

# Effects of Scale and Mixture Properties on Behavior of Turbulent Flames in Obstructed Areas

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## Abstract

Results of the study on the effect of scale and mixture properties on the behavior of turbulent flames in obstructed channels are presented. Two tubes (174 and 520 mm id and similar geometry of obstacles with blockage ratio BR = 0.6) were used in the tests. Mixture properties and scale were found to have a mutual effect on the behavior of turbulent flames. Despite of the effect of scale, a very significant difference in maximum propagation speeds was observed between slow and fast regimes for all scales. It was found, that mixture expansion ratio  $\sigma$  was the main parameter defining this difference in flame behavior.

## Introduction

The most dangerous accidental gaseous explosions occur in obstructed areas with significant degree of confinement. Deflagrations dominated by product expansion and by large scale vortexes (due to flow interactions with obstacles) provide favorable conditions for flame acceleration. Combustion regimes which are possible under these conditions range from benign combustion or flame quenching to fast combustion modes and even transition to detonation. For many practical applications, it is important to estimate whether the flame is able to accelerate efficiently under given initial conditions. An important fundamental problem which should be solved to provide a foundation for such predictions is an adequate description of the mutual affect of scale and mixture properties on resulting combustion mode. Although the influence of various factors, including scale, on the flame acceleration phenomenon was studied extensively, quantitative predictions are difficult to make, since turbulent velocity correlations require the current level of turbulence to be known in all phases of the process (see, e. g. [1-3]).

The present study addresses the effects of scale and mixture properties on the behavior of turbulent flames in confined obstructed areas. A set of dimensionless parameters was chosen which can influence the flame-flow-flame feedback in obstructed areas. These parameters are defined by intrinsic length, time and velocity scales of combustion processes and by mixture properties:

$$L/\delta, \sigma, S_L/c_{sr}, S_L/c_{sp}, \gamma_r, Le, \text{ and } \beta, \quad (1)$$

where  $L_T$  - integral length scale of turbulence,  $\delta$  - laminar flame thickness,  $\sigma$  - ratio of densities of reactants and products (expansion ratio),  $S_L$  - laminar flame speed,  $c_{sr}$  and  $c_{sp}$  - sound speeds in reactants and products,  $\gamma_r$  - specific heat ratio in reactants,  $Le$  - Lewis number,  $\beta = E_a(T_b - T_u)/(RT_b^2)$  - Zeldovich number,  $E_a$  - effective activation energy,  $T_u$  - initial, and  $T_b$  - maximum flame temperature.

## Experimental

The experiments were focused on the study of the effect of parameters (1). Two tubes (174 and 520 mm id and similar geometry of obstacles) were used in the tests. Length to diameter ratio was 65 for both tubes. Different mixtures were chosen in order to provide a wide range of the scaling parameters, and combinations with similar values of the parameters at different scales. The following types of mixtures were used in the tests:  $\alpha H_2 + \text{air}$ ;  $2H_2 + O_2 + \beta N_2$ ;  $2H_2 + O_2 + \beta Ar$ ;  $2H_2 + O_2 + \beta He$ . The values of  $\alpha$  and  $\beta$  were variable.

Four characteristic regimes of the flame propagation were observed in the tests: (1) flame acceleration and global quenching; (2) relatively slow and unstable flame propagation with local flame quenching and reignition; (3) choked flames followed flame acceleration; and (4) flame acceleration and transition to quasi-detonation. Examples are given in Figs. 1 and 2

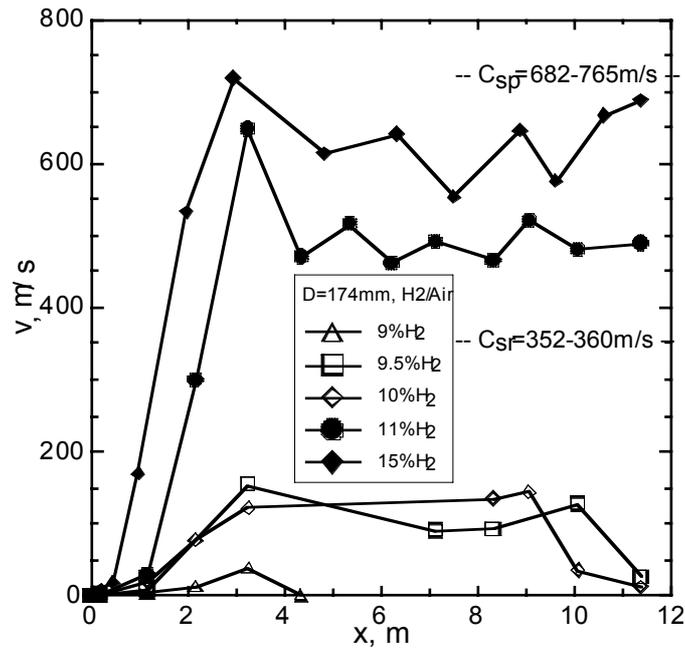


Figure 1. Flame propagation speed versus distance along the tube. For slow combustion regimes (empty points) speeds of flame head are given.

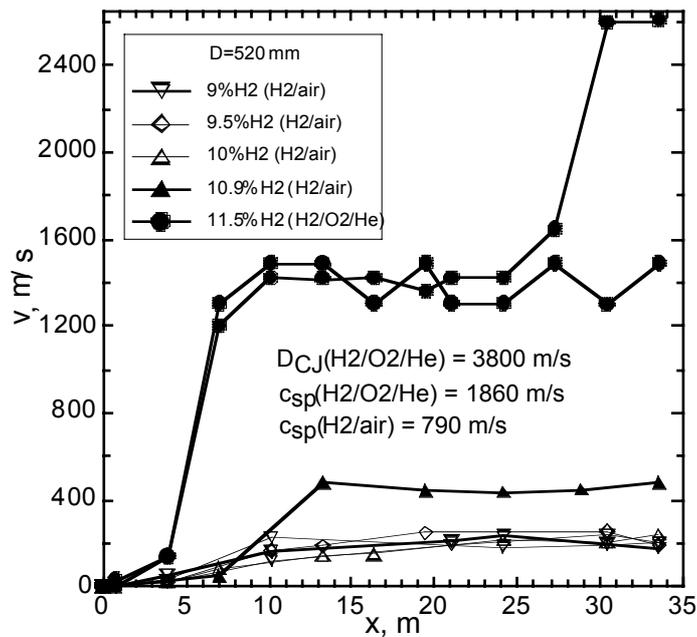


Figure 2. Flame propagation speed versus distance along the tube. For relatively slow combustion regimes (empty points) speed of flame head is given. Tests with H<sub>2</sub>/O<sub>2</sub>/He and H<sub>2</sub>/air mixtures in 520 mm tube.

## Discussion

The analysis based on the scaling parameters was found to be able to give useful results. It was observed that the trajectories of the flame propagation were similar in dimensionless coordinates  $x/\delta$ ,  $t/\tau$  with approximately similar values of  $L/\delta$ ,  $\sigma$ , and  $S_L/c_{sp}$ . In the initial phase of the flame acceleration (which was in the flamelet regime), the combination of  $L/\delta$  and  $\sigma$  was shown to be the most important factor defining average speed of the flame propagation (Fig. 3) and characteristic distance for flame acceleration.

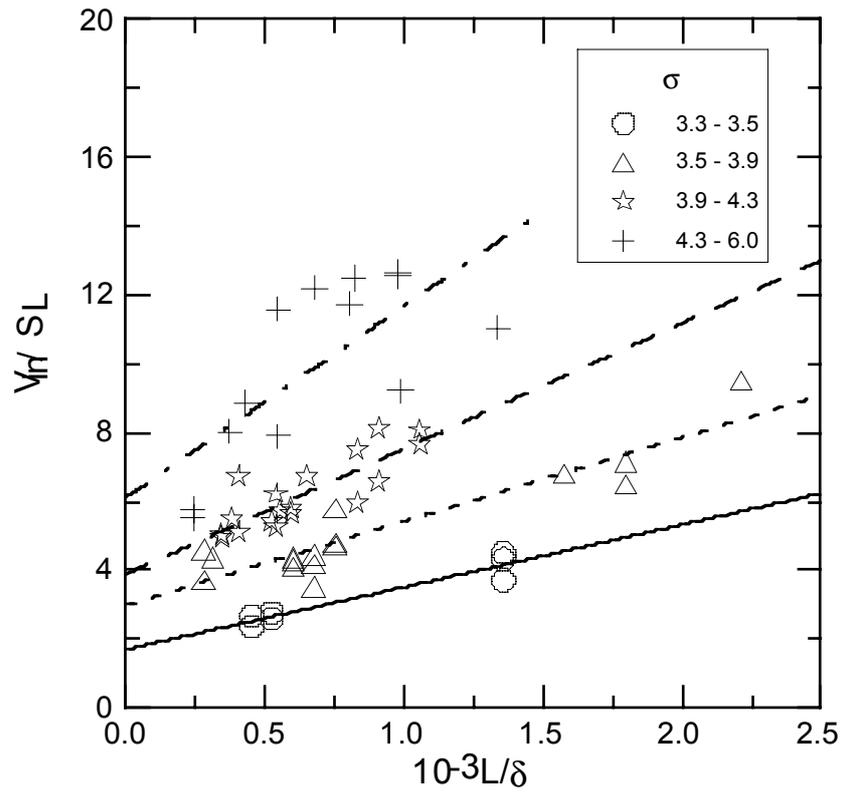


Figure 2. Dimensionless average flame speed in the initial phase versus scaling parameter  $L/\delta$  for different values of  $\sigma$ . Points -experimental data, lines - linear approximations.

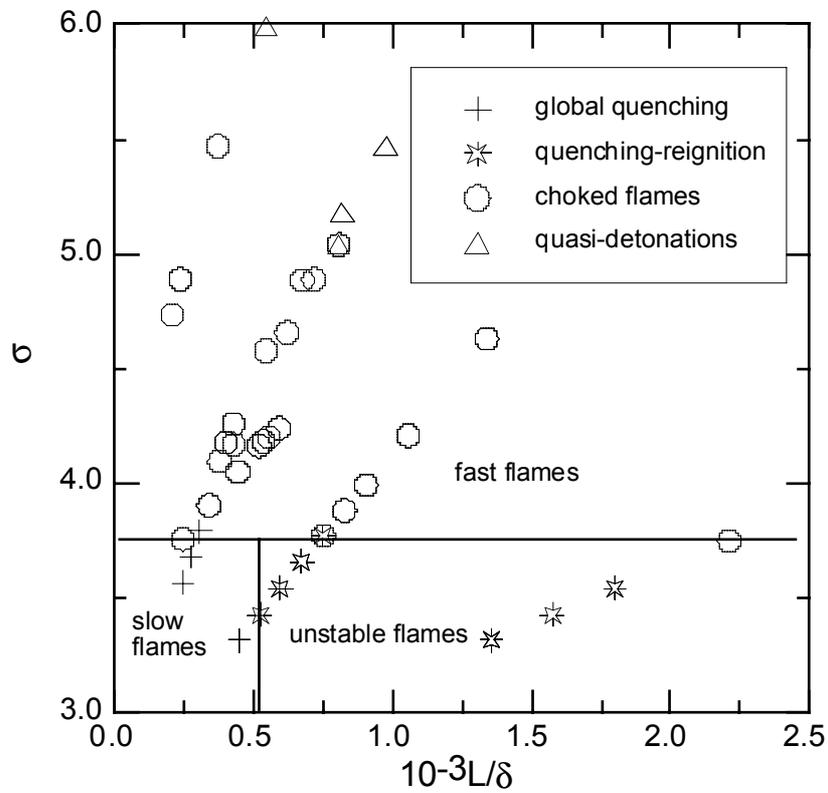


Figure 3. Resulting combustion regime as a function of scaling parameters  $L/\delta$  and  $\sigma$ .

A relative strength of combustion regimes, which resulted from flame acceleration in a sufficiently long obstructed tubes, was found out to depend on the combination of  $L/\delta$ ,  $\sigma$ , and  $S_L/c_{sp}$ . It was found out that the range of the scaling parameters  $L/\delta < 500$ ,  $\sigma < 3.75$  resulted in slow combustion regimes with global quenching. The range  $L/\delta > 500$ ,  $\sigma < 3.75$  corresponded to relatively slow and unstable flames. For  $\sigma > 3.75$ , fast combustion regimes (choked flames and quasi-detonations) were observed. The results are presented in Fig. 4. The results of the present discussion suggest that expansion ratio  $\sigma$  is the most important parameter which makes possible to divide mixtures into “weak” and “strong”. Flame acceleration can be very efficient in “strong” (large  $\sigma$ ) mixtures, while it is suppressed in “weak” (small  $\sigma$ ) mixtures, even under favorable conditions.

The results presented here do not show explicitly some significant effect of other parameters, including stability parameters  $\beta z$  and  $Le$ . However, the slow/fast flames border was actually identified for lean  $H_2$ /air and for stoichiometric  $H_2/O_2/N_2$  mixtures (in other mixtures the only fast flames were observed). For these mixtures,  $Le$  number was either close to 0.3 or 1, and  $\beta$  was almost constant and close to 6.5. Such a limited range of parameters is, probably, insufficient to determine the possible effect of  $Le$  number and, especially,  $\beta$  on flame acceleration efficiency. Thus, the critical value of  $\sigma \approx 3.75$  should not be considered as a universal constant. Changes of the critical  $\sigma$ -value may be principally expected in mixtures with different values of  $\beta$  and  $Le$ .

Experimental data of Ciccarelli et al. [4] for hydrogen mixtures at elevated initial temperature give a possibility to estimate the effect of  $\beta z$ . For  $T_u = 300K$ , fast flames were observed in [4] only in mixtures with  $\sigma > 3.7$ . This is in accord with the critical value of  $\sigma \approx 3.75$  found in our study, although the geometrical configuration in [4] was different. For elevated initial temperatures, data [34] give the following critical values:  $\sigma \approx 2.8$  for  $T_u = 400K$  ( $\beta \approx 5.5$ ),  $\sigma \approx 2.2$  for  $T_u = 500K$  ( $\beta \approx 4.5$ ), and  $\sigma \approx 2.1$  for  $T_u = 650K$  ( $\beta \approx 3.6$ ). These estimates show that more detailed analysis is required to evaluate effect of  $Le$  and  $\beta z$  on efficiency of flame acceleration.

## Summary

Experimental results showed that parameters  $L/\delta$  and  $\sigma$  were the most important ones among all set (1), defining flame acceleration rate. At the same time, the type (slow or fast) of final regime of flame propagation at sufficiently large scale was found out to depend mainly on the value of mixture expansion ratio  $\sigma$ . In view of this, it was suggested that all mixtures may be divided into “weak” and “strong”. Flame acceleration and development of fast combustion regimes is possible in strong mixtures under favorable conditions at sufficiently large scale. Flame acceleration in weak mixtures is inefficient, even under favorable conditions. A conservative criterion for flame acceleration may be defined as a requirement of large enough value of mixture expansion ratio  $\sigma > \sigma^*(\beta z, Le)$ , where  $\sigma^*$  is the critical value. It should be noted that the particular value  $\sigma^* = 3.75$  found out in the present study for hydrogen mixtures at normal initial temperature and pressure may be a function of the geometrical configuration, type of fuel, and changes of Zeldovich and Lewis numbers with initial conditions.

## References

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