Effect of Boundary Layer on Flame Acceleration and DDT

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Introduction

It has been shown by many investigators (see, e. g., Schelkin 1947, Soloukhin 1961, Urtiew 1966, Peraldi 1986, Khokhlov 2001) that the flow turbulence generated ahead of the flame due to interactions with tube walls may be important for the processes of Flame Acceleration (FA) and Deflagration to Detonation Transition (DDT). In relatively smooth tubes or channels, generation of a turbulent boundary layer in the flow ahead of the flame promotes flame acceleration. The local explosion, which finally results in the onset of detonation, often occurs near the tube wall in regions where the most intense flow-wall interactions take place.

Recently an experimental study was carried out (Kuznetsov 2003) on run-up distances to DDT in a smooth tube filled with stoichiometric hydrogen-oxygen mixture with initial pressures ranging from 0.2 to 8 bars. It was suggested that the turbulent boundary layer ahead of the flame plays an important role in flame acceleration and controls the scale of turbulent motions in the flow. A simple model was suggested to estimate the maximum boundary layer thickness, δ, at flame positions along the tube with an accuracy of about a factor of 2. The onset of detonation in these tests was observed as soon as the scale of the turbulent pulsations, δ, increased to up to about 10 times the cell size of the initial mixture during FA. It was suggested that this model gives a basis for estimation of the run-up distances to DDT in relatively smooth tubes. At the same time the model was based on purely theoretical considerations. Experimental data on the actual thickness of the boundary layer at flame positions along the tube and its role in the onset of detonations were not available.

The objective of the present work is to study the evolution of the boundary layer ahead of the accelerated flame in a relatively smooth channel and its role in the onset of detonations using high speed shadow photography.

Experimental

Experiments were performed in a stainless steel detonation tube of 6.05-m length with rectangular cross-section of 50x50 mm. The original roughness of the inner tube surface was about 50 μm, as manufactured. Two pairs of removable brass strips with the roughness of either 50 or 1000 μm were mounted on the top and bottom surfaces along the whole tube length to study the effect of the wall roughness.

One of the tube sections (400-mm long) was equipped with a glass window. This section could be positioned at various locations along the tube. A schlieren system with a stroboscopic pulse generator (10 kHz) and a high speed camera was used to record flame dynamics and DDT. The tube was equipped with pressure transducers and photodiodes. Tests were carried out with stoichiometric hydrogen–oxygen mixture at pressures from 0.2 to 0.75 bar. The mixture was ignited by means of a weak electric spark with 20mJ-energy.

Results

High-speed shadow cinematography was used to study the flame behavior and the effect of boundary layer on FA and DDT. It was observed that the accelerating flames generated lead shocks with Mach numbers from 1.45 to 1.54 (shock velocities from 750 to 800 m/s). The boundary layer was formed between the leading shocks and the flame front (see Fig. 1). The dependence of the boundary layer thickness, δ, on the distance, x, from the leading shock was found to be practically linear in the present tests: $\delta \approx 0.01x$.

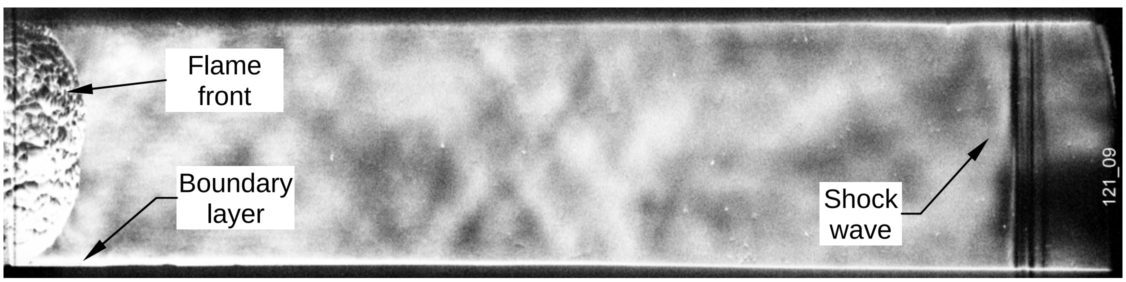

Figure 1. Shadow photographs of early stage of flame propagation (p_o=0.75 bar, window at 210-440 mm from ignition point).

The thickness of the boundary layer at flame positions depended on the distance between the flame and the shock. Figure 2 shows, as an example, the growth of the boundary layer thickness at flame positions along the channel.

The visible average thickness of the boundary layer at flame positions was measured using the shadow photographs obtained. It was found that as the thickness of the layer grew up, the layer became visually nonuniform with tongues of up to about 1.5 times thicker than the average value (see Fig. 2).

The flame acceleration processes were, as usual, repeatable only in terms of general trends. Each of the tests with the same initial pressure differed from others in details of the flame propagation process. As a result, the distance between the lead shock and the flame varied from test to test. These variations resulted in a scatter of the data for visible thickness of the boundary layer at flame positions along the tube. This scatter could be approximately characterized as ± 50%. In general, the model (Kuznetsov 2003) appeared to be a good approximation for the upper bound of the boundary layer thicknesses measured in the present tests.

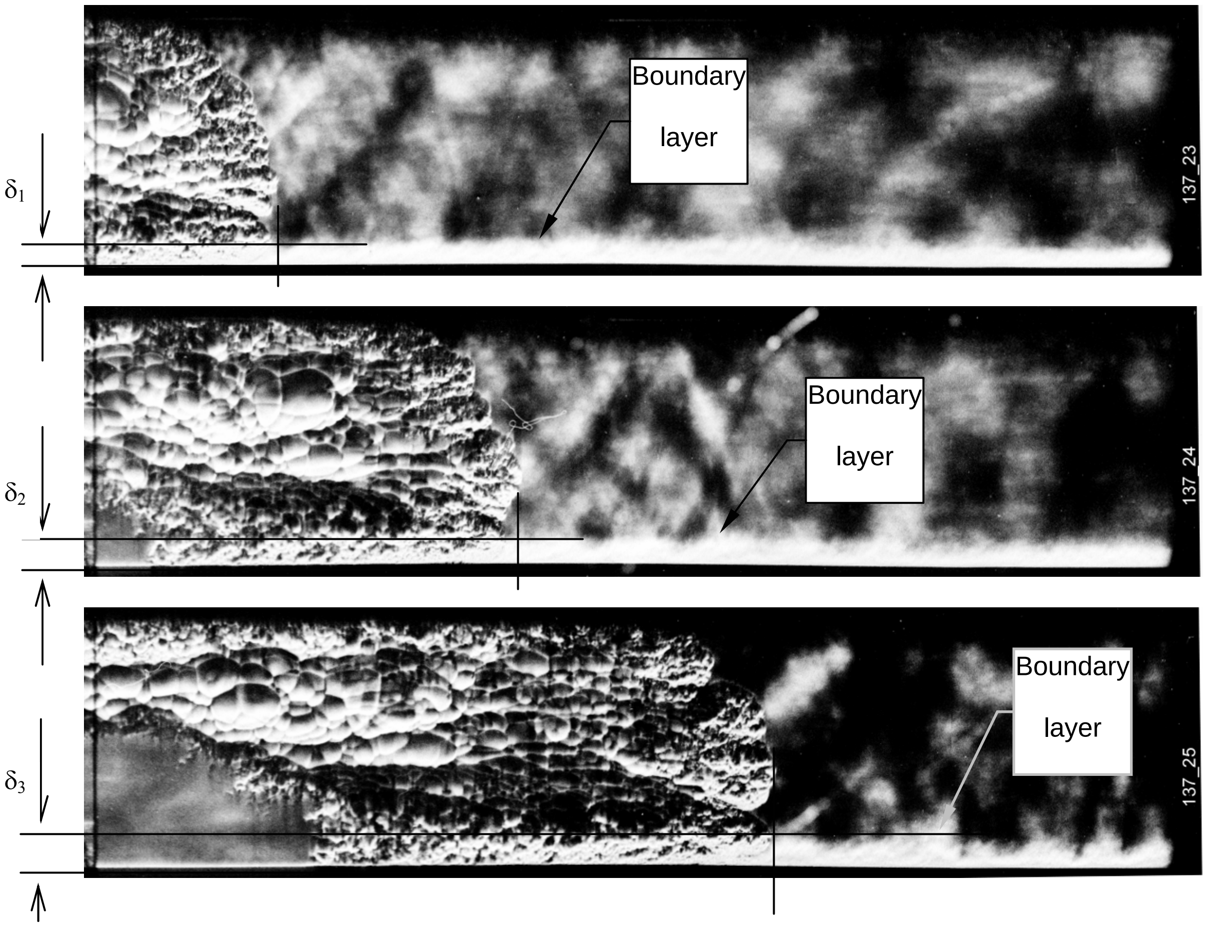

Figure 2. Shadow photographs of flame propagation process
(p_o=0.75 bar, window at 610-840 mm from ignition point)

For the initial pressure of 0.2 bar, it was found that the run-up distances to DDT were smaller compared to the model predictions and to the previous experimental results (Kuznetsov 2003). This was found to be connected with the influence of the reflected shock wave in a relatively short tube used in the present tests. For higher initial pressures of 0.5 and 0.75 bar, FA and DDT were not affected by the reflecting shock. The run-up distances appeared to be in agreement with the model.

The onset of detonations was caught by some of the shadow photographs. An example for the initial pressure of 0.55 bar and the wall roughness of d = 1000 μm is presented in Fig. 3. The flame velocity in Fig. 3, prior to the onset of detonation, is about 1000 m/s. In this particular case, the flame generates a sequence of pressure waves. These pressure waves interact with the lead part of the flame near the boundary layer. This interaction might be responsible for the final triggering of the onset of detonation. The origin of the detonation wave in the second frame of Fig. 3 seems to be located at the distance of about from 10 to 15 mm from the bottom wall. This approximately corresponds to the thickness of the boundary layer in this particular case. Although, Fig. 3 does not reveal the actual mechanism of the onset of detonation, it is important to notice that the characteristic sizes of nonuniformities of the flow ahead of the flame are of about the thickness of the boundary layer.

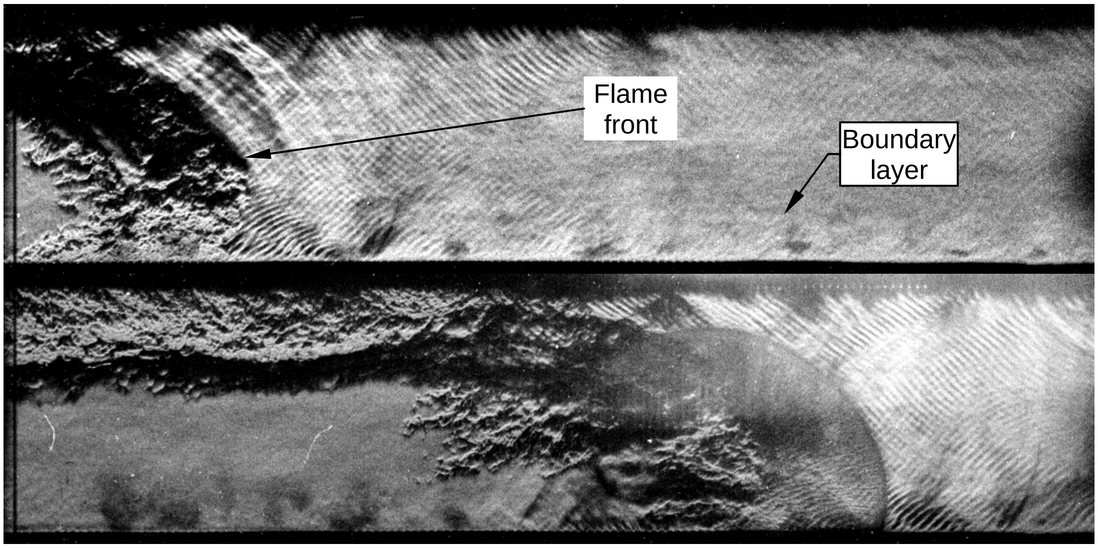

Figure 3. Shadow photographs of DDT process (p_o=0.55 bar, 1090-1320 mm from ignition)

Summary

The evolution of the boundary layer ahead of accelerated flames in a relatively smooth channel and its role in the onset of detonations was studied using high speed shadow photography. Stoichiometric hydrogen-oxygen mixtures at initial pressures from 0.2 to 0.75 bar were used.

The average visible thickness of the boundary layer at flame positions was found to be somewhat lower than predictions of the model suggested in (Kuznetsov, 2003). At the same time, the data scattered considerably in the tests due to variations of the details of flame acceleration for the same initial conditions, so that the model gave an estimate for the upper bound for the boundary layer thickness observed in the tests.

The run-up distances appeared to be in agreement with the theoretical model, with exception of the tests with the initial pressure of 0.2 bar, where the reflected shock affected the process of FA. The photographs of the onset of detonations showed that the detonations originated near the tube wall at a distance from the wall, which is close to the thickness of the boundary layer.

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