V. R. Kuznetsov ▲ V. A. Sabel'nikov

Turbulence AND Combustion

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TURBULENCE AND COMBUSTION

Revised and Augmented for the English Edition

V. R. Kuznetsov
Baranov Central Institute of
Aviation Motor Designing

V. A. Sabel'nikov
Zhukovsky Central Institute of
Aerohydrodynamics

English-Edition Editor

P. A. Libby
Department of Applied Mechanics and
Engineering Sciences
University of California, San Diego

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PREFACE

A significant part of the energy currently used is produced by burning gases or vaporized liquid fuel in turbulent flows. Seemingly, this method of obtaining energy will remain dominant for a long time to come, particularly in transportation. Therefore, the study of turbulent combustion is of considerable practical interest.

Investigations of turbulent combustion reveal a noticeable gap between fundamental and applied research which thwarts the development of the technology, since fuel combustion devices have reached high levels of development and further improvement of their performance is not feasible without thorough analysis of the fluid dynamic features of combustion chambers, in particular, the characteristics of turbulence. In the meantime, the theory of turbulence has lately progressed considerably. Naturally, an adequate quantitative description of all turbulent flows is not presently feasible. However, the available qualitative understanding of many features of turbulence, and the accumulated experimental data and dimensional considerations allow sufficiently accurate estimates to be made of the characteristics of turbulence in a wide class of flows. Furthermore, many features of the combustion of gases in laminar flow are currently clear. Therefore, these prerequisites for the creation of the theory of turbulent combustion exist.

The proposed monograph sets out to expound, from a single standpoint, the principles of this theory which have been formulated to date. The selection of the scope of problems on which the principal concepts, ideas, and the techniques of the theory have been largely dictated by the authors' own investigations. The very first stages of these investigations showed that the construction of the theory of turbulent combustion is impossible without the development of the theory of turbulence proper and, in particular, those parts which were less studied (intermittency, probability distributions of various fluid dynamic parameters). As is often the case, the investigation of the indicated problems acquired independent significance and it is hoped that the obtained results will affect the development of the theory of turbulence. These considerations determined the title of the book and the selection of the material. Despite its definite weakness and tendentiousness, such an approach apparently enables the fulfillment of the set task. The theory of turbulent combustion is still in the developmental stage. The authors realize that the proposed monograph is only a small (albeit necessary) step toward the solution of the problems of turbulence and turbulent combustion.

The monograph is comprised of an introduction, seven chapters, and conclusion. With the exception of §1.4, the first four chapters are devoted to the investigation of flows without chemical reactions. This investigation was conducted on the basis of the equations for probability distribution densities of various turbulence characteristics.

Chapter 1 covers intermittency of turbulent flows and its effect on the qualitative form of velocity and concentration probability distribution densities. In Chapter 2, equations for the probability distribution densities of various fluid dynamic quantities are derived and a review of the known closure methods of these equations is conducted.

In Chapter 3, an equation for the probability distribution density of a passive contaminant is analyzed. The solution of this equation is obtained, analyzed, and compared with the experiment. Investigated in Chapter 4 is the equation for the probability density of velocity difference at two points separated by a distance in the inertial range of the turbulent spectrum.

The results obtained in the first four chapters are utilized for the analysis of diffusion combustion (Chapter 5) and combustion of a homogeneous mixture (Chapter 6). The principal result of Chapter 5 is a method of computation of the main characteristics of turbulent diffusion combustion. The method accounts for the chain character of the chemical reactions. It is shown that the effect of turbulence on the conditions of progress of chemical reactions is determined by scalar dissipation. A method for the calculation of the concentration of nitrogen oxides is given.

In Chapter 6, a qualitative picture is constructed providing the framework for the effect of flame instability and the differences in the molecular transport coefficients on the progress of combustion of a homogeneous mixture. A number of nontrivial criteria have been obtained characterizing flame propagation. An estimate of the ultimate heat release of the combustion process is given on the basis of the theory of locally homogeneous turbulence, and it is shown that this heat release is substantially lower than that in normal flames if the integral turbulence scale is greater than the thickness of the normal flame front.

The development of the theory of turbulence and turbulent combustion, like the development of any physical theory, is impossible without a close and continuous link with experiment. Therefore, great attention is given to the selection and analysis of experimental data illustrating the adopted hypotheses and conclusions. The methods developed in the monograph can be used in scientific and applied problems that are associated with the investigation of the effect of turbulence on the progress of chemical reactions (for example, in chemical technology, in gas dynamic lasers and so on). The authors are hopeful that the present monograph will facilitate further mutual unravelling and enrichment of the methods of the theory of turbulence and the theory of turbulent combustion, and stimulate new investigations at the interface of these two theories.

All the main physical ideas and mathematical techniques of the theory of turbulence and theory of combustion are given in the text as deemed necessary for direct use in the theory of turbulent combustion. Additional information on the theory of turbulence, theory of combustion, and also the widely used (in the monograph) similarity theory can be found in the special literature (see Batchelor [1953], Townsend [1956], Hinze [1959], Monin and Yaglom [1965, 1967], Frank-Kamenetskii [1967], Shchetinkov [1965], Williams [1965], Sedov [1977], and other books which are referred to in the text of the monograph).

The development of the general plan of the monograph and the discussion of the separate chapters were conducted with the combined efforts of both authors; therefore, they are equally responsible for possible shortcomings and omissions.

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V. R. Kuznetsov
V. A. Sabel'nikov

INTRODUCTION

To construct the theory of turbulent combustion, one must combine, in a single unit, the methods and concepts that have been formed in two substantially differing branches of science—the theory of turbulence and the kinetics of chemical reactions. In order to do so, one must first of all establish which turbulence characteristics are of principal interest for the theory of combustion. The answer is furnished by the theory of laminar combustion which proceeds from the fact that the thickness of the zone where the processes of chemical conversion take place is much less than the characteristic dimension of the problem. For example, in laminar combustion of a homogeneous stoichiometric propane-air mixture under normal conditions the thickness of the reaction zone is less than 0.5 mm. Furthermore, during combustion strong temperature changes take place and the rates of chemical reactions are strongly dependent on the temperature. This circumstance also leads to the chemical reactions being localized in thin zones.

On the basis of these indicated features, methods have been developed in the theory of laminar combustion which enable the description of the phenomenon to be significantly simplified. Indeed, the zone of chemical reactions can be regarded as a boundary layer. Then, the solution of this internal problem (i.e., distribution of concentrations and temperature in the reaction zone) is found with the aid of relatively simple methods, since heat and mass transfer along the flame front in the equations of diffusion and heat transfer is insignificant and, hence, it suffices to integrate a system of ordinary differential equations. When solving the external problem, chemical reactions can be ignored, and the combination of the internal and external solutions enables the location of the flame front to be determined.

To illustrate this, we can cite two characteristic examples—laminar combustion of nonpremixed gases (diffusion combustion) and combustion of a homogeneous mixture. In the first case, an elegant technique, proposed by Burke and Schumann [1928], is used; namely, the so-called reduced concentration of the fuel is introduced $z = (\mathrm{St}\, c_\mathrm{f} - c_\mathrm{o} + 1)/(1 + \mathrm{St})$, where St is the stoichiometric factor (indicating the number of grams of the oxidant needed for the complete combustion of one gram of fuel), c is the mass concentration, and subscripts f and o refer to the fuel and oxidant, respectively. The quantity z can be interpreted as the concentration of the atoms in all the formed chemical compounds. Therefore, chemical reactions do not evidently affect its distribution, and the latter is found from the solution of the equation of diffusion without sources. Since chemical reactions occur rapidly, the concentration of the fuel and the oxidant at the flame front are simultaneously close to zero, i.e., the flame front, as a first approximation, is a surface on which condition $z = z_s = 1/(1 + \mathrm{St})$ is fulfilled. The investigation of the internal structure of the flame front in diffusion combustion was conducted by Zel'dovich [1949], on the assumption that the chemical reaction is a single step, and an irreversible process. This study is reduced to the solution of one ordinary differential equation with a nonlinear source term.

As another example, we can cite laminar combustion of a homogeneous mixture. The solution of this problem was obtained by Zel'dovich and Frank-Kamenetskii [1938 a, b] who analyzed propagation of the normal (plane) flame front. Two zones are identified in the flame. In the first (the preheat zone) chemical reactions are insignificant. In it, the mixture is heated as a result of convection and heat conduction. In the second zone, (zone of chemical reactions) chemical conversion of the reactants takes place. Convection in this zone is insignificant, and heat transfer is determined only by conduction. It is important that the thickness of the reaction zone is several times less than the thickness of the preheat zone. Therefore, the reaction zone can be regarded as a surface on which specific boundary conditions apply. The first condition is obvious—the temperature is equal to the temperature of the equilibrium products of combustion. The second condition links the jump of the temperature derivative normal to the reaction zone with the rate of the chemical reaction and the coefficients of molecular transport (the existence of such a jump follows from the fact that heat release is concentrated on the surface).

The method of Zel'dovich and Frank-Kamenetskii can also be used to describe the combustion of a homogeneous mixture in general flows. To this end, the heat transfer equation without sources and with two boundary conditions must be solved: 1) on the surface of the flame front the temperature is equal to the temperature of the combustion products and 2) at an infinite distance from the flame front the temperature is equal to the temperature of the fresh mixture. One more boundary condition for the jump of the temperature derivative along the normal to the reaction zone determines the location of the flame front.

The solution, in a number of cases, can be simplified further, since not only the thickness of the reaction zone, but also the thermal flame front thickness is frequently small compared with the characteristic dimension of the problem (as already mentioned, upon combustion of a homogeneous mixture of propane with air in normal conditions the main change of temperature occurs in a distance less than a millimeter). Therefore, the flame front can be regarded as a surface on which discontinuous changes of velocity, density, concentrations, and temperature take place. The velocity of this surface relative to the fresh mixture is a physicochemical constant which is often referred to as the normal propagation velocity u_n. Thus, the determination of the position of the flame front is reduced to the solution of a purely kinematic problem: to finding the surface which moves with velocity $u + u_n n$ (u is the velocity of the fresh mixture and n is the unit normal to the flame front).

It follows from the above that in the laminar combustion of both nonpremixed and homogeneous gases, the position of the flame front can be determined without consideration of the details of chemical kinetics.

The methods indicated above can be used for the analysis of the turbulent combustion of a homogeneous mixture (Damköhler [1940], Shchelkin [1943] and of turbulent diffusion combustion (Hawthorne, Wedell, and Hottel [1949]). There is little doubt at the present time that the reaction zone in turbulent diffusion combustion can be assumed to be thin (henceforth, the reaction zone is defined by the nonaveraged distributions of temperature and concentrations). As regards turbulent combustion of a homogeneous mixture, the known experimental data (though presently very limited) also indicate that the thickness of the reaction zone in the majority of cases is small compared with the characteristic dimension of the problem.

Thus, the investigation of turbulent combustion can be conducted in two stages. In the first stage, the internal structure of the reaction zone is studied. This structure is determined only by the local characteristics of turbulence. For example, if the reaction zone thickness is much less than the minimum spatial scale of velocity fluctuations, then it can be assumed that the velocity of the medium and the reduced concentration of the fuel in the vicinity of the reaction zone vary linearly. Such an approach has already been employed in the theory of combustion of a homogeneous mixture (Klimov [1963]). In the second stage, large-scale oscillations of the reaction zone, which lead to its mixing as a whole, are investigated. In this case, the amplitude characteristics of the oscillations are of main interest, since they determine the mean length of the combustion zone. In this stage, the details of chemical kinetics do not have particular significance.

In order to formulate which turbulence parameters and which methods of investigation ought to be used in each of the stages, let us consider the specific features of turbulent flows and the directions resulting from these features relative to the theory of turbulence. Two main approaches can be currently identified in this theory. The purpose of the first approach (traditional) is to find various statistical characteristics. The second appeared relatively recently with the development of powerful computers and is based on the numerical integration of the Navier-Stokes equations, i.e., on the elucidations of a more or less detailed picture of the flow. The investigation of the so-called coherent structures pertains to this direction, i.e., nonrandom or completely random large-scale velocity fluctuations.

The selection of the correct approach must be based on the principal feature of turbulence which is determined by the condition of large-scale flow characteristics.

To clarify, it should be remembered that any complex spatial velocity distribution can be represented in the form of superposition of harmonic oscillations. The wavelengths of large-scale oscillations in turbulent flows are comparable with the characteristic linear dimension of the flow. The wavelength of the small-scale oscillations is much less than the characteristic dimension of the flow and, most importantly, decreases with increasing Reynolds number. Therefore, in the superposition under consideration (i.e., in the turbulence spectrum) a large number of oscillations are considered with a larger range of wavelengths. Large-scale oscillations determine the energy of turbulence, and small-scale oscillations determine its dissipation, which is significant at all Reynolds numbers (i.e., at any viscosity, however small).

The last circumstance deserves particular attention. It is evident from the general considerations that large-scale velocity fluctuations are practically independent of viscosity, since the Reynolds numbers for them are usually very high. Such fluctuations are, however, unstable, as a result of which fluctuations with less spatial scale and somewhat lower Reynolds number are formed. This process continues until the fluctuations are so small in spatial scale that their Reynolds number becomes of the order of unity. These fluctuations are stable due to the strong effect of viscous dissipation. Therefore, with decreasing viscosity the scale of the smallest spatial fluctuation drops, leading to an increase in the velocity gradient and, hence, the energy dissipation stays, on the average, unchanged.

It follows from the described picture that the multiscale state of the processes of turbulent transport leads to self-similarity of turbulent flows with respect to Reynolds numbers. Expressed more precisely, this means that the mean values of all quantities, determined by large-scale velocity fluctuations, are independent of the Reynolds number if this number tends to infinity. To such quantities belong, for example, velocity, pressure or concentration of the inert contaminant and also the various intensities of these quantities. The principle of self-similarity with respect to Reynolds number is not, generally speaking, applicable to the description of the gradients of fluid dynamic parameters, since these gradients are determined by small-scale velocity fluctuations. The validity of the principle under consideration is well supported experimentally and does not presently cause particular doubts.

A number of important conclusions are drawn from this argument. First of all, it is evident that the description of the energy carrier and large-scale velocity fluctuations alone cannot be closed. Indeed, the evolution of such fluctuations is determined by viscous dissipation which depends on small-scale fluctuations. Furthermore, since the energy spectrum of the fluctuations is continuous, large- and small-scale fluctuations cannot be considered in isolation as in the theory of the laminar flow of a continuous medium when microscopic and molecular motions are considered. Therefore, only two paths are possible for constructing the theory of turbulence. In the first, all the characteristics of the fluctuation of all scales are considered. Moreover, viscous effects must be accounted for; consequently, the coefficient of kinematic viscosity must appear in such a theory. This path, however, involves superfluous information, since the main features of turbulence are independent of Reynolds numbers.

Therefore, the second path is more natural and is based on the search for universal links between the characteristics of small- and large-scale fluctuations. As is evident from the theory of Kolmogorov [1941] and Obukhov [1941], similar links do indeed exist, if the characteristic scales of the fluctuations determining the energy of turbulence and its dissipation are significantly different. These links are regarded as consequences of the principle of turbulence self-similarity with respect to Reynolds number.

Strictly speaking, such an approach presumes consideration of the limit of the Navier-Stokes equations when Re → ∞. In this case, difficulties arise, and in order to eliminate them we apply the known quantum mechanics reasoning which illustrates the need for statistical description of the problem. Pursuing the ideas of quantum mechanics, we consider whether it is possible to measure any quantity (including energy dissipation) at Re → ∞. The term "measurement" is naturally understood to mean not only the measurement proper with the aid of some physical instrument, but also the numerical solution of the Navier-Stokes equations.

Obviously, in any experiment or numerical solution of the Navier-Stokes equations only quantities averaged over some space–time domain are determined (such quantities are convenient to refer to as partially averaged). If the Reynolds number tends to infinity, then the problem of measurement (or numerical solution) becomes particularly important, since the spatial scales of velocity fluctuations determining dissipation tend to zero. Evidently, the theory has an objective value only if we consider the quantities having a limit when the dimension of the domain, over which averaging takes place, tends to zero (otherwise, different measuring devices or different numerical algorithms will yield inconsistent results). Thus, it is necessary to analyze the double limit when, on the one hand, the Reynolds number tends to infinity, and, on the other, the dimension of the domain l, over which averaging takes place, approaches zero. From the practical standpoint, this means that a series of tests are carried out in which quantities l and Re are varied, and the measurement results are then extrapolated in the region $l = 0$, Re $= \infty$.

The existing experimental data indicate quite definitely that such extrapolation is impossible. This conclusion is based on numerous tests in which intermittency was investigated, i.e., extremely irregular distribution of velocity and concentration gradients in turbulent flows when the regions with extremely small gradient values (nonturbulent fluid) alternate irregularly with the regions in which the values of the gradients are very large (turbulent fluid)—Corrsin [1943], Batchelor and Townsend [1949], Townsend [1956] and others. The rate of turbulence energy dissipation

$$\epsilon = \frac{1}{2}\nu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)^2$$

and the scalar dissipation of concentration nonhomogeneity

$$N = D\left(\frac{\partial z}{\partial x_k}\right)^2$$

(ν and D are the kinematic viscosity and molecular diffusion coefficient, respectively) are quadratic with respect to the gradients; therefore, the previous discussion is equally pertinent to the fields of ϵ and N, which play the most important role in the theory of turbulence and turbulent mixing.

In a nonturbulent fluid, energy dissipation and small-scale fluctuations are absent. In a turbulent fluid, dissipation and small-scale fluctuations always play an important role.

Therefore, if measurements are being conducted within turbulent fluid, and if l = const, there will always be a sufficiently large Reynolds number so that energy dissipation will change significantly within the measurement volume. Hence, the measured value of dissipation depends on the dimension and form of the domain over which averaging is effected. This means that there is apparently no objective means of finding partially averaged dissipation energy in a turbulent fluid. Thus, if Reynolds number tends to infinity, then only a statistical description of the flow in the turbulent fluid is possible (i.e., where $\epsilon > 0$). On the other hand, the deterministic description of flow in a nonturbulent fluid is possible, since small-scale velocity fluctuations are nonexistent and, hence, the determination of quantities ϵ and N is unnecessary.

Hence, the difficulties arising in the investigation of turbulence associated with the detailed picture of the flow are obvious. Indeed, the numerical integration of the Navier-Stokes equations is possible at not-so-high Reynolds numbers that are of principal interest in specific scientific and applied problems. To overcome these difficulties, a number of the so-called estimate turbulence models are proposed in which partially averaged flow characteristics are directly considered. The computation of these characteristics is based on equations of motion in which the effect of fluctuations with wavelengths which are less than the averaging scale is described by means of the coefficient of turbulent (more precisely, microturbulent) viscosity. However, it is evident that not all problems are solved with the aid of estimate models, since, as already mentioned, intermittency leads to the fact that there is no objective method for finding partially averaged energy dissipation. For the same reason, one cannot give a closed description of coherent structures.

Considerable difficulties also exist in the statistical approach. Three directions can be identified in this approach: 1) investigation of the formalism of the moments linked by the infinite chain of the Keller-Fridman equation [1924]; 2) the functional approach to the theory of turbulence based on the consideration of the characteristic functional introduced by Kolmogorov [1935] for which a linear equation in variational derivations was obtained by Hopf [1952]; and 3) formalism of finite–dimensional probability distributions, introduced relatively recently in the works of Monin [1967], Lundgren [1967], Novikov [1967], Ulinich and Lyubimov [1968], and Kuznetsov [1967].

Only the functional approach to the theory of turbulence is closed. However, the lack of a mathematical theory of the equations in variational derivatives and, equally important, the lack of clarity in the additional limitations which enable the identification of the number of functionals that are of interest for the theory of turbulence, do not allow, as yet, any firm results in this direction to be obtained.* Furthermore, the characteristic functional describes all the statistical properties of the velocity field, including the properties of small-scale fluctuations that are dependent

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*Detailed discussion of the problem and presentation of rigorous results which relate to Hopf's equation is included in a book by Vishik and Fursikov [1980].

on the Reynolds number. Consequently, such an approach is linked, in a sense, with the processing of superfluous information.

The other directions, including turbulence models, in which the main efforts are directed toward seeking the first two single-point moments of the velocity and concentration field, are based on accurate (though not closed) relations resulting from the Navier-Stokes equations. To close these relations, information gained from experience is introduced. Despite some success, this path did not lead, however, to the creation of a universal theory that is capable of describing all turbulent flows with sufficient practical accuracy.

Thus, considerable difficulties arise both upon using statistical methods and attempting to elucidate the details of the flow. Apparently, only the combination of both approaches, statistical and deterministic, permits the solution of the problem of describing turbulence. Such a combination, as will become clear now, is also important in the theory of turbulent combustion.

It was indicated earlier that the reaction zone thickness in the majority of cases is small. Therefore, for the approximate description of combustion a certain surface can be introduced close to which the reactions are localized. This surface is strongly distorted by turbulent fluctuations of different scales and, if it can thus be expressed, has the shape of a strongly crumpled piece of paper with multiple internal voids of widely varied sizes. Despite such a complex structure, two problems can be separately considered: 1) what is the internal structure of the reaction zone, and 2) what is the structure of the surface near to which it is localized?

Let us consider the first problem. Since the thickness of the chemical reaction zone is small, its structure is determined by the local characteristics of turbulence. On the basis of the theory of Kolmogorov [1941] and Obukhov [1941, 1949], it can be assumed that these characteristics are the coefficients of molecular transport, energy dissipation ϵ, and, if we are considering the combustion of nonpremixed gases, scalar dissipation N.

When investigating the internal structure of the reaction zone, statistical description of the process is, in a sense, superfluous. Indeed, if the reaction zone is locally planar, then all the characteristics of the process are described in a coordinate system, linked with some isotherm in this zone, by one-dimensional, quasi-stationary equations of diffusion and heat. These equations contain the components of the velocity of the medium, the normal to the reaction zone and, if we are considering combustion of nonpremixed gases, the reduced concentration of the fuel. In view of the fact that the reaction zone thickness is small, it can be assumed that these quantities are linearly dependent on the coordinate normal to the reaction zone. Therefore, the solution of the diffusion and heat equations inside the reaction zone can be obtained by means of simple methods. The solution obviously features direct velocity gradients and reduced concentration of the fuel which must be regarded as random parameters. Within the framework of such an approach, statistical methods are required only to determine the mean characteristics of the process inside the reaction zone.

It is quite clear that the solution of this problem is very closely associated with the investigation of statistical characteristics of the small-scale part of the turbulence spectrum. Hence, it is obvious that energy dissipation and scalar dissipations are of fundamental importance not only in the theory of turbulence (Kolmogorov [1941], Obukhov [1941, 1949]), but also in the theory of turbulent combustion.

Let us consider the second problem. The solution must be based on the analysis of probability distributions of various fluid dynamic parameters. Indeed, it is quite clear from geometrical considerations that the probability density of temperature (or concentration) can be linked with the volume enclosed between two adjacent isotherms—in particular, between those where the main conversion of the substance takes place. The latter volume is proportional to the surface near which chemical reactions are localized. This circumstance stipulates the particular role of probability densities in the theory of turbulent combustion. Formally, this role is evident in the fact that upon solution of the equations describing the behavior of the reacting gas, the rates of chemical reactions which are nonlinearly dependent on temperature and concentration are averaged.

At the stage of investigation under consideration, the details of chemical kinetics are of little importance. For example, in the combustion of nonpremixed gases the reaction zone is located near a surface on which the reduced concentration of fuel, i.e., concentration of the contaminant not taking part in the reaction, is constant. This means that the statistical characteristics of the flame front oscillations are directly dependent on the rate of chemical reaction, i.e., the problem is reduced to the investigation of probability distribution of the inert (nonreacting) contaminant.

In the combustion of homogeneous mixtures, the reaction zone is located near the surface on which the temperature is constant and close to the temperature of the combustion products. The description of large-scale fluctuations of the flame front is, thereby, reduced to the study of temperature probability distribution. The details of chemical kinetics do not have significance in this case either, since it can often be assumed that the velocity of the reaction zone relative to the medium is close to u_n and, thus, the specific features of the chemical reactions affect only the normal velocity of flame propagation.

When using these considerations in the investigation of turbulent combustion, a whole series of nontrivial effects must be taken into account. One of them is related to the effect of gas density change on the fluid dynamic structure of the flow as a result of which the mean velocity of the initial fuel components and combustion products changes. This process, first of all, acts on the large-scale part of the turbulence spectrum. Consequently, the characteristics of the latter depend weakly on the kinetics of chemical reaction and are mainly determined by the ratio of the densities of the initial fuel components and combustion products. In the combustion of a homogeneous mixture, in addition to the noted factors, a substantial role is played by the fluid dynamic (thermal) instability of the laminar flame which can, under specific conditions, lead to additional flow turbulence. From the linear theory of stability (Landau [1944]) it is known that the increment in the amplitude of the harmonic flame fluctuation increases with a decreasing scale of this fluctuation or with an increasing normal velocity of flame propagation. Therefore, small-scale turbulence must first increase. The characteristics of this turbulence are dependent on u_n, i.e., are determined by the rate of chemical reactions.

Another group of effects is associated with the influence of the processes of molecular transport on the structure of the chemical reaction zone. It should be emphasized, in this regard, that since the reaction zone thickness is small, its structure is determined by the small-scale part of the turbulence spectrum. The principle of self-similarity with respect to Reynolds number is not applicable to the latter. It should also be noted that the differences between the coefficients of molecular transport, which lead to a change in the composition and temperature in the reaction zone, play an important role.

Finally, when analyzing the internal structure of the flame front, the chain character of chemical reactions must be taken into account; i.e., one must bear in mind that chemical conversion occurs in several stages in which many intermediate substances are formed (atoms and free radicals).