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Transition in the propagation mechanism during flame acceleration in porous media

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Abstract

The combustion of stoichiometric hydrogen-air at various initial pressures was investigated in a 7.62 cm square cross-section channel filled with 1.27 cm diameter beads. The flame time-of-arrival and pressure time history along the channel were obtained by ionization probes and piezoelectric pressure transducers. Flame acceleration was found to be very rapid, e.g. at an initial pressure of 45 kPa the flame achieves a velocity of over 600 m/s in roughly 0.3 m. It was determined that at this high speed a well defined planar shock wave precedes a thick reaction zone. It was also shown that there is a transition in the flame propagation mechanism, similar to that observed in an obstacle laden channel [G. Ciccarelli and C. Johansen, The role of shock-flame interactions on flame acceleration in an obstacle laden channel, Proc. 22nd International Colloquium on the Dynamics of Explosions and Reactive Systems, Minsk, 2009]. By varying the initial pressure of the mixture, changes in the axial location of the transition between combustion propagation regimes was also observed. A soot foil technique was used to identify the transition in the propagation mechanism, as well as to provide information concerning the local flow field around the beads and the overall average flow direction.

Keywords: Porous media; Flame acceleration; Explosion

1. Introduction

Flame arrestors are commonly used in the chemical industry to prevent the escalation of accidental combustible mixture ignition to a violent explosion. An important part of a flame arrestor design is the use of porous media, such as wire mesh, ceramic beads, sand, or other high surface-area heat sinks. The basic principle is that the porous media extracts thermal energy from the flame resulting in a drop in gas temperature leading to quenching. The quenching effectiveness of the porous material depends on the pore characteristic dimensions as well as the flame properties (i.e., the flame thickness and laminar burning velocity) [1,2]. Flame quenching associated with the passage of a flame through a narrow passage is characterized by the Peclet number based on the laminar burning velocity and passage length-scale. For a given porous media initial pressure and temperature, there exists an upper and lower composition limit outside of which the flame is quenched.

Within the quenching composition limit a flame can propagate at different steady velocities up to

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the Chapman–Jouguet (CJ) velocity. Babkin et al. [3], Pinaev [4] and Makris et al. [5] studied steady flame and detonation propagation in vertically oriented tubes filled with sand and spherical beads of various sizes. The flame propagation was characterized by front velocity and pressure measurements made down the length of the tube. Babkin et al. [3] identified several different steady-state flame propagation regimes characterized by the propagation mechanism and the front velocity. They referred to the regimes as high velocity flames (0.1–10 m/s), sound velocity flames (100–300 m/s), low velocity detonations (500–1000 m/s) and normal detonations (1500–2000 m/s). Flame propagation in porous media at velocities greater than 5 m/s produce a local pressure rise ahead of the flame [4], where the steepness increases with propagation velocity.

Flame propagation in a unique porous media geometry consisting of a horizontal square cross-section channel partially filled with spherical beads was investigated in [6,7]. Different steady-state propagation modes were identified in the study. One interesting mode was the steady flame propagation in the gap above the bead layer at a velocity higher than the speed of sound of sound of the combustion products [7]. This was attributed to expansion of the combustion products from the bead layer into the gap behind the flame. It was found that when the gap height was larger than one detonation cell size deflagration-to-detonation (DDT) occurred in the gap resulting in detonation propagation above the bead layer. In general the flame acceleration leading up to DDT was driven by the flame propagation in the bead layer. The explosion front structure in the gap was recorded using high-speed schlieren photography and the detonation cellular structure was recorded using the soot foil technique. Light emission from high-speed combustion in the bead layer made it possible to track an oblique explosion front in the bead layer.

In most porous media flame studies, very little attention is given to flame acceleration leading to steady flame propagation. In this investigation flame acceleration leading to high-speed flame propagation in a porous media is investigated. The soot foil technique, normally used for recording detonation cellular structure, is used to determine the local flow field and flame orientation in a porous media. High-speed photography is used to visualize the explosion front.

2. Experimental setup

Experiments were carried out in a 1.22 m long horizontal channel with a 76 mm square cross-section. The channel consists of two equal length sections. An automotive spark ignition system is used to ignite the flame at the right end of the channel. The ignition channel section is equipped with a glass front window for high-speed visualization (see Fig. 1). An aluminum block is placed at the right end of the channel so that the spark plug is located at the right edge of the window, within the field of view. A Photron SA-1 CMOS video camera was used to record the self-luminous combustion front. The top and bottom surfaces of the ignition channel are equipped with equally spaced instrumentation ports that can house either ionization probes or fast response PCB piezoelectric pressure transducers. Four equally spaced pressure transducers (25.4 mm spacing) are mounted midspan of the back plate of the ignition channel, as shown in Fig. 1. The downstream channel section, not shown in Fig. 1, only has two instrumentation ports on the top and bottom surfaces. The channel was completely filled with 12.7 mm diameter aluminum oxide spherical beads. The test mixture is prepared in a separate mixing chamber by the method of partial pressures. Experiments were performed with hydrogen-air, only the results for stoichiometric mixtures are presented. Experiments were performed at room temperature and at initial pressures in the range of 33–45 kPa. At initial pressures below 33 kPa, ignition becomes difficult.

3. Results

Flame velocity versus distance measurements made at initial pressures of between 33 and 45 kPa are provided in Fig. 2. The vertical error bars represent the scatter in the velocity data points. The general trend is that in the first 0.3 m of travel the flame acceleration is faster for higher initial pressures but by 0.5 m the flame velocity data converge to the steady state velocity of 700 m/s, which according to [3] is in the “sound velocity flame regime”. The flame acceleration is not very repeatable between the P2 and P7 location, see Fig. 1. However, the scatter is very small further down the channel where steady-state is achieved.

A sequence of images obtained from a video taken of the flame acceleration process (right to left) at 45 kPa is provided in Fig. 3. The video

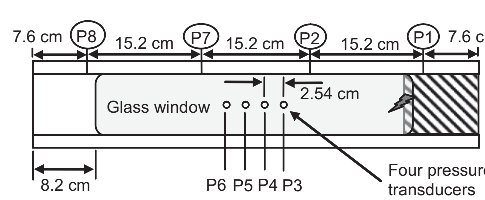

Fig. 1. Schematic of the flow visualization channel with an aluminum block installed at the right end. The channel has a 7.62 cm square cross-section.