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Experimental investigation on detonation dynamics through a reactivity sink

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ABSTRACT

This article reports on an experimental investigation into dynamical behaviours of detonation in non-uniform mixtures, generated from stoichiometric propane–oxygen, oxygen and ethane, with initial temperature and pressure 290 K and 20 kPa, respectively. Composition gradients are parallel to the direction of detonation propagation, with an equivalence ratio (ER) that first decreases from lean values and then increases to rich ones. Composition distributions are characterized according to the depth of the ER sink. Gradients are generated in a $50 \times 50\text{-mm}^2$-square cross-section and a 665-mm total length chamber. The mixture components are injected separately in the pre-evacuated chamber in their order of decreasing density through porous plates at the chamber top-end to ensure planar filling of the chamber. Non-uniform distributions are then precisely controlled as a function of time by means of optical oxygen sensors. A Chapman–Jouguet (CJ) detonation is transmitted at the chamber bottom-end from a 3.6-m-long driver tube. Fast pressure transducers, sooted plates and Schlieren visualizations coupled with high-speed cameras are used to characterize the longitudinal velocity, cellular structure and transmission, failure and re-initiation mechanisms of the detonation front. Shallowest ER sinks produce the supercritical transmission mode of the CJ detonation with continuous adaptation of velocity and multicellular structure to local composition. Deepest sinks lead to the subcritical behaviour characterized by sudden detonation failure from shock-flame decoupling when ER decreases, and without detonation re-initiation when ER increases again. Intermediate sink depths generate critical behaviour with detonation re-initiat ion at chamber walls from expanding combustion kernels and reflected transverse Mach waves and then from SWACER retro-active mechanism. An elaboration of the failure criterion used in a previous study is found to well predict conditions for shock-flame decoupling.

1. Introduction

Accidental or intentional reactive mixtures often show spatial distributions of composition and temperature. Leakages of fuels from tanks or ducts generate explosive clouds with larger fuel concentrations close to the location of the leaks. In Pulsed or Rotating Detonation Engines (PDE, RDE), fresh reactants are injected separately for safety and practical reasons, so they are not uniformly distributed. Also, they mix within residual burnt gases produced by the previous detonation cycle. These products may then act as inert additives in the newly injected reactive mixture. Imperfect mixing of reactants and their dilution with burnt gases are sources of non-ideality for the detonation process because the characteristic time of mixing is longer than that of the detonation run.

Composition non-uniformities are thus considered as one of the origins of the differences between predicted and measured performances of detonation engines [1–5], and their control is an important issue in their development and in their implementation. In-situ composition measurements are indeed difficult to perform in detonation engines. Nevertheless, Brophy and Hanson [6] have studied experimentally the influence of non-uniform distributions of composition on the performances of a PDE. They have shown that specific impulse can be larger if equivalence ratio decreases from stoichiometry instead of having the constant value associated with the mean composition in the chamber. Rankin et al. [7] have recently presented visualizations of the flow field in the chamber of an optically accessible non-premixed RDE, but they could not discuss the influences of composition non-uniformities. Burr and Yu [8] have studied the behaviour of a detonation propagating in

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a straight tube equipped with discrete cross-flow injectors of hydrogen and oxygen, a configuration that can be seen as an analog to a RDE with an axial injection and unwrapped in the azimuthal direction. They have described several unsteady dynamics such as detonation failure and re-initiation, but they did not report quantitatively on the actual distribution of composition.

Numerical simulations taking into account non-premixed injection of reactants and mitigation from burnt gases could help understand the influence of composition gradients though such non-uniformities have not been often included in modelings of PDE [9] or RDE [10,11]. Realistic simulations face the difficulty to resolve the interplay of several phenomenon, such as turbulence and mixing which to date remain individually key modeling issues. Also, simplified chemical kinetics is often considered, e.g., a single-step reaction model or an induction parameter, which cannot represent quantitatively many phenomena of detonation dynamics. The latter are strongly dependent on chemical kinetics, such as the regularity of the cellular structure of detonation fronts, the shock-flame decoupling and re-initiation mechanisms, the marginal propagation regimes [12], and the coexistence of deflagrative and detonative combustion domains. As an example of modeling difficulties combining the interplay of several phenomena, Gaillard [13] has recently presented a numerical study of detonation propagation in hydrogen- oxygen compositions obtained by means of non-premixed injections for a geometric configuration nearly identical to that of Burr and Yu [8]. The calculations included mixing, turbulence and detailed chemical kinetics with attention focused on injection and mixing. A best arrangement for separate injectors of hydrogen and oxygen was thus proposed but the local cellular structure of the detonation reaction zone could not be resolved.

In most applications or accidents involving the detonation process, composition gradients in non-uniform distributions are three-dimensional, which complicates the analysis of their influence on the detonation behaviour. From a fundamental viewpoint, gradients with a fixed orientation with respect to the propagation direction of detonation should therefore be investigated. Several authors have studied detonations in gaseous mixtures with composition gradients normal, e.g., [14–18], or parallel to the propagation direction, e.g., [19–28], some of which were discussed in our previous article [26]. In the latter work, we have experimentally investigated the dynamical behaviour of detonation with gradients of composition parallel to the direction of the detonation propagation and monotonic variations of the equivalence ratio (ER), from rich or lean values towards leaner ones. The detonation was Chapman–Jouguet (CJ) and multi-cellular and was propagating in a uniform composition before entering the domain with the composition gradients. We have presented details on the detonation behaviour, especially in domains where the gradient is maximum, and at locations where the techniques retained in previous studies could not return information due to the presence of mechanical interfaces. We have found that the detonation dynamics strongly depends on the steepness of the composition distribution and on the local and the initial ER values. In particular, we have observed a sudden one-dimensional detonation failure in a lean to leaner distribution with a large gradient, and a progressive failure through marginal propagation modes with a small gradient and lower local ERs. We have proposed a quantitative criterion for predicting the conditions for the sudden one-dimensional failure mechanism. Recently, we have performed two-dimensional numerical simulations in monotonic gradients of composition [27,28] that reproduce these dynamical behaviours, and the criterion was then proved to be also a useful predictive tool for assessing the capability of numerical simulations to capture detonation behaviours in such gradients.

In the present article, we report on an extension of our former experimental investigation [26] to the case of gradients of composition parallel to the direction of detonation propagation with non-monotonic variations of ER [27,29]. We consider distributions of composition such that the ER first decreases from lean values then increases to rich ones, and we characterize them according to the depth of the ER sink. To some extent, this configuration is similar to one of the periods of the configuration of Burr and Yu [8]. In Section 2, we describe the experimental set-up that we have designed in order to generate composition gradients strictly parallel to the direction of the detonation propagation, the procedure to generate and characterize reproducible and precise initial distributions, and the measurement techniques. In Section 3, we present the results. In Section 4, we analyze the failure mechanism by shock-flame decoupling in the domains of decreasing reactivity using a reformulation of our criterion first proposed in [26]. In Section 5, we give the phenomenological elements that indicate that the dynamical behaviours identified in our experiments actually fit in the classical interpretive frame of detonation dynamics.

2. Experimental set-up and measurement techniques

We have used the same experimental set-up and procedure as in our previous study [26], and we summarize here their descriptions for comprehensiveness. The set-up comprised two main parts (Fig. 1), i.e. the chamber in which non-uniform compositions were generated, and the ignition tube that contained a uniform detonable composition. The chamber had a 50×50-mm^2-square cross-section and a 665-mm-total length. The ignition tube had same square cross-section as the chamber and its developed length was 3570 mm. These parts were separated by means of a pneumatically-actuated knife-gate valve. Before injection of components, the knife-gate valve was opened, and the ignition tube and the chamber were emptied out below 0.2 kPa (2 mbar) by means of a vacuum pump. The knife-gate valve was closed during generation of the non-uniform composition in the chamber and filling of the ignition tube. The valve was opened when the desired non-uniform distribution was obtained, and this opening triggered the firing sequence beginning with ignition of the uniform composition in the ignition tube. The spark of an automotive plug was used to generate a deflagration, and a 50-cm-length Shchelkin spiral then promoted transition to detonation within a much shorter distance than the tube length, typically 1 m. This ensured that the ignition tube was long enough so that the CJ detonation regime was obtained before entering the chamber.

The non-monotonic ER distributions were generated from three gaseous components, namely the stoichiometric propane–oxygen mixture ($C_3H_8 + 5O_2$), pure oxygen (O_2) and pure ethane (C_2H_6). One-dimensional composition gradients parallel to the chamber vertical axis were obtained by injecting successively these three gases through a plenum located at the exit-end of the chamber. The plenum and the chamber had the same cross-section. They were separated by a stack of two porous plates in order to ensure surface filling of the chamber and to suppress the turbulent jet effect that a point-source injection would have induced. The non-uniform distributions then resulted from time-controlled diffusion of reactants. An automated system of injection was used to achieve reproducibility of the chamber filling. The supply lines of the gaseous components were thus equipped with solenoid valves actuated from pressure monitoring in the chamber. The non-monotonic distributions were then generated by separately injecting the three mixture components in their order of decreasing density, i.e. first $C_3H_8 + 5O_2$, then O_2 and finally C_2H_6. This procedure suppresses buoyancy effects (Rayleigh–Taylor instabilities), so composition gradients are strictly parallel to the chamber vertical axis. At the end of the injection procedure, the pressures in the ignition tube and in the chamber were measured identical to within 2%. In all experiments of this work, pressure and temperature of final distributions were $P_0 = 20$ kPa (0.2 bar) and $T_0 = 290$ K,