Lean spherical hydrogen–air flames at 4 orders of magnitude in size and ignition energy

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Abstract. The subjects of this work are: identification of features of common and different for the flame propagation in volumes from 3 l to 30 m$^3$; comparison of the flame propagation modes upon ignition with energies from 1 mJ to 5 J; explanation of differences in results when using different shells that limit the volume of the combustible mixture. A series of experiments on spherical propagation of flame front in various shells is conducted. The position and morphology of the flame front was recorded with ir camera Infratec ImageIR 8320 with spectral range 2–5.7 µm and schlieren device IAB-451 equipped with high-speed camera VideoSprint G2. Dependences of the flame front position versus time are obtained.

1. Introduction

Self-sustained release of chemical energy in the oxidation of gaseous fuels has got wide practical application for obtaining energy or products of complete or partial oxidation. Propagation of a flame in homogeneous mixtures of fuel with an oxidizer is the common used test problem for many theoretical and numerical models of combustion. Despite the simplicity of setting the initial and boundary conditions, the spherical propagation of a flame is associated with a large number of physical phenomena that transform the one-dimensional spherical propagation of a smooth flame front into a complex three-dimensional task.

Propagation of the flame in the initially quiescent gas is accompanied by the release of heat and, usually, the expansion of the combustion products, which drive in motion a combustible mixture ahead of the flame front. The propagation of a flame in the resulting flow is accompanied by dissipative processes that would lead to an equilibrium linear system, where the counteraction is proportional to the amplitude of the action. But the nonlinear system, which is the front of the flame, as a result of elementary perturbations and dissipative processes, forms structures that lead to increased perturbations and the development of instabilities. For the first time, the connection between coherent structures and dissipative processes was noted by Prigogine [1]. He also introduced the term—dissipative structures.

A striking example of dissipative structures is the hydrodynamic instability of the flame—the Darrieus–Landau instability. This type of instability was first obtained mathematically by Landau in the assumption of an infinitely thin flame front [2]. Later in the works of Istratov...
and Librovich [3], the proposed approach was supplemented by a flame front model of finite thickness. The supplemented model showed good agreement with the experimental data [4].

Another example is the diffusive-thermal instability, which demonstrates an increase in the surface and velocity of flame propagation, caused by the disbalance of heat and matter transport through the flame front [5].

The development of instabilities in the flame front leads not only to its acceleration, but also to the occurrence of pulsations in the pressure and the velocity of the gas in the vicinity of the expanding flame front. In papers [6, 7], an opinion was expressed on the establishment of the Kolmogorov cascade for the scale of turbulent pulsations, which lead to acceleration of the flame front in accordance with a power law with exponent equal to 1.5 [4, 6, 8].

In any case, the acceleration of the flame caused by the instabilities of the front is described by statistical methods. Instead of a deterministic description, one should use the distribution functions for the parameters of the descriptive equation.

This paper is devoted to observing the free spherical flame front propagation in 15% hydrogen–air mixture in the volumes of 0.003, 9, 15 and 30 m$^3$. The ignition energy was 0.001 and 5 J. Under identical initial conditions, differences in flame propagation velocities were obtained and analyzed. The scale and dynamics of the observed inhomogeneities of the flame front are recorded.

2. Experimental details

The experiments were carried out at two experimental facilities: a laboratory setup and an explosion chamber 13Ya3 (Moscow Regional Explosion Center for Collective Use of Russian Academy of Sciences).

The laboratory setup (figure 1) is equipped with a system for preparation of a combustible mixture, a device for fixing the latex shell, an ignition system with an energy of 1 mJ and a system of schlieren imaging with VideoSprint G2 camera that allows registration at a frequency of up to 1000 fps. Part of the experiments was carried out using a soap film to restrict the region of the combustible mixture from the ambient air.
A combustible mixture with a hydrogen content of 15% was prepared in a 40 l cylinder at an overpressure of 5 atm. Before the series of experiments, the mixture was aged for at least 24 hours. Before filling the shell, the supply lines and the block for fixing the latex or soap shell were blown by a combustible mixture of 5 l. A series of experiments on the flame propagation in different shells was carried out with the same composition of the combustible mixture.

The explosion chamber 13Ya3 (figure 2) is equipped with a system for preparing a combustible mixture, a fan for stirring the combustible mixture inside the shell, a latex shell fixing device, a flame ignition system with an energy of 1 mJ or 5 J, and an ir imaging system with an InfraTek 8320 camera with registration rate up to 300 fps.

A combustible mixture with a hydrogen content of 15% was prepared directly in the shell. The hydrogen from the cylinder and the air were fed into the shell through the flowmeters. After filling, the gas in the shell was stirred for 30 min, 30 min after the fan was turned off, the mixture was ignited by a spark with an energy of 1 mJ or an exploding wire with an energy of 5 J.

2.1. Error analysis

In a laboratory setup, the mixture was prepared using a 0.15 accuracy class manometer. When preparing a mixture with a hydrogen content of 15%, the relative deviation of the composition from the preset could be up to 1%. The position of the flame front was determined with an absolute error of 2 pixels, which corresponds to a relative error of 0.4%. Exposure time was 200 µs, that is, the relative error of time determination was 1%.

In the 13Ya3 chamber, the mixture was prepared using flowmeters PROMASS 80F of 0.35 accuracy class and PROWIRL 72F of 0.75 accuracy class. When preparing a mixture with a hydrogen content of 15%, the relative deviation of the composition from the preset could be up to 0.5%. The position of the flame front was determined with an absolute error of 2 pixels, which corresponds to a relative error of 0.6%. The exposure time was 10 µs, that is, the relative error of time determination was 0.01%.

Since the measurements of quantities are independent and random, the relative error of the trajectory is determined by the formula:

\[
\delta = \sqrt{\left(\frac{\Delta C}{C}\right)^2 + \left(\frac{\Delta R}{R}\right)^2 + \left(\frac{\Delta t}{t}\right)^2},
\]

where \(C\) to be mixture composition, \(R\) to be flame radius, \(t\) to be time moment [9].

The total measurement error at the laboratory setup is 1.5%, in the chamber 13Ya3—0.8%.

3. Technique for processing experimental data. Development of the image processing program for the spherical flame front

3.1. Determination of the center of the flame (the point of the spark)

The first picture is selected (figure 3). To search for a spark, it was decided to find the area with maximum brightness. On the edges of the picture, there were often bright areas (scale, gleams, etc). Therefore, the spark was searched only in the central region of the picture (1 in figure 3). The linear dimensions of this region are equal to half the linear dimensions of the figure. For all possible areas of 11 × 11 pixels in size, the average brightness was found. The center of the region with the maximum brightness (2 in figure 3) was the point of the spark.

3.2. Determination of the flame area

From the center of the flame, four rays were released (up, down, left, right). On these rays, the brightness dependence was plotted as a function of the distance to the center (figure 4). Further, a constant value \(b = \lambda b_{\text{max}} + (1 - \lambda) b_{\text{start}}\) was drawn. Where \(\lambda\) to be the adjustable coefficient
Figure 2. Explosion chamber 13Ya3: 1—ignition point; 2—shell with combustible mixture; 3—InfraTek 8320 camera; 4—ignition system; 5—feed system.

that determines the width of the search area (in our case 0.2 is optimal value for reasons of accuracy and processing time); $b_{\text{max}}$ to be maximum brightness, $b_{\text{start}}$ to be brightness in the center. As a result, a point with a minimum radius whose brightness exceeded $b$ was chosen. Or in other words: the left intersection of the brightness dependence and the straight line was taken. Since there could be bright points inside the flame, the maximum of the values obtained was chosen as the radius. As a region of the flame, a certain neighborhood of the resulting radius with a width of 20–80 pixels was selected (figure 5), depending on the curvature of the flame.
Figure 3. Determination of the center of the flame (the point of the spark): 1—the central area; 2—area with maximum brightness.

Figure 4. Approximate radius determination. Arrow points the value of approximate radius.

3.3. Constructing the dependence of the flame radius on the angle
The next step is determination of the flame radius for all possible directions. As an angle step, we chose the angle $\delta \alpha = 1/R_a$ of the radians, where $R_a$ to be radius obtained in previous step. Thus, the arc pitch was equal to 1 pixel. The radius for each direction was found similar to that in point 2, but only the flame region was taken into account. $\lambda$ was chosen closer to 1 (most often 0.9). The search was conducted from right to left (the point with the maximum radius, whose brightness exceeded $b$) was selected. Thus, the dependence of the flame radius on the angle for each picture was obtained. The mean values of the radius of the flame front for each experiment were calculated as the mean values of the functions describing the dependence of the radius on the direction angle.

3.4. Determination of the characteristic dimensions of the instabilities
To determine the characteristic size of the instabilities, a fast Fourier transform (FFT) [10] was applied to the dependence of the radius on the angle. Thus, the dependence of the instability amplitude on the angular size of the instability was obtained (figure 6). As a result, several frequencies with an amplitude greater than a quarter of a pixel were selected. In this case, with two close angular size values, one was selected with the maximum amplitude.
4. Experimental results

4.1. Experiments in volumes 9–30 m³
Experiments on the flame propagation in 15% hydrogen–air mixtures in volumes 9–30 m³ were carried out in latex shells upon initiation with energies of 1 mJ and 5 J. The characteristic picture is shown in figure 7. The photo shows a developed cellular structure of the flame.

The average values of the radius obtained as a result of processing infrared photographs of the flame are shown in the graphs in figure 8.

The results presented in figure 8 show that with an increase in the ignition energy by a factor of 5000, the average value of the pre-exponent increases by 6 times. In this case, the natural dispersion of both the exponents pre-exponents allows the flame propagation upon ignition by an exploding wire with a velocity lower than at ignition by a weak spark (experiments 5, 7 and 11 in table 1).
Figure 7. Typical ir photograph of a cellular flame in the latex shell: 1—cellular flame; 2—shell.

Figure 8. Dependences of the flame front radii versus time upon ignition by energy of 1 mJ and 5 J.

In all experiments, flame acceleration is observed. Diagrams $x-t$ of the propagation of the flame front in logarithmic axes, shown in figure 9, demonstrate the acceleration according to the power law of the form

$$R = At^n,$$

and the exponent $n$ varies little in different experiments. To determine the statistical regularities of the flame acceleration, the diagrams $x-t$ were approximated by equations of the form of (2). Further, the diagrams $x-t$ were again approximated by equations of the form of (2) with the exponent $n = 1.3$ equal to the average value obtained from the first stage. As a result, the values of the pre-exponential for different experiments were obtained, which can be compared and plotted on a single graph, because they have the same dimension. The values of the exponent
Figure 9. Dependences of the flame front radii versus time upon ignition by energy of 1 mJ and 5 J in logarithmic coordinates.

Table 1. Parameters of the experiments and values of the exponent.

| #  | $E$, J | $V$, m³ | $n$ | $A$, $10^{-4}$ m/s¹³ |
|----|--------|---------|-----|---------------------|
| 1  | 5      | 15      | 1.05| 5.94                |
| 2  | 5      | 15      | 1.22| 5.07                |
| 3  | 5      | 30      | 1.33| 6.41                |
| 4  | 5      | 30      | 1.28| 6.52                |
| 5  | 5      | 30      | 1.42| 4.47                |
| 6  | 0.001  | 9       | 1.37| 3.19                |
| 7  | 0.001  | 9       | 1.29| 4.61                |
| 8  | 0.001  | 9       | 1.23| 3.08                |
| 9  | 0.001  | 9       | 1.37| 2.89                |
| 10 | 0.001  | 9       | 1.29| 3.12                |
| 11 | 0.001  | 9       | 1.27| 4.52                |
| 12 | 0.001  | 9       | 1.29| 3.45                |

and the parameters of the experiments are presented in table 1. The values of the pre-exponent $A$ presented in table 1 are for exponent value $n = 1.3$.

Figure 10 shows the differential distribution function of the pre-exponents. The values of 8–12 in the graph correspond to the first five experiments, where the ignition energy is equal to 5 J. Thus, an increase in the ignition energy leads to an increase in both the probable flame velocity and the dispersion of the velocity values.

For a more graphic demonstration of the flame-front inhomogeneities, the angular evolvents of successive photographs of the flame front are shown in figure 11. Figure 12 indicates the angle periods of the maximum amplitude of the oscillations. From figure 12 one can see that at small flame radii one mode of inhomogeneities is clearly presented. As the flame radius increases, the inhomogeneities of this angular dimension are keeping, but inhomogeneities of smaller angular dimensions arise.
Figure 10. The probability density of the distribution of the pre-exponents in experiments in the volumes 9–30 m³.

Figure 11. Dependences of the flame fronts radii at 5 time moments on direction angle (angular evolvents).

To clarify the pattern of the formation of inhomogeneities cascade, we should pay attention to figure 13. One can see a linear increase of the dimensions of the inhomogeneities formed at the initial stages, and the formation of new inhomogeneities. At the initial stage of propagation, inhomogeneities of the same size are seen. With an increase in the radius of the flame front to 0.67 m and the scale of the first-order perturbations to 0.29 m, second-order perturbations with a scale of 0.16 m develop on first-order perturbations. With an increase in the front radius of the flame to 1.2 m and a scale of perturbations of the second order up to 0.29 m, scale is 0.15 m. As the radius of the flame front increases from 0.45 to 1.65 m, perturbations of five consecutive orders are observed, and the minimum size of the observed disturbances decreases from 0.2 to 0.1 m.
Figure 12. Dependences of the angular dimensions of observed inhomogeneities of the flame front on the average radius of the flame. The numbers in the legend indicate the order of the disturbance.

Figure 13. Dependences of the linear dimensions of the observed inhomogeneities of the flame front on the average radius of the flame. The numbers in the legend indicate the order of the disturbance.

4.2. Experiments in volumes 3–5 l

Experiments in small volumes were carried out in latex shells and soap bubbles. Typical schlieren photographs are shown in figure 14. In both cases, a developed cellular structure of the flame is visible.

The dependencies shown in figure 15 demonstrate the difference in diagrams $x-t$ of the flame propagation in the same gas mixture in different shells and in the same shell. The dispersion of trajectories in experiments in identical shells is caused by the stochastic character of the development of the flame front instabilities and, as a consequence, the non-determinism of the flame-surface shape at each subsequent moment. An instability that develops from a random perturbation or from a disturbance caused by the interaction of already developing instabilities
Figure 14. Typical schlieren photographs of the cellular flame in the latex shell (left) and in the soap bubble (right) in 15% hydrogen–air mixture at the moment of time 30 ms after ignition by 1 mJ spark.

Figure 15. Dependences of the radii of the flame front versus time upon ignition with energy by 1 mJ. The filled symbols correspond to the flame in the latex shell, the open ones to the soap bubble.

can not be predicted for a period of time longer than the time of development of an individual instability. Moreover, due to the large number of developing instabilities on the flame front and the uniform laws of their development, the pattern of flame acceleration differs little in various experiments.

A noticeable difference between trajectories during flame propagation in latex and soap shells can be caused by an increased water content in the combustible mixture restricted by a soap film.

As for experiments in volumes of several cubic meters, the trajectories were approximated by equations of the form of function (2). The approximation showed an acceleration in accordance with the power law with an average exponent \( n = 1.09 \). The values of the pre-exponent vary within 30% for each type of shell. From the obtained values of the pre-exponent, the dependences of the probability density of the obtained values were built figure 16.
Figure 16. The probability density of the distribution of pre-exponents in volumes 3–5 l in the latex (balloon) and soap (bubble) shells.

The resulting differential distribution functions show an increased probability of accelerating the flame with a pre-exponent, which differs from the mean by 5% in both the larger and the smaller directions. In the vicinity of the mean values, a dip is observed, indicating a bifurcation of the scenario of flame acceleration at the initial stage of flame growth. At small flame sizes comparable with the dimensions of the inhomogeneities, individual inhomogeneities play an important role in the formation of the flame surface. Accordingly, the development and location of individual inhomogeneities have the greatest effect at the initial stages, when the radius of the flame is small. As the radius of the flame front increases, statistical averaging is included, and the effect of unit inhomogeneities decreases.

5. Conclusions
Diagrams $x-t$ of a spherical hydrogen–air flame propagation in volumes 3–30 m$^3$ are obtained. It was found that with unchanged values of the composition of the combustible mixture, the envelope volume and the ignition energy the time dependences of the average flame radius differ from experiment to experiment. This lack of repeatability of the experiments was obtained both in small volumes of 3–5 l and in large volumes of 9–30 m$^3$. The observed discrepancy can not be explained by the error in the composition of the mixture and measurements, but can be explained by the development of instabilities on the flame front. The development of instabilities has the greatest influence at the initial stage, when the radius of the flame front is the same order of value with the linear dimensions of the inhomogeneities.

Statistical interpretation of the spherical flame acceleration characteristics in volumes from 3 l to 30 m$^3$ is done. Features of distribution functions of pre-exponents are revealed, which demonstrate the significant influence of single random perturbations at the initial stage of quasispherical flame front formation.

The influence of the ignition energy with the comparison of the flame propagation with the ignition energy of 1 mJ and 5 J was found. The deviation of the pre-exponents of the flame acceleration caused by the change in the ignition energy by 3 orders of magnitude increases the acceleration pre-exponents in 1.6 times.

The scales of inhomogeneities in the flame front are determined experimentally. The dynamics of formation of a inhomogeneities cascade that forms a structure of the flame surface is constructed.

The effect of water vapor, which reduces the propagation velocity of the hydrogen–air flame by 20%, is observed in experiments in shells from a soap film.
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