Photographic Study of Unstable Turbulent Flames in Obstructed Channels

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Abstract

A study of dynamic behavior of unsteady turbulent flame propagation in obstructed channels is presented. Experiments were made in an obstructed rectangular with blockage ratios equal to 0.1, 0.3, 0.6, and 0.9. Hydrogen-air and stoichiometric hydrogen-oxygen mixtures diluted by argon or helium were tested Processes of flame acceleration in the obstacle field were studied using shadow photography. Detailed photographic sequences of images were obtained for typical regimes of flame propagation.

Introduction

Development of models for description of turbulent flame propagation requires experimental data showing detailed picture of the flame propagation process. Data on the structure of turbulent flames are studied extensively, including measurements of mean velocities, composition, temperature and the fluctuations intensities of these quantities, etc. This kind of studies is usually performed at static simplified conditions, which allow comprehensive and accurate measurements. Another sort of data is also required which allows to resolve dynamic of the flame propagation process in details. This is especially the case for large eddy dominated deflagrations, where flame interactions with the flame produced compressible turbulent flow defines the most important features of the process. Accidental explosions in confined and congested areas are examples of such processes. The objective of the present work is to study dynamic of unsteady turbulent flame propagation in obstructed channels. Effects of mixture properties and obstacle configuration on dynamic of flame propagation was studied in the tests.

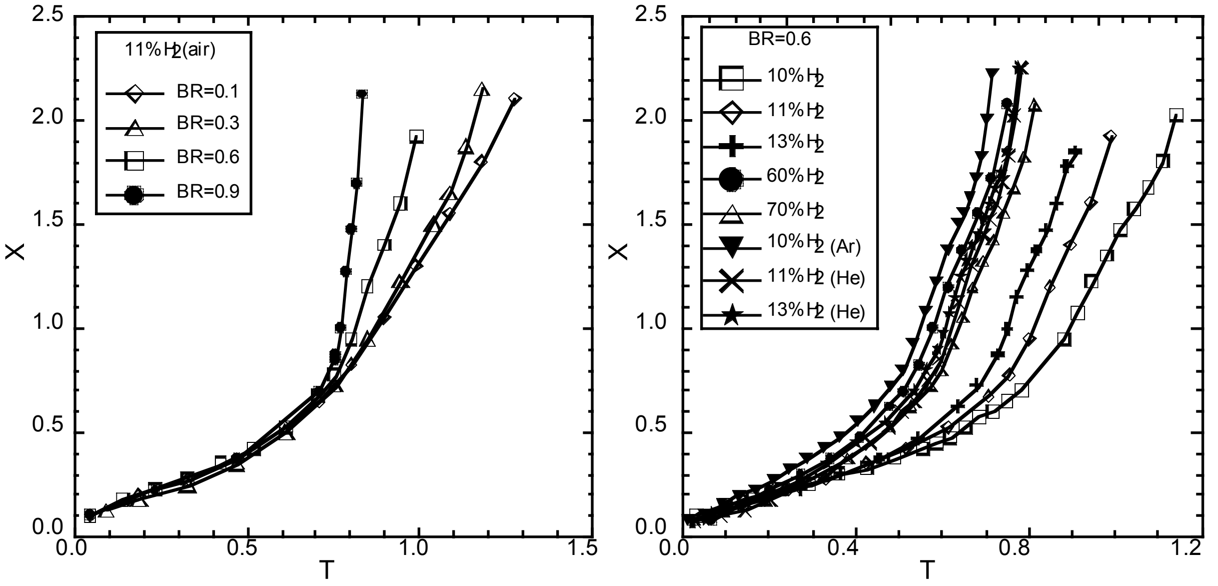
Experimental

Experiments were made in a rectangular channel of 5.28 m long, 80x80 mm cross section with obstacles spaced by one transverse size. Blockage ratios BR were 0.1, 0.3, 0.6, and 0.9. The channel consists of six sections. One of them was equipped by transparent window. It possible to place the window at any position along the channel. Measurements included combination of high speed Schlieren photography (stroboscopic pulse generator 200-5000 Hz and camera with up to 20000 frames per second) combined with time-of arrival photodiodes and pressure transducers.

Hydrogen-air and stoichiometric hydrogen-oxygen mixtures diluted by argon or helium were tested. Mixture parameters varied in a wide range: laminar flame speeds S_L were from 0.17 to 2.13 m/s; specific heat ratio $\gamma = c_p/c_v$ ranged from 1.4 to 1.61; sound speeds in reagents c_r were from 330 to 860 m/s; mixture expansion ratios σ varied from 3.31 to 5.47, Lewis numbers Le were from 0.389 to 3.83.

Results

It was shown that the mixture properties and blockage ratio have a mutual effect on the behavior of turbulent flames. In the initial phase of flame acceleration (up to first obstacle) weak turbulence was generated mostly by thermal-diffusion instability. Cellular structure of flame surface was observed in shadow photographs for mixtures with Le<1. A noticeable effect of obstacles start to reveal itself at the distance of about 0.5-0.6 of that to the first obstacle. Following on flame acceleration is defined mainly by interactions of the flow with obstacles. Examples are presented in Fig. 1. Figure 1a shows the effect of blockage ratio on initial phase of flame propagation for mixture of 10% H_2 in air. Deviation of flame propagation speed from that for laminar flame ($\sigma \cdot S_L$) is observed starting from x/L = 0.5. Figure 1b shows the effect of mixture composition on initial stage of flame propagation for BR = 0.6.



a b

Figure 1. Dimensionless X-T diagrams of initial period flame propagation for different BR (a) and mixtures (b): $X = x/L$; $T = t/t_o$, where L is channel height, $t_o = L/(\sigma \cdot S_L)$ - characteristic time.

Detailed photographic sequences of images were obtained for the following typical regimes of propagation: flame acceleration and global quenching in 10% H_2/air mixture (BR = 0.9); relatively slow unstable flame propagation with local quenching-reignition in 10% H_2/air mixture (BR = 0.6, 0.3); choked flame in 70% H_2/air mixture (BR = 0.6, 0.3). Examples of shadow photographs are presented in Fig. 2. Detailed sequences of shadow photographs were found to include many important details. Here we will give only a short description of some of them, and highlight characteristic features of the flame propagation processes.

Large vortexes in the flow behind the obstacles are essential feature of turbulent flame propagation. Their sizes are certainly influenced by the sizes of obstacles and transverse size of the channel.

Turbulence in the shear flow may also be important in some regimes of flame propagation. Relatively small scale vortexes are developed in the shear flow due to Kelvin - Helmholz instability.

Nonuniform character of the flow ahead the flame is typical for some combustion regimes. Relatively weak flow can become stronger and weaker again with time.

Velocity gradients in the flow ahead of the flame are strong in some cases. This is evident from strength of the vortexes in the wake flow behind the obstacles. It is worth to notice that fast flame propagation can result in a local increase of the flow speed just ahead of the flame.

Incomplete combustion at high turbulence is typical for weak mixtures. It is usual that flame propagates through a number of obstacles, is partially quenched thereafter, and comes backward into partially unreacted material.

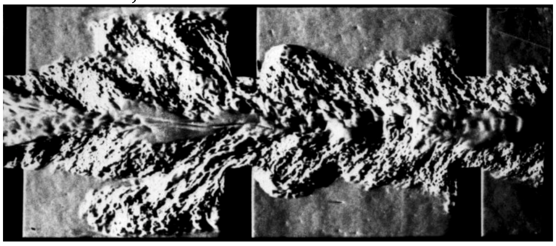
Global quenching is typical for weak mixtures and large BR.

Local flame acceleration and deceleration is observed as a result of flame interactions with turbulent flow. Some parts of mixture along the tube are burned faster and some slower. This results in complicated character of the flow. In some times and locations the flow propagates along the direction from ignition, and in other times and locations it goes in opposite direction.

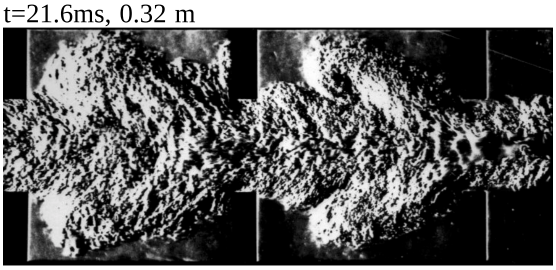
Mechanism which suppresses flame acceleration process in relatively weak mixtures reveals itself in the photographs. A characteristic example can be found in Picture 21. After preceding flame acceleration, a flame tongue detaches from the main flame surface and is transported with the flow ahead. At sufficiently high local flow speed (resulted from previous stages of combustion) the reaction is partially quenched by turbulence in the tongue. Following attenuation of the turbulent intensity results in mixture reignition in the tongue and in propagation of flame downstream and upstream to partially unreacted material. Such a sequence may be repeated several times. Depending on the mixture properties and on BR, global quenching or quasi-steady flame propagation at low average speeds can be observed.

t=18.5ms, 0 m

t=20.2ms, 0.16 m



t=21.6ms, 0.32 m



t=24.9ms, 2.4 m

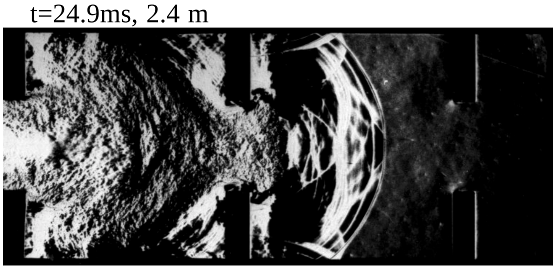
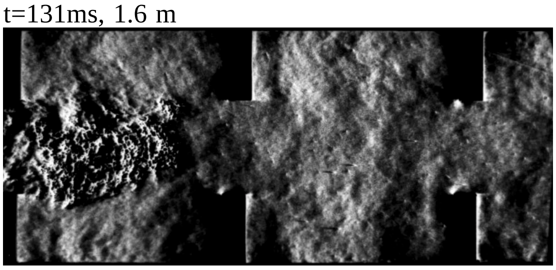
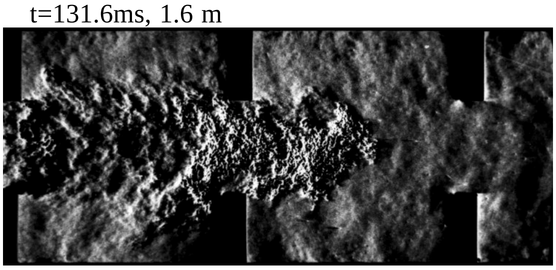


Figure 2. Sequence of shadow photographs for flame propagation in 70% H2-air mixture with BR = 0.6. Time after ignition and distance of the left side of view area from ignition location are shown above the photos.

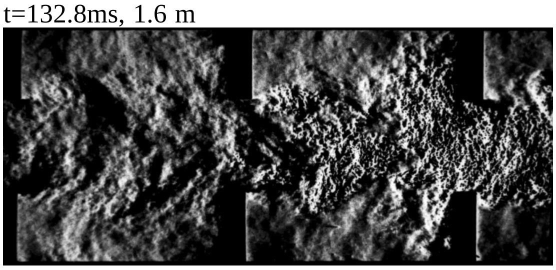
t=131ms, 1.6 m



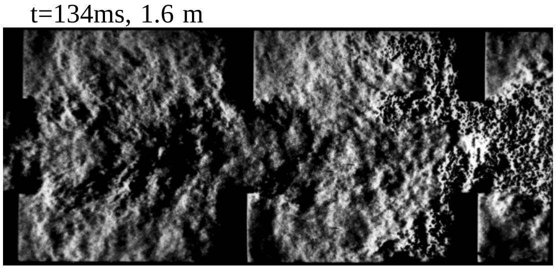
t=131.6ms, 1.6 m



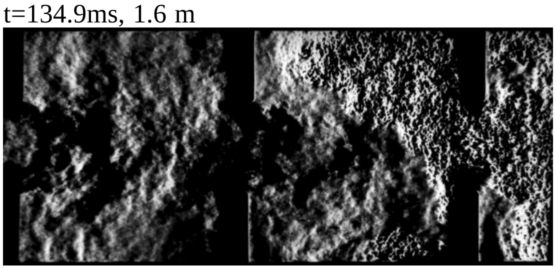
t=132.8ms, 1.6 m



t=134ms, 1.6 m



t=134.9ms, 1.6 m



t=136.4ms, 1.6 m

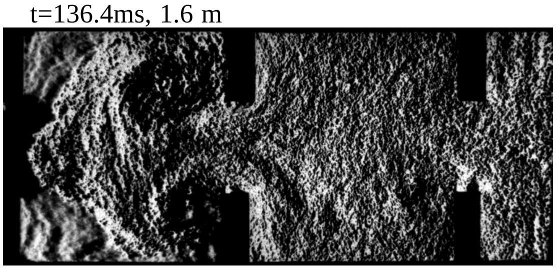


Figure 3. Sequence of shadow photographs for flame propagation in 10% H2-air mixture with BR = 0.6. Time after ignition and distance of the left side of view area from ignition location are shown above the photos.