The role of instability mechanisms in gas flame acceleration

A E Elyanov\textsuperscript{1,2}, V V Golub\textsuperscript{1}, A Yu Mikushkin\textsuperscript{1,3}, V A Petukhov\textsuperscript{1} and V V Volodin\textsuperscript{1}

\textsuperscript{1} Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13 Bldg 2, Moscow 125412, Russia
\textsuperscript{2} Department of Physics, Lomonosov Moscow State University, Leninskiye Gory 1 Bldg 2, Moscow 119991, Russia
\textsuperscript{3} Bauman Moscow State Technical University, 2nd Baumanskaya Street 5, Moscow 105005, Russia
E-mail: golub@ihed.ras.ru

Abstract. To study the role of individual mechanisms of the flame-front instability, a series of experiments was carried out on the propagation of a spherical flame. Transparent latex shells were filled with pre-prepared hydrogen–air mixture. In various series of experiments, the percentage of hydrogen was varied. The ignition of the flame was produced by a spark discharge with an energy of 1 mJ, a discharger located in the center of the shell. Experimentally, the scattering parameters of the spherical hydrogen–air flame acceleration was found with a constant mixture composition and combustion initiation energy. It was found that at the initial stage of propagation, both acceleration and deceleration of flame front occurs. The parameters of the flame front propagation experimentally obtained are supplemented by calculations carried out using analytical models.

1. Introduction

Self-sustaining release of chemical energy during the oxidation of gas fuels has wide practical application to produce the energy or products of complete or partial oxidation. In addition to the energy aspects of combustion, it is extremely important to gain knowledge about the patterns of flame propagation in stationary mixtures to ensure safety at industrial facilities.

The propagation of flame in homogeneous mixtures of fuel gas with an oxidizing agent is the main test problem for many theoretical and numerical models of combustion. Despite the simplicity of setting the initial and boundary conditions, the spherical flame propagation is combined with many physical phenomena that transform the propagation of a spherical smooth flame front into a complex three-dimensional flow.

A vivid example of the flame-front instability is hydrodynamic instability (also known as the Darrieus–Landau instability). For the first time, this type of instability was mathematically obtained by L D Landau in the approximation of an infinitely thin flame front [1]. In the future works of A G Istratov and V B Librovich [2] the proposed approach was supplemented by a model of the flame front of finite thickness. The supplemented model showed good agreement with the experimental data [3].
Another example is diffusive-thermal instability, which exhibits an increase in the surface and speed of flame propagation due to an imbalance of heat and substance transfer through the flame front [4]. The development of inhomogeneities in the flame front leads not only to its acceleration, but also to the appearance of pressure and velocity pulsations in the vicinity of the expanding flame front. In this case, an important role is played by the release of thermal energy during dissipation of kinetic energy within the shear flow region. In [5, 6] an opinion on the establishment of the Kolmogorov cascade of turbulent pulsation scales was expressed. This leads to a flame front acceleration according to a power law with an exponent of 1.5 [7, 8].

The present work is devoted to the investigation of a free spherical flame front acceleration in a volume of 4 l. The ignition energy was 1 mJ. The growth mechanisms of flame front inhomogeneities are analyzed.

2. Experimental details
The laboratory setup consists of a gas mixing system, a shell filling system, a spark igniter and an imaging system. The combustible mixture was premixed in a cylinder under a pressure of 5 atm. After preparation, the mixture was kept in a cylinder for at least 24 hours for complete mixing. In various experiments, the latex envelopes were filled with the combustible mixture. The hydrogen content in the hydrogen–air mixture was 15 and 20 vol %. The pressure was atmospheric, the volume of the shell was $4 \pm 1$ l. The mixture was ignited 1 minute after filling to ensure immobility of the mixture during ignition. Ignition was carried out in the center of the shell, the energy was 1 mJ. It should be noted that in each series of experiments a single gas cylinder with a previously prepared mixture was used. Thus, it was possible to avoid scatter of experimental results associated with the error in preparing the mixture.

High-speed video registration was carried out with a frequency of 500 and 1000 frames per second. In such modes, the frame size was $1280 \times 1000$ and $1280 \times 500$ pixels. The camera recorded the position and shape of the flame front depending on the time. A large amount of experimental data obtained with the use of high-speed cameras is associated with the problem of data processing. Automation of processing experimental data is discussed in some detail in the literature [9]. Since each experimental work has its own characteristics of obtaining images and the object under study, we have developed our own technique of automatic image processing.

Ignition point is considered known, and after the image was binarized, the distance between the center of ignition and the flame front in pixels was calculated. After, it was multiplied by the scale coefficient to be converted to the units of length. To speed up the processing, a program was created in the MatLab environment. The error of results obtained by such measurements with automated processing do not exceed 3%.

3. Experimental results
A series of flame propagation experiments were carried out in a hydrogen–air mixture with a hydrogen content of 15 vol %. The flame propagation in a 15 vol % hydrogen–air mixture is globally spherical, and the effects of the ascent of a cloud of combustion products are not observed at flame radii corresponding to the experimental ones. The average radius was determined as the angle-average distance from the initiation point to the point of the maximum gradient of optical density in a plane perpendicular to the optical axis. Since the flame propagates globally spherically, the average radius obtained by this method corresponds to the average radius along the entire front. The results are presented in figure 1. Different signs denoting experimental points indicate different experiments, serve solely to distinguish between experiments in a series. The flame propagation conditions were the same in all experiments. The composition, pressure, temperature of the mixture and the energy of ignition were unchanged. In this case, a significant dispersion of the dependences of the average radii of the flame front on time was observed. This dispersion is explained by the probabilistic nature of the origin of flame front inhomogeneities.
Figure 1. $R-t$-diagrams of flame propagation in 80 experiments in a mixture of air and 15 vol% hydrogen.

and the statistical laws of their interaction, which leads to statistical dispersion within the same series of experiments with the same mixture and ignition parameters. At the same time, in all experiments from the series, the growth of heterogeneities in the flame front is caused by the same mechanisms.

As mentioned above, the combustible mixture was prepared once for the whole series of experiments, the error of measuring the position of the flame front is 3%, which makes it possible to consider this dispersion is not related to the error of the mixture composition and image processing.

The $R-t$-diagrams in figure 1 were approximated by power functions of the form $r = At^n$, as it is usually done in recent works on the propagation of a spherical flame [10]. The values of the exponent $n$ were averaged, $\langle n \rangle = 1.09$. After that, the $R-t$-diagrams were re-approximated by power functions of the form $r = At^{1.09}$. As a result, the value of the preexponential factor $A$ was obtained for each experiment. The resulting array of values of the preexponential factors was used to construct the dependence of the probability density of flame propagation according to a power law with a pre-exponential factor $A$ (figure 2).

Probability density is approximated by superposition of two normal distribution functions with a medians of 2.17 and 2.73 and dispersions of $1.44 \times 10^{-2}$ and $1.6 \times 10^{-1}$ accordingly:

$$f(A) = \frac{0.73}{0.12\sqrt{2\pi}} \exp \left[ -\frac{(A - 2.17)^2}{0.0288} \right] + \frac{0.27}{0.4\sqrt{2\pi}} \exp \left[ -\frac{(A - 2.73)^2}{0.32} \right]. \quad (1)$$

When considering $R-t$-diagram [figure 3(a)], it is clearly seen that the $R-t$-dependence is not linear, but the flame propagates with acceleration and deceleration. The $R-t$-diagram was approximated by a polynomial function of the fourth degree. The first derivative of the flame radius versus time is the dependence of the flame velocity versus time. This shows that there are regions where the velocity increases and decreases, figure 3(b). The second derivative of the flame radius versus time is the flame acceleration versus time, figure 3(c).
4. Discussion

Lean hydrogen–air flames are unstable by the diffusive-thermal (DT) mechanism (Lewis number less than 0.4). Flame instability by the Darrieus–Landau (DL) mechanism is observed at Reynolds numbers of $10^2$ to $10^3$, which is also true in our case. In some areas, the flame front moves with acceleration, which is a necessary condition for instability according to the Rayleigh–Taylor (RT) mechanism.

Flame front instability mechanisms are described using the dependences of the growth rate on the size of the heterogeneity ($\lambda$). Usually in calculations the wave number $k = 2\pi/\lambda$ is used. Analytical formulas of dependences are given in table 1. A positive value of the growth rate indicates the development of instability; a negative one indicates its attenuation. The greater the growth rate, the stronger the action of the instability mechanism on this inhomogeneity of the front. The growth rate of the DT instability is inversely proportional to the square of its wavelength. The growth rate of the DL instability is inversely proportional to the wavelength. The growth rate of the RT instability is not depending on the wavelength.
### Table 1. Analytical growth rates for DT, DL and RT instabilities on the inhomogeneities wave number [6, 11]: $L_M$ to be Markstein length; $S_L$ to be normal flame speed; $D$ to be diffusion coefficient; $\delta$ to be flame thickness; $\Theta$ to be combustion products expansion ratio; $\ddot{R}$ to be flame front acceleration; $At$ to be Atwood number at the border of combustible mixture and combustion products; $\nu$ to be combustible mixture viscosity.

| Mechanism | Growth Rate |
|-----------|-------------|
| DT        | $\omega = -L_M S_L k^2 - 4D\delta k^4$ [6] |
| DL        | $\omega = 0.5(1 - \frac{1}{\Theta}) S_L k - L_M S_L k^2$ [6] |
| RT        | $\omega = (\ddot{R}At)^{2/3}\nu^{-1/3}/\sqrt{2}$ [11] |

### Table 2. The sizes of inhomogeneities corresponding to the transition of mechanisms DT–DL and DL–RT.

| Inhomogeneity Size | DT–DL | DL–RT |
|--------------------|-------|-------|
| $\lambda$(15 vol % $H_2)$, m | $2.5 \times 10^{-3}$ | $2 \times 10^{-3}$ |
| $\lambda$(20 vol % $H_2)$, m | | |

### Figure 4. Dependencies of the growth rate of instability according to the mechanisms of DT (green line), DL (red line) and RT (blue line): (a) in full scale and (b) in an enlarged scale.

The measured values of the flame front acceleration and the properties of the considered combustible mixtures were used to calculate the growth rates of the flame front inhomogeneities using various mechanisms. The growth rates of DT and DL instabilities tend to zero with increasing inhomogeneity wavelength, while the same Rayleigh–Taylor instability parameter remains constant. This means that the Rayleigh–Taylor instability may be observed when burning in large volumes. The condition for the transition of one mechanism of instability to another is the equality of their growth rates. Table 2 shows the sizes of the inhomogeneities, at which the growth rates for different mechanisms of instability become equal. It is seen that the transition from the DT instability to DL occurs at small sizes, and the transition of DL to RT mechanism occurs at a large size of the inhomogeneity.
Figure 4 presents a comparison of the growth rates of the DT, DL and RT mechanisms of flame propagation in 15 vol% hydrogen–air mixture. Small perturbations with a wave number above 3300 m\(^{-1}\) are suppressed by the DT and DL mechanisms (the growth rate is negative). Perturbations with a wave number below 3000 m\(^{-1}\) grow by the DT mechanism to the value of the wave number 2600 m\(^{-1}\), when the growth rate by the DL mechanism begins to exceed the growth rate by the DT mechanism. The growth rate rises to the value of the wave number 1300 m\(^{-1}\), then begins to decrease and becomes equal to the growth rate of the RT mechanism to the value of the wave number 3.5 m\(^{-1}\).

5. Conclusions
Experimentally, the scattering parameters of the spherical hydrogen–air flame acceleration were found with a constant mixture composition and combustion ignition energy. Based on the experimental data, the dependence of the probability density of the flame acceleration parameter on the value of the pre-exponential factor is developed. The sizes of inhomogeneities are calculated, at which the mechanism of instability of the flame front changes in mixtures with a hydrogen content of 15 and 20 vol%.

The Rayleigh–Taylor instability in 15 vol% the hydrogen–air mixture can be observed with linear dimensions of the cloud of combustion products greater than 2 m.

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