THEORY OF TURBULENT COMBUSTION OF A HOMOGENEOUS FUEL MIXTURE AT HIGH REYNOLDS NUMBERS

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Model representations of the mechanics of combustion are used extensively in analyzing turbulent combustion. Two limit cases of combustion corresponding to the characteristic scales of turbulence L, which is much greater or much less compared to the thickness of the normal laminar combustion front in the fuel mixture under consideration b_n, are distinguished [1]. In the first case ($L \gg b_n$) combustion occurs in thin fronts, strongly curved because of the turbulent motion of the medium (surface mechanism of combustion). The combustion surface is hence often represented as an ordinary laminar flame front being propagated at the velocity u_n relative to the fuel mixture (from similarity considerations, its thickness is $b_n \sim a/u_n$, in order of magnitude, where a is the molecular coefficient of thermal diffusivity). In the second case ($L \ll b_n$), the action of turbulence reduces to just an increase in the transfer coefficients in the combustion zone (volume mechanism of combustion). A qualitative investigation of combustion in this case reduces to the analysis of the laminar front with the replacement of the molecular by turbulent transfer coefficients.

In the case of large turbulence Reynolds numbers $Re_t = u'L/\nu \gg 1$ (u' is the root-mean-square value of the velocity pulsations characterizing the turbulence energy, L is the characteristic size of the energy containing vortexes, usually taken equal to the integral of the turbulence scale; and ν is the kinematic coefficient of molecular viscosity), a continuous turbulence spectrum is characteristic, consequently, a developed turbulence microstructure with vortices less than b_n can exist in the flow for $L \gg b_n$, which will exert substantial influence on the structure of the instantaneous combustion front and can intensify the transport processes. This results in a need to examine an intermediate model conserving the features of both limit cases, in which a strongly curved flame front exists in the combustion zone, which is thin in comparison to the average width of the heat liberation zone (this front is considered as a random surface below). However, the thickness of such an instantaneous combustion front and its propagation velocity relative to fresh mixtures are much greater than for the normal laminar flame front [2].

Such a combustion model is examined below, the domain of the turbulence parameters where it is valid is found, and the dependence of the turbulent combustion velocity u_t on the turbulence parameters and physicochemical characteristics of the fuel mixture is determined. This analysis uses dimensional analysis considerations contained in the known Π theorem [3] in addition to results following from kinematic regularities of the model taken.

Let us consider a one-dimensional combustion zone (the average parameters depend on one space coordinate along which the combustion wave is propagated) which is developed after it has been set in contact with a fresh cold mixture and hot combustion products after a certain initial time. Here the quantity u_t is defined as the mean volume of the fresh mixture which burns per unit time per unit surface of a plane perpendicular to the direction of flame propagation. In the general case, because of nonstationarity of the average width of such a one-dimensional combustion zone, u_t does not agree with the propagation velocity of its leading front, which is ordinarily determined in experiments.

Let us note that there exist adherents of the volume model for $L \gg b_n$ and $Re_t \gg 1$. One of the arguments is analyzed in the following expressions in [4]: "By returning to fine-scale turbulence, we recall the discussion found in the literature which is transformed into a good example of sophistry when it is not accompanied by quantitative estimates. The discussion is the following. Fine-scale turbulence, which is always present in the spectrum of scales, extends the normal flame combustion zone. Coarser scales become small relative to the expanded zone. By falling into the combustion zone, they extend it still more, etc. All the scales gradually are drawn into the combustion zone. Hence, there is no sense in comparing turbulence scales to the width of the normal combustion zone, which is not and cannot be in a turbulent flame."

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The estimates in [4] and experiments do not confirm the possibility of the existence of a volume combustion mechanism in real cases. Thus, a direct experimental investigation of the structure of a homogeneous combustion zone for a gasoline–air mixture at 20–25-m/sec velocities for a 0.4-m-diameter burner by measuring the instantaneous temperatures with a low-inertial thermometer showed that finite probabilities for the temperature of the initial mixture and the temperature of the combustion products exist in the combustion zone while the probability of intermediate temperatures is low, i.e., the surface combustion mechanism holds [5]. Nevertheless, in a theoretical analysis the question of the physical reason for the absence of such a sequential involvement of all the coarser vortices in the combustion front remains and the need arises for an estimation of the limit thickness of the combustion front $b_{n.t}$ (by which the instantaneous zone separating the fresh fuel mixture and the combustion products is to be understood) and its propagation velocity over the fuel mixture $u_{n.t}$.

1. Let us examine such turbulence parameters and physicochemical characteristics of the mixture for which vortices with a size on the order of the thickness of the expanded combustion front $b_{n.t}$ and governing the intensity of the process in the front are referred to the inertial interval of the turbulence spectrum:

$$L \gg b_{n.t} \gg \eta = \nu^{3/4}\varepsilon^{-1/4} \sim L\mathrm{Re}_t^{-3/4}, \tag{1.1}$$

where η is the Kolmogorov scale, which agrees, in order of magnitude, with the size of the minimal vortices existing in the turbulent flow, ε is the rate of dissipation of turbulence energy governed by the energy content of the vortices and equal to $\varepsilon \sim u'^3/L$ from dimensional analysis ([6], for instance).

The pulsation energy spectrum in the domain of the inertial interval, which is independent of viscosity and governs the rate of dissipation from dimensional considerations, will have the form [6]

$$E(k) \sim \varepsilon^{2/3}k^{-5/3}.$$

Here k is the wave number, the corresponding vortex size equals 1/k in order of magnitude. The root-mean-square magnitude of the velocity pulsations $u'_{n.t}$, which is determined by vortices contained in a layer of thickness $b_{n.t}$ and their integrated scale $L_{n.t}$, are written in terms of the energy spectrum on the basis of ordinary expressions:

$$u'^2_{n.t} \sim \int_{1/b_{n.t}}^{\infty} E(k)\,dk \sim \varepsilon^{2/3}b_{n.t}^{2/3}, \quad L_{n.t} \sim \int_{1/b_{n.t}}^{0} k^{-1}E(k)\,dk \Big/ \int_{1/b_{n.t}}^{\infty} E(k)\,dk \sim b_{n.t}. \tag{1.2}$$

from which the coefficient of turbulent thermal diffusivity in the front will be

$$a_{n.t} \sim u'_{n.t}L_{n.t} \sim \varepsilon^{1/3}b_{n.t}^{4/3}. \tag{1.3}$$

The expression (1.3) also follows directly from dimensional analysis since $a_{n.t}$ for the inertial interval should be independent of the molecular viscosity and is defined by ε and $b_{n.t}$. Substituting the expression $b_{n.t}$ following from (1.3) into the right side of the inequality (1.1), we obtain (a is the coefficient of molecular thermal diffusivity)

$$a_{n.t}^{3/4} \gg \nu^{3/4} \sim a^{3/4}, \tag{1.4}$$

i.e., the contribution of the molecular processes to the intensity of transfer in the combustion front is insignificant.

The velocity of combustion front propagation and its thickness are functions of $a_{n.t}$ and the characteristic time of chemical reaction in the front t_c, from which we obtain analogously to the case of laminar combustion by using dimensional analysis considerations:

$$u_{n.t} \sim (a_{n.t}/t_c)^{1/2}, \quad b_{n.t} \sim (a_{n.t}t_c)^{1/2}. \tag{1.5}$$

It follows from (1.3) and (1.5) that

$$u_{n.t} \sim u'(t_c/t_t)^{1/2}, \; b_{n.t} \sim L(t_c/t_t)^{3/2}, \; a_{n.t} \sim a_t(t_c/t_t)^2, \tag{1.6}$$

where $a_t \sim u'L$ is the coefficient of turbulent thermal diffusivity, and $t_t \sim L/u'$ is the characteristic time of the turbulent pulsations.

The relationships (1.5) are the actual conditions of the fact that in a coordinate system where the combustion front is fixed, the heat fluxes in the front because of heat conduction and convection, and heat liberation because of chemical reaction have one order of magnitude, i.e.,

$$C_p\rho a_{n.t} \cdot \Delta T/b_{n.t} \sim c_p\rho u_{n.t}\Delta T \sim Q \cdot w \cdot b_{n.t}, \tag{1.7}$$

where ΔT is the temperature increment in the front; w, the mean rate of reaction of the fuel; and Q, the thermal effect of the reaction. Indeed

$$Qc_0 \sim \rho c_p \Delta T, \quad t_c \sim c_0/w,$$

where c_0 is the initial fuel concentration.

The relationships (1.5) follow directly from (1.7). Therefore, the expansion of the combustion front and involvement of more and more coarse vortices occurs until equilibrium is established between the convection, heat conduction, and chemical reaction processes, as occurs even in the case of laminar combustion when [2]

$$t_c \sim \frac{a}{u_n^2}, \quad b_n \sim (at_c)^{1/2}. \tag{1.8}$$

Let us henceforth assume that the chemical reaction time t_c is identical for laminar and turbulent combustion, then according to (1.6) and (1.8)

$$u_{n.t} \sim u' \left(\frac{u'}{L}\frac{a}{u_n^2}\right)^{1/2}, \quad b_{n.t} \sim L\left(\frac{u'}{L}\frac{a}{u_n^2}\right)^{3/2}, \quad a_{n.t} \sim a_t \left(\frac{u'}{L}\frac{a}{u_n^2}\right)^2. \tag{1.9}$$

Comparing (1.5) and (1.8) and taking account of (1.4) results in

$$u_{n.t} \gg u_n, \quad b_{n.t} \gg b_n.$$

It should be noted that the assumption of invariability of the reaction time t_c during laminar and turbulent combustion, which holds, for instance, for an identical functional form of the temperature distribution across the instantaneous combustion front and in the absence of noticeable temperature pulsations therein for turbulent combustion $\overline{T'^2}/\Theta^2 \ll 1$, is sufficiently strong in both cases (Θ is the characteristic temperature range of the chemical reaction). The fact is that in conformity with (1.2), the characteristic scale of the vortices in the instantaneous combustion front is commensurate with its width, which can result in a high pulsation level. An estimate of the temperature pulsation intensity requires the reliance on balance equations for the temperature pulsations $\overline{T}'^2$ in the coordinate system in which the instantaneous combustion front is fixed. Equating the convective transfer, the generation associated with the mean temperature gradient, the diffusion and dissipation $\overline{T}'^2$, which can be estimated respectively as

$$u_{n.t}\frac{d\overline{T'^2}}{dx} \sim u_{n.t}\frac{\overline{T'^2}}{b_{n.t}}, \quad a_{n.t}\left(\frac{d\overline{T}}{dx}\right)^2 \sim a_{n.t}\frac{\Delta T^2}{b_{n.t}^2},$$

$$\frac{d}{dx}\left(a_{n.t}\frac{d\overline{T'^2}}{dx}\right) \sim a_{n.t}\frac{\overline{T'^2}}{b_{n.t}^2}, \quad \frac{\overline{T'^2}u'_{n.t}}{L_{n.t}},$$

in order of magnitude, and using (1.2) and (1.6), we obtain $\overline{T'^2}/(\Delta T)^2 \sim 1$.

This estimate shows that the expanded combustion front differs in structure from the extended laminar front zone which holds for $L \ll b_n$ and more often corresponds to the microvolume combustion model [2], which is characterized by a high level of temperature pulsations in the instantaneous combustion zone, resulting in an increase in the relative width of the substantial heat liberation zone in the front as compared with the laminar combustion case.

The condition for the existence of a strongly expanded combustion front (the right side of (1.1)) becomes after (1.6) and (1.8) have been used

$$\left(\frac{t_c}{t_t}\sqrt{\mathrm{Re}_t}\right)^{3/2} \sim (\varepsilon/a)^{3/4}(a/u_n^2)^{3/2} \gg 1. \tag{1.10}$$

Using the expression for ε in terms of the turbulence microscale λ: $\xi = 15\nu u'^2/\lambda^2$, we obtain $(u'/\lambda)^{3/2} \gg (u_n^2/a)^{3/2}$ from (1.10), which is practically in agreement with the condition for the strong influence of turbulence on the laminar flame front $u'/\lambda > u_n^2/a$, proposed in [7]. By using the expression for η in terms of ε from (1.1) the inequality (1.10) is converted into the form $\eta^3 \ll a^3/u_n^3$, i.e., at least there should be $\eta < b_n$, which agrees physically with the initial hypotheses of the model. Let us also note that (1.10) yields an upper bound on Re_t, or $\mathrm{Re}_t \ll (u'/u_n)^3$, for fixed u' and u_n, which can be spoiled for too large L.

The left side of (1.1) becomes after (1.6) and (1.8) have been used

$$\left(\frac{t_c}{t_t}\right)^{3/2} \sim (\varepsilon/u'^3 \cdot a/u_n^2)^{3/2} \ll 1. \tag{1.11}$$

It follows from condition (1.11) that the residence time of the substance in the front $t_f \sim b_{n.t}/u_{n.t}$ (which also characterizes the buildup time of the stationary values of $b_{n.t}$ and $u_{n.t}$) equal to $t_f \sim t_c$, according to (1.9), should also be much less than the dissipation time $t_d \sim u'^2/\varepsilon \sim L/u' \sim t_t$. This inequality as the condition for the existence of a surface combustion mechanism is mentioned in [4].

2. The turbulent combustion velocity u_t can be represented in the form

$$u_t = u_{n.t}\overline{\left(\frac{\delta S}{\delta S_0}\right)}. \tag{2.1}$$

Here δS is the area of the combustion front surface element, δS_0 the area of the projection on this element on a plane perpendicular to the direction of flame propagation, and the upper bar is the averaging symbol.

Let us consider that at each instant the surface of the front is a unique random function of the transverse coordinate $x = h(y, z)$, which is apparently admissible for qualitative estimates since the probability of meeting a front ambiguity does not exceed 0.1-0.2 [5] according to experimental results (x is the coordinate along which the reaction wave is propagated). Then

$$\overline{\left(\frac{\delta S}{\delta S_0}\right)} = \overline{\left(1 + \left(\frac{\partial h}{\partial x}\right)^2 + \left(\frac{\partial h}{\partial y}\right)^2\right)^{1/2}} = \overline{(1 + |\operatorname{grad} h|^2)^{1/2}}.$$

In the case of the combustion surface mechanism we are interested in $\overline{(\delta S/\delta S_0)} \gg 1$

$$\overline{\left(\frac{\delta S}{\delta S_0}\right)} \approx \overline{|\operatorname{grad} h|} \sim \overline{(|\operatorname{grad} h|^2)^{1/2}} = \frac{\Sigma}{\Lambda}, \tag{2.2}$$

where $\Sigma^2 = \overline{(x - \bar{x})^2}$; Λ is the microscale of the length of the random front surface inserted by analogy with the case of a random function of one variable, in the form

$$\Lambda = \Sigma/|\overline{\operatorname{grad} h}|.$$

For the case of a random function of one variable $\xi(t)$, $\overline{\xi(t)} = 0$ the usual definition of microscale has the form

$$\Lambda^2 = \overline{\xi^2}\Big/\overline{\left(\frac{d\xi}{dt}\right)^2}.$$

The coefficient of proportionality in (2.2), which equals one in order of magnitude, is calculated directly in the case of a normal (Gaussian) law for the probability density of instantaneous values of |grad h|:

$$\overline{\left(\frac{\partial S}{\partial S_0}\right)} = \int_{-\infty}^{+\infty} \frac{|\operatorname{grad} h|}{\sqrt{2\pi\,\overline{|\operatorname{grad} h|^2}}} \exp\left[-\frac{|\operatorname{grad} h|^2}{2\,\overline{|\operatorname{grad} h|^2}}\, d(|\operatorname{grad} h|)\right] = \sqrt{\frac{2}{\pi}\,\overline{|\operatorname{grad} h|^2}} = \sqrt{\frac{2}{\pi}}\,\frac{\Sigma}{\Lambda}.$$

Taking $\Sigma \sim L$ for the estimate, it follows from (2.2) that $\Lambda \ll L$ for the surface combustion mechanism.

Let us examine the case when $u_{n.t} \ll u'$. If (1.6) and (1.8) are used, this condition takes the form

$$L^{1/3} \gg b_{n.t}^{1/3} \quad \left(\frac{t_c}{t_t}\right)^{1/2} \sim \left(\frac{\varepsilon}{u'^3}\cdot\frac{a}{u_n^2}\right)^{1/2} \ll 1, \tag{2.3}$$

i.e., is stronger than the inequality (1.11). In this case, in the time range

$$L/u' \ll t \ll L/u_{n.t} \tag{2.4}$$

the combustion front can be considered to consist approximately of the same fluid particles (since the displacement of the front relative to the medium is much less than L during this time), and Σ^2 is subject to the customary turbulent diffusion relationship

$$\Sigma^2 \sim u'Lt. \tag{2.5}$$

The value of Λ is a function of L, u', $b_{n.t}$, $u_{n.t}$, and t. On the basis of a dimensional analysis theorem, this functional relation can be written in the following dimensionless form

$$\Lambda/b_{n.t} = G_1(u't/b_{n.t},\ u'/u_{n.t},\ L/b_{n.t}).$$

Taking into account the relation between $u'/u_{n.t}$ and $L/b_{n.t}$ that follows from (1.6), and using the condition of stationarity of u_t according to (2.1), we obtain for the validity of (2.5)

$$\Lambda/b_{n.t} = (u't/b_{n.t})^{1/2} G_2(L/b_{n.t}). \tag{2.6}$$

According to (2.3), the argument of the function G_2 is large. Let us present reasoning that hence $G_2 = \text{const} \sim 1$. Indeed, if this is so, then $b_{n.t} \ll \Lambda \ll L$ upon compliance with (2.4). Hence, vortices of the size L transfer perturbations on the order of Λ as a whole to the front and Λ cannot depend explicitly on L, i.e., $G_2 = \text{const}$. It follows from (2.2), (2.5), and (2.6) that

$$\overline{(\delta S/\delta S_0)} \approx (L/b_{n.t})^{1/2}. \tag{2.7}$$

The expressions (1.6), which are valid when the width of the extended combustion front corresponds to the domain of the inertial interval of the energy spectrum, were used in obtaining (2.7). If this is not so, particularly for the existence of laminar combustion fronts, then (2.7) does not hold.

Let us emphasize that the stationarity of the combustion front area does not contradict the nonstationarity of the width of the average combustion zone since the quantity Σ is determined primarily by vortices in which the order of the pulsations is u' and the size is L, while the area is determined by much fewer vortices in which the pulsations are commensurate with the value of the front velocity $u_{n.t}$ (the dependence of $\overline{(\delta S/\delta S_0)}$ on L does not contradict this because of the existence of equilibrium between the turbulence macro- and microstructure). This results in static equilibrium between the increase in the surface area of the front because of turbulent pulsations and its diminution because of displacement of the combustion front relative to the medium, the buildup time of a constant value of area is hence much less than L/u'. The increase in Σ is associated with the fact that equilibrium between the expansion of the mean combustion zone because of turbulent diffusion and its narrowing because of front displacement relative to the medium is not achieved at the times (2.4). Such equilibrium can be achieved for $t \sim L/u_{n.t}$.

Let us note that some considerations from dimensional analysis yield only

$$\overline{(\delta S/\delta S_0)} = H(L/b_{n.t}). \tag{2.8}$$

It follows from (2.7) and (2.8) that the function H does not tend to a constant as the argument increases. Physically this is conceivable since the area of an infinitely thin material surface increases monotonically with time in turbulent flows. Hence, as $b_{n.t}$ (and thereby $u_{n.t}$) tends to zero, the stationary magnitude of the area can be arbitrarily large. The power-law dependence in (2.7) is actually a manifestation of self-similarity of the second kind examined in [9, 10], however, it follows here from a qualitative analysis rather than from the exact equations of the problem (which are not in the approach under consideration).

The relationships (2.1), (2.7), (1.6), and (1.8) yield the final result

$$u_t = Au'^{3/4}u_n^{1/2}a^{-1/4}L^{1/4} \sim u'\left(\frac{t_t}{t_c}\right)^{1/4}, \tag{2.9}$$

which holds upon compliance with the inequalities (1.10), (2.3), and (2.4), where A is an empirical parameter of the order of one.

Because of the smallness of the value of the exponent $(t_t/t_c)^{1/4} \approx \text{const} \sim 1$ (for instance, $t_t/t_c \sim 10^2$ $(t_t/t_c)^{1/4} \sim 3$ in (2.9) the approximate expression $u_t \sim u'$, relative to (2.9), follows, which agrees with the result obtained on the basis of simple geometric considerations in [4].

If (2.9) is rewritten in the form $u_t/u' \sim (L/u' \cdot u_n^2/a)^{1/4}$ and (2.3) is taken into account, we obtain that $u_t > u'$. An estimate for Σ in the time range (2.4) follows from (2.4) and (2.5), and can be considered as the characteristic width of the turbulent combustion zone:

$$1 \leqslant \Sigma^2/L^2 \ll (u'^3/\varepsilon \cdot u_n^2/a)^{1/2} \sim \left(\frac{t_t}{t_c}\right)^{1/2}. \tag{2.10}$$

Let us again emphasize that here we understand u_t to be the mean volume combustion velocity which is considered during the combustion time when the average width of the one-dimensional reaction wave increases according to the law of turbulent diffusion. The velocity of its forward boundary, determined by instantaneous ejections of the combustion products into the cold mixture, can exceed the quantity u_t substantially, where in substance the propagation velocity of such single ejections is not related to u_t.

It can be represented that the width of the one-dimensional zone reaches stationary values for much greater combustion times, and the values of the forward boundary velocity and of u_t will be equal. In this case u_t will be determined by the propagation velocity over the cold mixture of incendiary foci being propagated because of the relatively scarce, but significant, ejections of combustion products into the fresh mixture, and the known "rapid" mechanism of combustion propagation will be realized. The instantaneous combustion sur-

face will automatically be readjusted so that the relationship (2.1) would be satisfied for this value of the combustion propagation velocity. The quantity $u_{n.t}$ and the mean spacing between such ejections will affect the value of the stationary average width along the reaction.

3. Let us analyze the condition for compliance with (1.10) and (2.3) in experiments and the correlation between the relationships (2.9) and (2.10) for u_t and Σ with experimental results. Let us examine the following characteristic mode: the combustion of a stoichiometric mixture of hydrocarbon fuel at normal pressure and a 300°K initial fuel mixture temperature in a 0.2-m-diameter pipe at the mean velocity 100 m/sec, a = 0.2 m^2/sec, u_n = 0.4 m/sec, u' = 5 m/sec, L = 1 cm, ν = 0.15 cm^4/sec. Substitution of these values in the inequalities (1.4) and (2.3) yields $8 \gg 1$ (i.e., the Kolmogorov dimension is half the thickness of the normal combustion front) and $0.3 \ll 1$, respectively. Because of the asymptotic nature of the combustion model developed, it is admissible to consider the existence conditions for the models to be satisfied in tests.

Since u_n grows with the rise in the initial mixture temperature (for T_0 = 300°C we have $u_n \sim 1.5$ m/sec and $u_n \sim 3$ m/sec for T_0 = 600°C), a sufficiently high velocity pulsation level and sufficiently large turbulence scales are needed to comply with conditions (1.10) and (2.3), which can be achieved in high-speed flows in large-scale installations when using turbulizing gratings with large perforations. It follows from an analysis of (1.10) and (2.3) that the results are made inapplicable to describe combustion in low-speed flows and for a low pulsation intensity level ($u' \sim u_n$), as well as for too small integrated turbulence scales L ($u_{n.t} \sim u_t$) or for too high turbulence scales and intensities (it is apparently difficult to realize this latter case in practice). Hence, the results obtained, particularly (2.9), are valid to describe the turbulence combustion process in ramjet chambers and in large industrial installations. There is less foundation for their application in small laboratory installations with low-flow speeds although, as often turns out in applications, such relationships based on asymptotic estimates can turn out to be applicable to describe experiments and in a broader range of parameters than was assumed in obtaining them.

Let us present some comparisons between the deductions obtained and experimental results for which a systematic survey can be found, e.g., in [2, 10, 11]. The exponenet in the relationship between the turbulent combustion velocity and the mixture velocity pulsations, equal to 0.7-0.8, which corresponds to (2.9), is presented in [2]. The relation to the pressure can be obtained if the pressure dependence for u_n and a is taken into account. Since $a \sim p^{-1}$, and $u_n \sim p^{-(0.2-0.3)}$ for propane, we find $u_t \sim p^{0.10-0.15}$ from (2.9), which corresponds to test results [12], where $u_t \sim p^{0.12}$. Analogous relationships are also obtained in [13]. There are several different dependences of the turbulent combustion velocity on the pressure presented in [2], but the turbulence parameters varied with the change in pressure in these papers, in contrast to [12] in which turbulizing gratings conserving a constant value of u' were selected every time as the pressure changed.

An empirical formula for the turbulent combustion velocity $u_t \sim L^{0.18}$, which is quite similar to (2.9), is presented in [14]. Analogously, since $u_n \sim T_0^2$, $a \sim T_0^2$, the relation between the turbulent combustion velocity and the initial temperature has the form $u_t \sim T_0^{0.5}$, which is close to the experimental dependence $u \sim T_0^{0.4}$ [15].

The effective coefficient of thermal diffusivity a in the dimensional relationships of the theory of a laminar flame front must be known to determine the influence of the fuel mixture composition. Analysis of the experimental data and some theoretical considerations about the influence of "diffusion stratification" presented in [16] showed that the effective coefficient of thermal diffusivity can depend significantly on the mixture composition. Analysis of a series of experimental results on the influence of the pressure of an air–gasoline fuel mixture (in the p = 0.2-4.5 bar range), the temperature (393-793°K), the stream velocity (u = 30-100 m/sec), the excess oxidizer factor (α = 0.6-1.4) in a square channel of 50 × 50-mm section on the turbulent combustion velocity (determined along the forward front), which has been obtained in [17] with the dependence for a according to [16] taken into account, showed that the numerical values for A in (2.9) lie in the 0.6-1.2 range.

Expansion of the average combustion zone, which corresponds approximately to expansion of the turbulent mixing zone for the same stream turbulence parameters, is observed in tests upon withdrawing from the site of ignition. The turbulent combustion velocity along the combustion zone is hence approximately constant [2, 10]. In the one-dimensional nonstationary combustion zone, this corresponds to its expansion in time with the conservation of the quantity u_t.

The order of the ratio Σ / L can be $\Sigma / L \sim 1$-10 because of inequality (2.10). Taking into account that the combustion zone width is actually $b_t \sim (4\text{-}6)\Sigma$, this estimate explains that the limit values of the average heat liberation zone width are not determined successfully for the organization of combustion in channels (where $L/D \sim 0.1$ and D is the diameter), and combustion takes place in the expanding tongues.

Numerical values of the exponents in the expressions for $u_{n.t}$, $b_{n.t}$, $a_{n.t}$, and u_t in (1.9) and (2.9) are obtained without relying on any empirical numerical values and follow from qualitative considerations, on whose basis the governing parameters of the problem are selected. Hence, not only dimensional analysis considerations are drawn upon, but also a representation of the instantaneous combustion front as a random surface, which resulted in an estimate for the area (2.2) which cannot be obtained on the basis of dimensional analysis. Using some similarity reasoning can result in limited results, and particularly, does not permit determination of the numerical values of the exponent or making deductions about the width of the combustion zone [17]. The proposed analogous power-law dependences for u_t (e.g., see [10]) actually contain empirical parameters.

Let us note that exactly the same expression for u_t was obtained in [19], after the present research had been performed (the results of which are contained in [18]), by starting from completely different representation of the stationary width of the average zone and the laminar instantaneous fronts on the basis of a qualitative analysis without relying upon empirical constants and the equations for the combined probability density distributions of the temperature and velocity.

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