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Experimental investigation of detonation quenching in non-uniform compositions

Stéphane Boulal[a,b,*], Pierre Vidal[a], Ratiba Zitoun[a]

[a] Institute Pprime (UPR 3346 CNRS), Fluid Thermal and Combustion Sciences Department, ENSMA, BP 40109, 86960 Futuroscope-Chasseneuil, France
[b] SAFRAN Aircraft Engines Villaroche, Rond-Point René Ravaud – Réau, 77550 Moissy-Cramayel, France

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ABSTRACT

This paper presents an experimental investigation into the dynamical behavior of detonation in non-uniform mixtures of propane and oxygen at initial pressure and temperature of 200 mbar and 290 K, respectively, with gradients of initial composition parallel to the direction of detonation propagation. The experiments were carried out in a 50 × 50-mm^2-square section, 665-mm-long, vertical chamber. Filling was made from the chamber top-end by means of a planar, separate injection of the mixture components. The non-uniform distributions in the chamber were then controlled by molecular diffusion with diffusion time defining the composition gradient. A Chapman–Jouguet detonation was smoothly transmitted at the chamber bottom-end from a 3.6-m-long driver tube connected to the chamber. Injection and diffusion were monitored in such a way that the mixture composition at the chamber bottom-end was the same as the uniform composition in the driver tube at ignition time. Fast pressure transducers, sooted plates, Schlieren and CH* chemiluminescence visualizations were used to characterize the longitudinal velocities and cell widths, the front structure, the propagation modes and the quenching mechanisms of detonation. Detonation dynamics was found to depend on the steepness of the composition distribution and on the local and initial values of the equivalence ratio. In particular, a sudden one-dimensional detonation quenching of the multicellular detonation was observed in a lean to leaner distribution with a large gradient, whereas a progressive quenching through marginal propagation was obtained with a small gradient and a lower local equivalence ratio. The quenching mechanisms appear to be controlled by the rates of variation of composition and of detonation characteristic lengths: the faster the rate of change, the more sudden the quenching.

1. Introduction

Investigations on detonation wave propagation in composition gradients have been primarily concerned with hazards resulting from accidental leaks of hydrogen in nuclear power plants or of fuel from tanks or ducts. The explosive cloud formed with the air after the leak necessarily involves a spatial distribution of composition. Also, increasing interest in detonation-based propulsive systems, such as Pulsed or Rotating Detonation Engines (PDE, RDE), for replacing conventional isobaric combustion engines, requires several fundamental aspects to be investigated [1–4]. One of them is the effect of a non-uniform distribution of initial composition on detonation's existence and propagation [5,6].

For convenience, most numerical studies on detonation engines have considered premixed compositions of fuel and oxidizer [7,8]. However, for safety and practical reasons, a separate injection of reactants should be considered. In operating conditions, the characteristic time for fuel-oxidizer mixing is much longer than the characteristic run-time of detonation in the chamber. Therefore, detonation fronts propagate in a mixture with a non-uniform distribution of initial composition. Likewise, the simultaneous presence of fresh injected reactants and residues of detonation products is a source of non-uniformities of composition. Unmixed fractions of fuel and oxidizer or burned residues act as inert additives that might be partly responsible for the differences between the predicted and measured performances of detonation engines.

The influence of non-uniformities of composition in a RDE chamber has never been experimentally investigated due to the difficulty in performing in situ composition measurements. Gaillard et al. [9] numerically studied different types of non-premixed injection configurations in non-reacting conditions. They observed that separate injection results in a composition gradient mainly

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* Corresponding author at: Institute Pprime (UPR 3346 CNRS), Fluid Thermal and Combustion Sciences Department, ENSMA, BP 40109, 86960 Futuroscope-Chasseneuil, France.

E-mail address: stephane.boulal@ensma.fr (S. Boulal).

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parallel to the propagation direction, i.e., the azimuthal direction of the chamber. Nordeen et al. [10] numerically investigated the influence of a non-perfect mixing of reactants on the performance of a two-dimensional RDE. They concluded that mixing has a limited influence on performance, but plays a role in the control of stability and existence of steadily rotating detonations.

Brophy and Hanson [11] experimentally showed that a stratified initial distribution in a PDE that begins stoichiometric at the entry-end of the chamber and gradually becomes leaner produces a higher specific impulse than an axially-uniform distribution with the same mean composition. Perkins and Sung [12] numerically studied different linear composition gradients in the axial and transverse directions of a detonation tube. They observed that uniform and non-uniform distributions with the same mean composition produce the same specific impulses – within 1%. They concluded that, in their conditions, good mixing was not a prerequisite for optimal PDE performance. However, they emphasized that their results were strictly limited to composition distributions that remain fully detonable over the entire tube length. Actually, detonation engine chambers are likely to exhibit non-uniformities of composition which might cross the detonability limits of the considered reactive mixtures.

Multi-directional composition and temperature gradients exist during the operation of detonation engines, and thus, from a fundamental viewpoint, generic composition gradient orientations with respect to the detonation propagation direction should be investigated separately. Several authors have studied experimentally [13–15] or numerically [16,17] deflagration-to-detonation transitions (DDT) and the resulting detonations in gaseous mixtures with composition gradients normal to the propagation direction. However, the case of composition gradients parallel to the detonation propagation direction appears to have received less attention. Donato et al. [18] studied detonation transmission in a 25.4-mm-diameter tube from a highly sensitive mixture to a less sensitive one and conversely. In the case of a composition gradient with increasing sensitivity, they found that the transmitted detonation rapidly adjusts to the condition of local energy release. In the case of a composition gradient with decreasing sensitivity, they found that the transmitted detonation is locally overdriven. Kuznetsov et al. [19,20] performed similar works on detonation transmission across a decreasing sensitivity composition gradient in a 174-mm-diameter tube and also studied the influence of the driver length. They found that the less sensitive the acceptor, the larger the driver length needed for successful detonation transmission. For relatively large gradients, detonation decays in the non-uniform region but can reinitiate downstream if the driver is long enough. The larger the overdrive of the steady detonation in the driver, compared with that in the acceptor, the sharper the gradient necessary for detonation decay. They proposed a critical sensitivity gradient for driver-acceptor sets that depends strongly on the difference in the energy content but not on the donor length. The authors concluded that detonation decay in composition gradients is mainly determined by the difference in the mean width of the cellular structures on the steady detonation fronts in the driver and in the acceptor. Bjerketvedt et al. [21] studied the transmission of a detonation across an inert region in a 125-mm-diameter tube divided into three sections, i.e., the donor, inert and acceptor. They found that detonation reinitiation in the acceptor is mainly governed by the Chapman–Jouguet (CJ) properties in the donor, the width of the inert section, the sensitivity of the gas in the acceptor, and the steepness of the composition gradient in the inert region. Thomas et al. [22] performed a similar work in tubes with a 22 × 10-mm^2-rectangular cross-section and a 50-mm-diameter. They concluded that small composition gradients can facilitate the transmission whereas large gradients may dissociate the shock front and the reaction zone, thereby leading to detonation quenching. Sochet et al. [23] studied the detonability of a gaseous cloud in which the composition gradient was formed after the rupture of the soap surface of a hemispherical volume filled with a gaseous mixture and through diffusion with the surrounding air. They measured critical parameters in terms of nominal energy and diffusion time that return conditions for which the explosive charge fully or partially detonates.

In this paper, we present an experimental investigation on detonation dynamics and quenching for the case of gradients of initial composition parallel to the direction of detonation propagation [18–22]. The specificity of this study is that we have designed an experimental set-up capable of generating a controlled non-uniform initial domain within a fully-instrumented test channel and of unambiguously separating the unsteady phenomena due to detonation initiation from those due to initial non-uniformities. In this way, we can have a direct and continuous access to the instantaneous dynamics of detonation propagation and quenching, in particular, at positions around which the largest changes in initial compositions are located.

The experimental set-up, the procedure to generate and characterize reproducible non-uniform initial compositions and the measurement techniques are described in Section 2. The results are presented in Section 3, then synthesized and analyzed in Section 4.

2. Experimental set-up and measurement techniques

The experimental set-up comprised two parts (Fig. 1). The first was the chamber in which non-uniform compositions were generated. The second was the ignition tube which contained a uniform detonable composition. The chamber and the tube were separated by means of a knife-gate valve. A CJ detonation was generated in the ignition tube and used to obtain a self-sustained detonation at the entry-end of the chamber. The knife-gate valve was closed during the generation of the non-uniform composition in the chamber and opened immediately before detonating the uniform mixture in the ignition tube.

The experimental set-up was designed so as to meet two conditions. The first was that the composition in the chamber be uniform over each cross-section in order that the composition gradient is strictly one-dimensional and parallel to the direction of detonation propagation. The second was that compositions on each side of the knife-gate valve be identical in order to suppress transient phenomena due to detonation transmission from the ignition tube to the chamber.

One-dimensional composition gradients parallel to the chamber vertical axis were generated by injecting separately the components of the mixture through a plenum located at the exit-end of the chamber (Fig. 2). The plenum and the chamber have the same cross-section and are separated by a stack of two porous plates that ensures surface filling of the chamber and suppresses the turbulent jet effect that would result from a point injection. Molecular diffusion of reactants was then used to obtain non-uniform distributions of initial composition as functions of time. In order to prevent buoyancy, gaseous components were injected in decreasing order of density. The knife-gate valve was pneumatically actuated and used to trigger the firing sequence at opening. The spark of an automotive plug was used to generate a deflagration in the uniform mixture in the ignition tube and a 50-cm-length Shchelkin spiral was used to promote transition to detonation within a shorter distance than the tube length, typically 1 m. The non-uniform distribution in the chamber was considered frozen during the firing sequence because the diffusion characteristic time is much longer than those of valve actuation and of the detonation's generation and run in the ignition tube. In order to ensure reproducibility of chamber filling, an automated injection system was built, based on pressure monitoring and