Slow and Fast Deflagrations in Hydrocarbon-Air Mixtures

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Introduction

Many practical applications require data on critical conditions for development of fast supersonic combustion regimes in gaseous mixtures. It is important to know whether the flame is able to accelerate under given conditions resulting in fast supersonic deflagrations and, possibly, in the transition to detonation, or the flame acceleration is inefficient ending at a benign subsonic combustion or flame quenching.

A series of experimental and analytical work was made recently on the behavior of turbulent flames in mixtures based on hydrogen fuel by Kuznetsov, et al. (1999) and Dorofeev et al (2000). It was found that in tube geometry with different configurations of obstacles, a well defined difference in flame behavior can be observed dividing cases of slow, subsonic flames and fast combustion regimes (choked flames and detonations). It was suggested that this difference gives a well-defined measure of the effectiveness of flame acceleration (FA). Analysis of experimental data for hydrogen combustibles showed that the basic flame parameters, such as mixture expansion ratio σ, Zeldovich and Lewis numbers (β and *Le)* could be used to estimate a priori a *potential* for effective FA in hydrogen mixtures. It was found also that the scale increase results in more effective FA.

Compared to hydrogen, there is a lack of similar data for mixtures of hydrocarbon fuels with air. Experimental study by Peraldi, et al., (1986) provides important data for hydrocarbon fuels. However, the main attention in this and other studies with hydrocarbon fuels in tubes was given to fast deflagrations and to deflagration-to-detonation transition (Lee, et al., 1994; Lindstedt and Michels, 1989). The objectives of the present work are to obtain additional data for mixtures of hydrocarbons in air, and to study critical conditions for FA in these mixtures. Mixtures of hydrocarbon fuels are characterized by higher effective activation energies compared to that in hydrogen mixtures. It is therefore important to analyze the difference in critical conditions for FA in hydrogen and hydrocarbon fuels.

Experimental

Tests were performed in two different explosion tubes, one 12-m long with an inner-diameter of 174-mm and the other 520-mm inner-diameter and 34.5-m long. The tubes were equipped with orifice plate obstacles spaced at one tube diameter, with blockage ratios of 0.3 and 0.6. A weak electrical spark was used to ignite the mixtures at one end of the tube. Fast-response piezoelectric pressure transducers, photo-diodes and ionization probes were used to measure pressure and flame time-of-arrival. Experiments were made at normal initial conditions (t = 20 C, P = 1 atm) using methane-air, ethylene-air, and propane-air mixtures. Both fuel-rich and -lean mixtures were studied in the tests.

Results

Figures 1 and 3 show, as an example, flame propagation velocities versus distance along the tubes. Examples are shown for propane-air mixtures. Based on the test data presented in Figs. 1 and 2, two flame propagation regimes can be clearly distinguished. In the first regime the flame achieves a velocity well below sound velocity in reactants. Global quenching of flame was also observed in some of the tests.

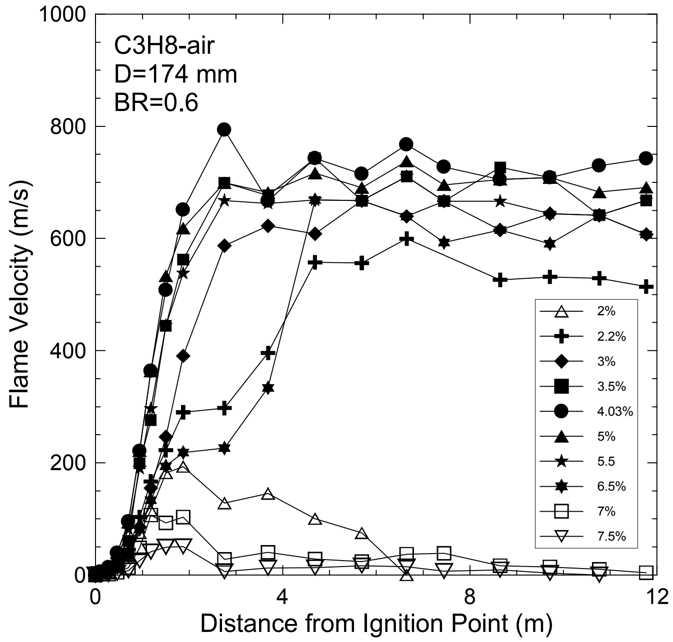

Figure 1. Flame velocities versus distance in propane-air mixtures in 174-mm tube (BR=0.6)

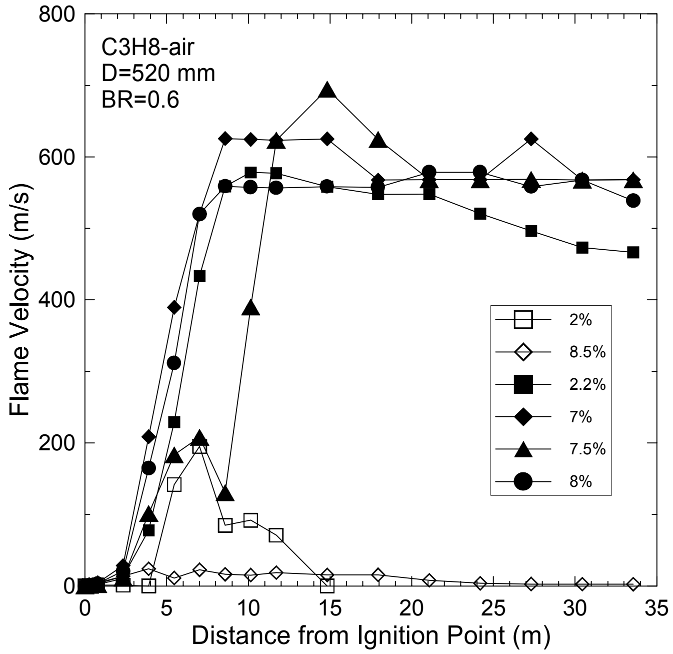

Figure 2. Flame velocities versus distance in propane-air mixtures in 520-mm tube (BR=0.6)

In the second regime the flame achieves a steady-state velocity which is roughly equal to sound speed in combustion products. This is known as the "choking" regime (Lee et al., 1984). Such a behavior of flames in obstructed channels is very similar to that observed for hydrogen mixtures by Kuznetsov, et al. (1999).

The critical compositions for the border between fast and slow flames are collected in Table 1. The data shown in Table 1 correspond to the least energetic mixtures (both, lean and rich) where fast flames were observed. Also shown in Table 1 are expansion rations σ for these critical mixtures. The blockage ratio did not influence significantly the critical boundary for development of fast flames. The same observation was made in tests of Kuznetsov, et al. (1999) for hydrogen mixtures.

Data presented in Table 1 show that the range of compositions where fast flames were observed in our tests is relatively wider in comparison with data of Peraldi, et al. (1986). In lean mixtures, there are practically the same critical boundaries as found by Peraldi, while rich mixtures show different behavior.

Table 1. Composition limits where fast flames were observed.

Mixture	174-mm tube		520-mm tube	
	Fuel content, vol. %	Expansion ratio, σ	Fuel content, vol. %	Expansion ratio, σ
CH_4 – air (lean)	6.5	5.95		
CH_4 – air (rich)	13.5	7.10		
C_2H_4 – air (lean)	3.5	5.50	3.5	5.50
C_2H_4 – air (rich)	16	6.76	22	6.16
C_3H_8 – air (lean)	2.2	5.49	2.2	5.49
C_3H_8 – air (rich)	6.5	7.46	8	6.97

It is seen, also, that critical compositions in lean mixtures do not depend on the tube size. On the rich side, a significant shift of critical boundary is observed with the increase of the tube diameter. This effect was not observed in hydrogen mixtures in tests of Kuznetsov, et al. (1999). We need to note that fast flames were developed in the present tests with increase of fuel concentration up to rich flammability limit in 520-mm tube. Further increase of fuel concentration above limits shown in Table 1 for 520-mm tube required special measures to ignite the mixture. In particular, local enrichment with air was made near ignition point. This permitted ignition, but flame propagated initially through nonuniform mixture.

Discussion

Data obtained in the present series of tests are generally in accord with our earlier results (Kuznetsov, et al., 1999 and Dorofeev, et al., 2000) on description of critical conditions for effective FA in hydrogen mixtures. It was shown that large enough mixture expansion ratio, σ, is necessary for potential development of fast flames. Corresponding critical conditions can be expressed in the form: $\sigma > \sigma^*(\beta, L_T/\delta)$, where $\beta = E_a(T_b - T_u)/T_b^2$, is Zeldovich number, E_a is effective activation energy, T_u and T_b are initial and adiabatic flame temperatures, L_T/δ is the ratio of integral turbulent scale to laminar flame thickness. It was also found that the influence of the scale ratio on the critical conditions is relatively weak in cases of large enough scale ($L_T/\delta > 100$).

Critical conditions for development of fast flames in mixtures of hydrocarbon fuels are characterized by values of expansion ratio $\sigma^* > 5.5$. These critical values are greater then those for hydrogen mixtures found to be $\sigma^* = 3.75 \pm 0.25$ at normal initial temperature by Kuznetsov, et. al (1999). Such a difference can be attributed to relatively high Zeldovich numbers for hydrocarbon flames. The effect of Zeldovich number on critical conditions for flame acceleration is presented in Fig. 3. Critical data for hydrogen flames with positive Markstein number and data obtained in this work are combined in Fig. 3. The points shown include subcritical and supercritical cases, which are the most close to the fast flame boundary. Effective activation energies were determined for each particular point from experimental data on laminar burning velocities according to the approach presented by Dorofeev, et al. (2000). It is seen that critical value of the expansion ratio increases with increase of

Zeldovich number. Some scatter of data points in Fig. 3 can be explained by uncertainty in estimation of effective activation energies. It is also possible that parameter L_T/δ plays a role changing critical values of expansion ratio.

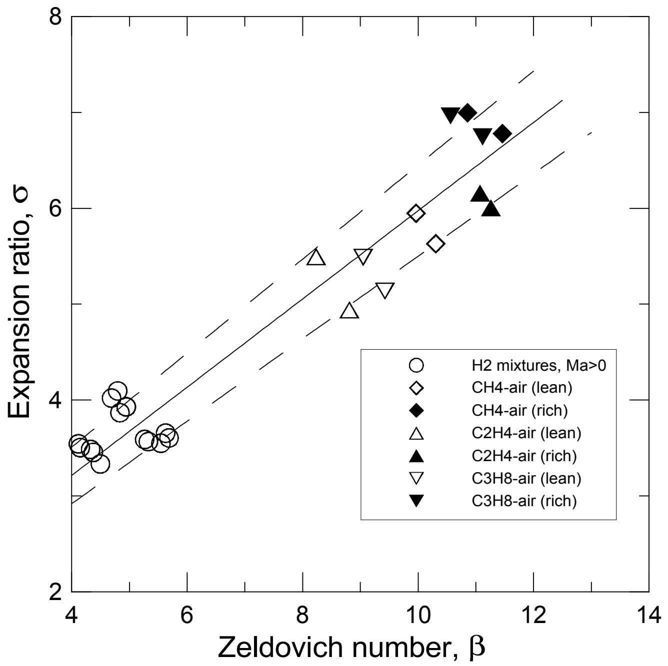

Figure 3. Critical mixture expansion ratios for possible development of fast flames in channels with obstacles as a function of Zeldovich number. Data for hydrogen and hydrocarbon flames with positive Markstein numbers. Solid line shows approximately the borderline; dashed lines show deviation ± 7% in critical σ-values.

The influence of tube size on critical conditions for FA in rich mixtures of hydrocarbons is different from results obtained for hydrogen combustibles in the same tubes. We should note, however, that in smaller tubes similar effect was observed in hydrogen mixtures as well. What is responsible for the effect of scale? Why no effect is observed in lean mixtures of hydrocarbons? Two possible explanations can be suggested. The first one is based on comparison of parameter L_T/δ. For nearly critical lean mixtures the parameter L_T/δ is about from 200 to 300 in 174-mm tube, while for rich mixtures L_T/δ decreases down to the range from70 to 200. The values of L_T/δ in rich mixtures appear thus very close to the critical value of 100, where strong effect of scale was observed in smaller tubes for hydrogen mixtures by Kuznetsov, et al. (1999). Accurate analysis of the effect of L_T/δ is difficult at the present time for hydrocarbon fuels, especially for rich side, because of significant uncertainty in determination of δ - values. Data on laminar burning velocities are scarce near FA limit on the rich side, and extrapolation of the data is not reliable.

The second explanation for the effect of scale is connected with possible role of radiative heat losses. It is reasonable to expect that contribution from radiation to heat losses from combustion zone is greater in rich mixtures of hydrocarbons compared to that for lean and hydrogen mixtures. This is due to soot formation in rich flames. Radiative heat losses can play an important role, if optical thickness of the reaction zone appeared to be comparable with the tube size. In this case, additional heat losses could result in decrease of effective expansion ratio and suppress FA in small tube. This explanation is supported by the observation that the biggest difference between two tubes was found in C_2H_4 – mixture, the most productive in soot formation.

Summary

We have presented results of experiments on behavior of turbulent flames of hydrocarbon mixtures in obstructed tubes. Critical conditions for development of fast deflagrations were studied. It was found that similar to hydrogen combustibles two propagation regimes can be sharply distinguished: subsonic slow flames and supersonic fast flames. Critical mixture compositions for development of fast flames were determined in the tests. It was found that critical conditions for FA can be described in terms of a function of mixture expansion ratio on dimensionless effective activation energy (or Zeldovich number). Critical values of expansion ratio increase with Zeldovich number. The results appeared to be in qualitative and quantitative agreement with our earlier studies for hydrogen mixtures.

A significant effect of scale was observed for hydrocarbon mixtures at the rich side. The range of compositions, where fast flames were developed was wider in 520-mm tube, compared to that in 174-mm tube. The same effect was found earlier for hydrogen mixtures, but at smaller scale. An explanation for the effect can be based on relatively high flame thickness in rich mixtures of hydrocarbon fuels. Radiative heat losses may also play a role.

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