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Flame propagation across a flexible obstacle in a square cross-section channel

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ABSTRACT

Flame propagation across a single flexible fence-type obstacle was studied experimentally in a square cross-section channel, and compared to results obtained using similar blockage ratio (BR) rigid obstacles. The experiments were carried out with different BRs in premixed stoichiometric hydrogen-air mixtures, at initial conditions of 101 kPa and 298 K. High-speed Schlieren photography was employed to gain insight into the flame front structure and the flame tip velocity. Pressure transducers were used to measure the pressure at different axial positions near the obstacle. Flame propagation was found to be strongly influenced by the flow contraction of the unburned gas upstream of the obstacle, and the separated flow downstream of the obstacle. The most significant effect of the flexible obstacle, compared to the rigid obstacle, was observed for BRs above 0.71. The flame front evolution was dominated by the shear layer coming off the obstacle leading-edge and the vortex downstream from the obstacle. For the rigid obstacle BRs tested, the shear layer coming off the obstacle leading-edge reattached to the top of the obstacle, resulting in a vortex (i.e., recirculation-zone) downstream of the obstacle. For the high BR flexible obstacles (BR > 0.43), significant obstacle deformation (downstream tilt and vertical compression), and an associated decrease in BR, resulted in slightly lower flame tip velocities past the obstacle. The downstream obstacle tilt resulted in a different type of separated flow, compared to that observed in the rigid obstacle, where the shear layer didn't reattach to the top of the obstacle. The resulting vortex and strong shear layer confined the flame tip to the top part of the channel, delaying the consumption of the unburned gas immediately downstream of the obstacle. The deformation of the flexible obstacle reduced the peak pressure and the rate of pressure rise compared to that obtained with the rigid obstacles.

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Introduction

Great interest in new alternative fuels has been generated by the increasing concerns about energy shortage and environmental pollution in the use of fossil fuels [1–4]. Hydrogen has attracted increasing attention as a potential substitute within the industrial and academic community because of its zero emission [5,6]. Hydrogen, however, is a very explosive material, characterized by a wide flammability range, high reactivity, and low ignition energy [7,8]. Any leakage of hydrogen into a confined space can result in a highly reactive mixture with air, and therefore a weak ignition source, i.e. a hot surface and electrical spark, may initiate an explosion [6,9]. For example, a hydrogen-air explosion at the Fukushima nuclear power station in 2011 is believed to have caused significant damage [10,11]. It is therefore necessary to study flame propagation in premixed hydrogen-air flame in closed chambers, both in terms of combustion applications as well as explosion safety.

Research on flame propagation in tubes dates back many years to the pioneering work of Mallard and Le Chatelier [12]. The characteristics and dynamics of premixed flame propagation has been studied in detail ever since. Weak ignition of a combustible gas gives rise to a slow laminar flame propagating into the unburned mixture. Flow is produced in the unburned gas ahead of the flame front due to thermal expansion of the combustion products. The flow-field in the unburned gas is perturbed by interactions with obstacles. Under certain conditions, i.e. at high Reynolds number, turbulence is generated in the boundary layers and downstream of the obstacles, where a recirculation zone is produced. The interaction of the flame front and the combustion-generated flow increases the flame surface area and enhances the volumetric burning rate, which is responsible for the initial flame acceleration. When the flame speed exceeds the speed of sound in the unburned gas, the flame acceleration is further enhanced. At this phase, shock waves form as the result of the coalescence of compressed waves produced by the accelerating flame. Interactions between the flame and the reflected shocks from the channel wall and obstacles, which triggers R-M instability, increase the flame surface and thus the energy release rate.

Ciccarelli et al. [13,14] suggested that flame acceleration process is governed by several parameters, including mixture reactivity and blockage ratio (BR). Moen et al. [15] performed experiments in a tube with different BR obstacles and suggested that the controlling factor that drives flame acceleration is the large-scale flow field distortions generated by the obstacles, and that the flame speed depends critically on BR. Veser et al. [16] performed an experimental and numerical study of flame propagation in a circular tube equipped with various BR plates and suggested that the flame surface enhancement is of importance to flame acceleration. Na'inna et al. [17] studied the effects of BR and obstacle separation distance on flame acceleration and proposed that turbulence generated in the unburned gas from obstacles induces flame acceleration and that turbulent intensity is dependent on flow velocity and BR. Dorofeev [18,19] developed several models that correlate flame velocity with BR. Johansen and Ciccarelli [20] conducted a series of experiments in an obstructed channel to study the mechanism responsible for flame acceleration by visualizing the unburned gas flow over the obstacles ahead of the flame. They showed that flame acceleration, during the early stage of acceleration, was driven by flame entrainment into the recirculation zone downstream of the obstacles, as well as the interaction of the flame with the shear layer coming of the inner-edge of the obstacle. Moen et al. [15] found that there is a critical BR, beyond which the flame speed does not increase with BR. One probable explanation for this is that the increase in heat and momentum losses across the obstacles with larger BR counteracts the positive effects [21].

A larger volume of literature has been reported on the process and mechanism of flame acceleration in rigid-obstacles-laden channels, but very few studies are found on the flame propagation in channels with flexible obstacles. Flexible obstacles could be encountered in various explosion scenarios. For example, the explosion at the Buncefield Oil Storage Depot, UK in 2005, that involved the release of gasoline from a storage tank into the surrounding facility producing a large vapor cloud. The subsequent investigation showed that flame acceleration in a tree grove led to the initiation of a detonation wave [22]. Based on experimental measurements and numerical simulation, Bakke et al. [23] suggested that trees have an influence on flame acceleration and concluded that initial flame acceleration can be attributed to the positive feedback between the turbulence generated by the trees and the combustion front. In most explosion studies, trees and bushes are treated as rigid obstacles; however, the deformation of trees and bushes by aerodynamic forces associated with the unburned gas flow has failed to be considered. In a recent study it was shown that obstacle deformation plays a significant role on the unburned gas flow structure and flame acceleration [24].

Although significant efforts have been devoted to the flame acceleration across flexible obstacles, details concerning the flame acceleration mechanism are still not clear. To fill the gap-in-knowledge, flame propagation across flexible obstacles were experimentally studied, and compared to results obtained using similar BR rigid obstacles. The results provide important missing data on the explosion hazards associated with flexible obstacles, especially compared to the rigid obstacles, and will be an important contribution to the literature. In addition, such a fundamental study will shed light on the complex interaction of a flame and deformed obstacle, that will provide basic data to validate codes for simulation.

Experimental apparatus and procedures

Fig. 1 presents a schematic of the experimental apparatus. It consists of a horizontal square cross-section combustion channel, a schlieren system, a pressure signal recording system, a gas mixing system, a high-voltage ignition system, and a synchronization controller. The combustion channel, which is placed perpendicularly to the parallel schlieren light, is comprised of one optical module and one non-optical module, each with a cross-section of 70 mm × 70 mm and a length of 500 mm. Two rectangular quartz glass windows with a thickness of 40 mm were installed on the front and back sides