating in the self-similar mode [1-4].

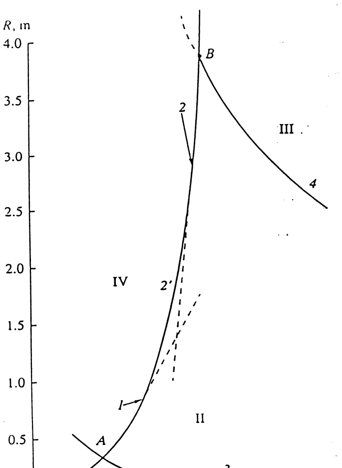

Fig 2 Dependence $R(u_b)$ for spherical flames calculated by formulas (2)-(4).

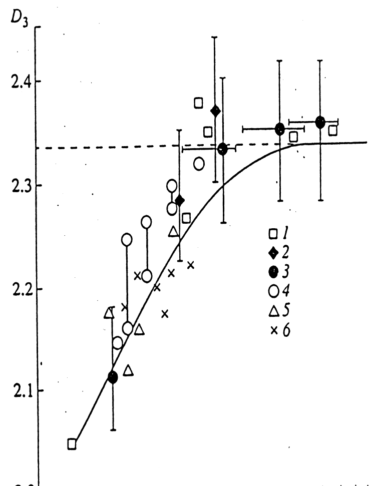

Fig 3 The fractal dimension of the flame front surface as a function of relative intensity of external turbulence u'/u": (1-3) propane-air flames of different compositions in internal combustion engines [11], (4-6) turbulent flames in Bunsen burner [12,13]; the broken line indicates the limiting mode D_3= 7/3, and the solid curve indicates the results of [19].