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# Visualization of the unburned gas flow field ahead of an accelerating flame in an obstructed square channel

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ABSTRACT

The effect of blockage ratio on the early phase of the flame acceleration process was investigated in an obstructed square cross-section channel. Flame acceleration was promoted by an array of top- and bottom-surface mounted obstacles that were distributed along the entire channel length at an equal spacing corresponding to one channel height. It was determined that flame acceleration is more pronounced for higher blockage obstacles during the initial stage of flame acceleration up to a flame velocity below the speed of sound of the reactants. The progression of the flame shape and flame area was determined by constructing a series of three-dimensional flame surface models using synchronized orthogonal schlieren images. A novel schlieren based photographic technique was used to visualize the unburned gas flow field ahead of the flame front. A small amount of helium gas is injected into the channel before ignition, and the evolution of the helium diluted unburned gas pocket is tracked simultaneously with the flame front. Using this technique the formation of a vortex downstream of each obstacle was observed. The size of the vortex increases with time until it reaches the channel wall and completely spans the distance between adjacent obstacles. A shear layer develops separating the core flow from the recirculation zone between the obstacles. The evolution of oscillations in centerline flame velocity is discussed in the context of the development of these flow structures in the unburned gas.

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## 1. Introduction

Flame propagation in obstructed channels has been studied for many years [1], primarily in connection with explosion safety. The interaction of the flame and the unburned gas flow field generated ahead of the flame provides an efficient feed-back loop that can lead to flame acceleration up to a velocity relative to a fixed observer on the order of the speed of sound of the combustion products, i.e., roughly 1000 m/s. Initially the geometric increase in flame area caused by the large-scale flow structures produced by the obstacles is responsible for flame acceleration. As flame acceleration proceeds and the unburned gas flow becomes turbulent, the transport of mass and momentum into the flame is augmented and the resulting increase in the burning rate further enhances flame acceleration. As a result of these two effects, strong flame acceleration can lead to the production of a precursor shock wave with overpressures on the order of the adiabatic constant volume explosion pressure. In this last stage shock flame interactions can lead to severe flame distortion which further supports flame acceleration and in extreme cases, causes transition to detonation. The process of detonation initiation occurring at the culmination of flame acceleration is referred to as deflagration-to-detonation transition (DDT). Comprehensive reviews of flame acceleration and DDT can be found in [2–4].

The flame acceleration process is governed by several parameters, including mixture reactivity and the ratio of the obstacle blockage area and the channel cross-section area, i.e., BR [5]. Veser et al. [6] performed experiments in a circular tube quipped with different BR orifice plates and performed corresponding three-dimensional gas dynamic simulations. The calculations did not include turbulence and assumed a constant burning velocity equal to ten times the laminar burning velocity. Based on a comparison of the experimental and numerical results, they showed that a "choked" flame can be generated by flame area enhancement resulting from the interaction of the unburned gas flow ahead of the flame with the obstacles. A choked flame is a flame that propagates at a velocity limited to the speed of sound of the combustion products. It can be shown via a one-dimensional, double-discontinuity (flame-shock) analysis that a critical flame velocity corresponds to the condition where the flame velocity equals the speed of sound in the products [7]. This flame velocity is important because for values less than this the combustion products remain at rest as there is communication between the flame and the closed end where the gas must be stationary. For flame velocities above this critical value an expansion fan must be present to drop the particle velocity to zero at the closed end. Veser et al. [6]

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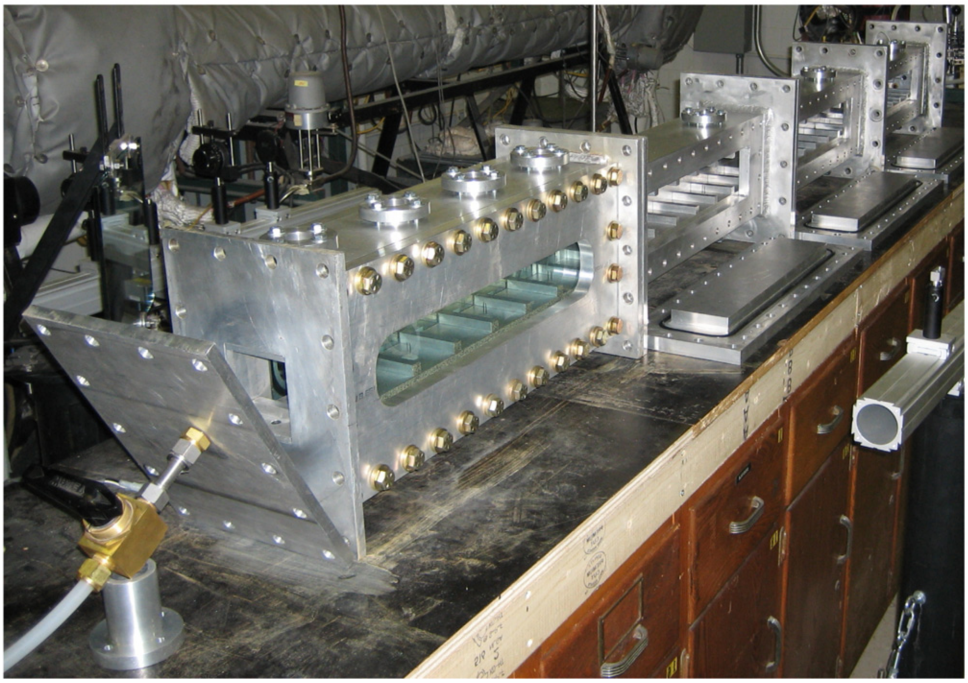

**Fig. 1.** Experimental apparatus.

proposed a simple analytical model that describes the evolution of the flame surface area and predicts the choked flame run-up distance.

In most studies flame propagation velocity down the length of the channel is deduced from the flame time-of-arrival measured by ionization and photodiode probes. Piezoelectric pressure transducers are used to record the pressure transient at different axial locations in the channel. This pressure data can be used to track the development of the shock wave ahead of the flame and the onset of detonation. More recently, high-speed schlieren video has been used to capture the complex turbulent flame shape during flame acceleration [8]. As discussed above the flame shape is dictated predominately by the unburned gas flow-field ahead of the flame, which is dominated by turbulent flow structures such as large eddies and shear layers produced downstream of obstacles [9]. To get a better understanding of the flame propagation mechanism it is imperative to characterize the flow field ahead of an accelerating flame for different channel geometries.

In this study, a novel schlieren based photographic technique, where helium gas is injected ahead of the flame, is used as a tracer to provide a two-dimensional map of the flow field structure ahead of the flame. With knowledge of the flow field structure ahead of the flame insight can be obtained concerning the evolution of the flame surface resulting from the interaction of the flame with this flow field. The objective of the study is to investigate the early stage of the flame acceleration process, i.e., up to flame velocities on the order of the speed of sound of the reactants, and not the DDT phenomenon. The channel height and width are smaller than the detonation cell size for the mixture used and thus detonation initiation is not expected to occur.

## 2. Experimental setup

Experiments were performed in a modular aluminum 6061-T6 combustion channel shown in Fig. 1. The 2.44 m long channel is comprised of three non-optical modules and one optical module, each with a square cross-section of 7.6 cm × 7.6 cm. Each non-optical module is equipped with two instrumentation ports spaced 30.5 cm apart and 15.2 cm from the end flanges on both the top and bottom surfaces. The instrumentation configuration for all of the flame acceleration tests involved four piezoelectric pressure sensors mounted in instrumentation ports on the top surface. Ionization probes were mounted in each available instrumentation port on the bottom channel surface and protruded 1.5 cm into the test section.

A schematic of the optical module shown in Fig. 2 indicates the position of eight instrumentation ports spaced 15.2 cm apart and 7.6 cm from each end flange. Two 1.9 cm thick glass windows are integrated into the channel front and back sides to facilitate 7.6 cm × 44.5 cm of optical access for the visualization of the flame acceleration process. As shown in Fig. 3, visualization of the flame is obtained by positioning the optical module perpendicular to the parallel light produced by a single-pass schlieren system. The schlieren system consists of a 35 Watt Xenon arc lamp, two 25.4 cm diameter parabolic mirrors, and a Photron 1024 PCI high speed digital camera. In most of the tests the camera was operated with a 1.5 µs shutter and at 3000 frames per second with a spatial pixel resolution of 1028 × 524. Flame acceleration was enhanced through an array of top- and bottom-surface mounted obstacles that were distributed along the entire channel length at an equal spacing corresponding to one channel height. The 1.3 cm thick obstacles spanned the width of the channel producing a two-dimensional geometry.

All the experiments were carried out using stoichiometric methane–air, which was prepared in a separate mixing chamber via the method of partial pressures. The mixing chamber was equipped with an impeller that was driven externally by a pneumatic motor. After 15 min of mixing and 30 min of evacuation of the channel down to a pressure of 0.2 kPa absolute, the methane–air mixture was loaded into the apparatus to a final pressure of 47 kPa absolute. Ignition of the mixture is facilitated through the capacitive discharge of approximately 250 mJ of energy through an automotive spark plug mounted on the center of one of the end flanges, which is designated as position A in Fig. 2. In some limited testing the end wall was extended to the position of obstacle 2 so that the igniter is in the field-of-view, designated as position B in Fig. 2.

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