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Detonation mode and frequency analysis under high loss conditions for stoichiometric propane-oxygen

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ABSTRACT

The propagation characteristics of galloping detonations were quantified with a high-time-resolution velocity diagnostic. Combustion waves were initiated in 30-m lengths of 4.1-mm inner diameter transparent tubing filled with stoichiometric propane–oxygen mixtures. Chemiluminescence from the resulting waves was imaged to determine the luminous wave front position and velocity every 83.3 μ. As the mixture initial pressure was decreased from 20 to 7 kPa, the wave was observed to become increasingly unsteady and transition from steady detonation to a galloping detonation. While wave velocities averaged over the full tube length smoothly decreased with initial pressure down to half of the Chapman–Jouguet detonation velocity (D_{CJ}) at the quenching limit, the actual propagation mechanism was seen to be a galloping wave with a cycle period of approximately 1.0 ms, corresponding to a cycle length of 1.3–2.0 m or 317–488 tube diameters depending on the average wave speed. The long test section length of 7300 tube diameters allowed observation of up to 20 galloping cycles, allowing for statistical analysis of the wave dynamics. In the galloping regime, a bimodal velocity distribution was observed with peaks centered near 0.4 D_{CJ} and 0.95 D_{CJ}. Decreasing initial pressure increasingly favored the low velocity mode. Galloping frequencies ranged from 0.8 to 1.0 kHz and were insensitive to initial mixture pressure. Wave deflagration-to-detonation transition and detonation failure trajectories were found to be repeatable in a given test and also across different initial mixture pressures. The temporal duration of wave dwell at the low and high velocity modes during galloping was also quantified. It was found that the mean wave dwell duration in the low velocity mode was a weak function of initial mixture pressure, while the mean dwell time in the high velocity mode depended exponentially on initial mixture pressure. Analysis of the velocity histories using dynamical systems ideas demonstrated trajectories that varied from stable to limit cycles to aperiodic motion with decreasing initial pressure. The results indicate that galloping detonation is a persistent phenomenon at long tube lengths.

1. Introduction

Detonation in tubing with diameters approaching the detonation reaction zone length has been shown to be capable of propagating at average velocities that are significantly below the Chapman–Jouguet (CJ) velocity that occurs in larger-diameter tubing. Prior studies have shown a smooth decrease in average detonation velocity in small diameter tubing with decreasing initial pressure P_0 for stoichiometric propane–oxygen, reaching velocities as low as 0.5 D_{CJ}, where D_{CJ} is the Chapman–Jouguet detonation velocity, before the tube quenching limit was reached (Fig. 1). This phenomenon has been the subject of considerable interest [1–5] for many decades with recent literature reviewed by Jackson [6] and Camargo et al. [7].

Some earlier efforts have used microwave interferometry to obtain high-resolution detonation velocity histories of these near-limit detonations [2,4,10]. Lee et al. [2] processed such velocity histories to obtain histograms that quantitatively described six detonation modes as mixtures approached the failure limit. As initial mixture pressure decreased for a given tube diameter d, self-sustained detonations would transition to detonations with velocity fluctuations. These fluctuations were initially small in magnitude, resulting in unstable waves with instantaneous speeds of

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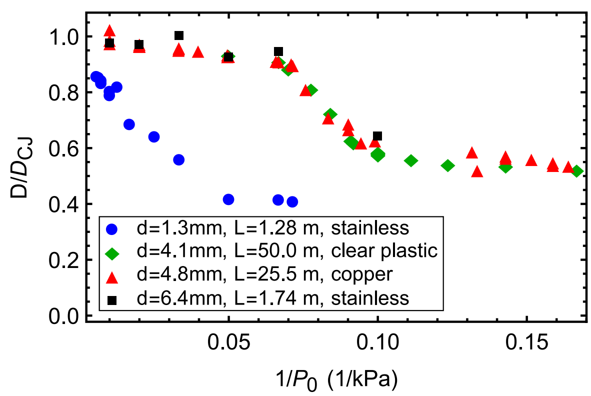

Fig. 1. Average combustion wave velocity data for C_3H_8+$5O_2$ versus inverse pressure for different tube diameters; stainless steel tube data is from Ref. [6], the copper data is from Ref. [8] as reported by Ref. [9], and the clear plastic tubing data is that discussed in the present paper. The test geometries for the 1.3-mm and 6.4-mm diameter tests used straight tube lengths, while the tubing was formed into spirals for the 4.1-mm and 4.8-mm tests.

0.7–0.9 D_{CJ}. The result of further pressure decreases was mixture dependent and attributed to the relative stability [11] of each mixture tested [2]. The effective activation energy, denoted by θ, is often used to quantify a mixture's detonation stability [12]. Mixtures with higher values of θ generally exhibit more irregular cellular structure and detonation velocity fluctuations near failure. Lee et al. [2] found that, for mixtures with high effective activation energies, lowering mixture pressures could result in the onset of three additional modes: (1) galloping detonations with instantaneous wave speeds between 0.4 and 1.5 D_{CJ}, followed by (2) a purely deflagrative mode propagating near 0.4 D_{CJ}, followed by (3) reaction quenching. Mixtures with lower effective activation energies did not exhibit the galloping or deflagrative modes and instead would only quench upon further pressure decreases. Their results were likely geometry specific as the detonation velocity in these near-limit detonations is expected to depend on the coupling between the mixture chemical kinetics and the gas-dynamic response to any confinement (in the form of momentum and thermal boundary losses).

The extremely long length of the galloping cycle has made its characterization difficult. Edwards et al. [10] observed up to four galloping cycles in a tube of rectangular cross section over a distance of 20 m ($L/d = 870$). Lee et al. [2] were not able to observe multiple galloping cycles in their 10-m ($L/d = 260$) tube and noted that "an ambiguity in the identification of the galloping mode and the failure mode may exist" due to this limitation. Haloua et al. [4] were similarly not able to observe more than two cycles in their 25-m ($L/d = 645$) tube. More recently, Wu and Wang [13] inferred two galloping cycles from high-speed cinematography in a 1500-diameter long tube, but with camera sensitivity that was only able to register luminosity during the peak velocity phase. Subsequently, Gao et al. [5] obtained up to five galloping cycles in tubes as long as 1625 diameters, but with spatially discrete diagnostics. Thus, high-resolution observations of the full galloping cycle have been limited, with little opportunity to study its long-term evolution to determine if the mode is independent of initial ignition conditions, repeatable, and persistent over long times.

In this work, we use a novel, transparent, and spiral tube geometry with high-speed video to obtain high-temporal-resolution velocity measurements of the luminous front present in galloping detonations over distances of 30 m ($L/d > 7300$) in stoichiometric propane–oxygen mixtures from 7 to 20 kPa. Over the tested pressure range, this mixture has a high effective activation energy ($\theta \approx$ 11 from Schultz and Shepherd [12]) and is considered to be highly unstable with detonation cell sizes ranging from $\lambda =$ 19–5.6 mm ($\lambda/d =$ 4.6–1.4) for the pressure range of 7–20 kPa [14]. The initial mixture pressure P_0 was varied to obtain different detonation propagation modes. The observation length is sufficiently long to allow for measurement of up to 20 galloping cycles per test, allowing for quantitative and statistical analysis of the galloping phenomenon. Velocity–time profiles of galloping detonation are presented as a function of mixture pressure. Histograms are used to quantify the velocity probability at each test condition. These results are then interpolated to form a velocity probability map versus initial mixture pressure. A map of galloping frequency versus initial pressure is also reported. The timing and repeatability associated with the individual components of the galloping cycle are analyzed. Finally, the stability of the longitudinal velocity pulsations was analyzed and compared to results from one-dimensional detonation calculations.

We emphasize that our measurement technique records only the position and velocity of the luminous front associated with the combustion, in similar fashion to works which use photodiode sensors. We do not measure the position of the leading shock wave, which is commonly reported by numerical simulations, by pressure transducers and by schlieren measurements. In contrast, microwave interferometry studies report the velocity of the ionization front associated with a combustion event or dissociation behind a strong shock. Each of these features may exhibit different dynamics as the shock decouples and recouples with the reaction zone in the unsteady galloping regime.

2. Experiment

Combustion waves were propagated though small-diameter, transparent, polyurethane tubing filled with stoichiometric propane–oxygen mixtures of varying initial pressure. A schematic of the experimental setup is shown in Fig. 2. A deflagration was initiated with a 40-mJ spark. The resulting combustion wave then passed through a 15.4-m length of 4.8-mm inner diameter copper tubing to allow it to relax from the initiation event before reaching the first of three average

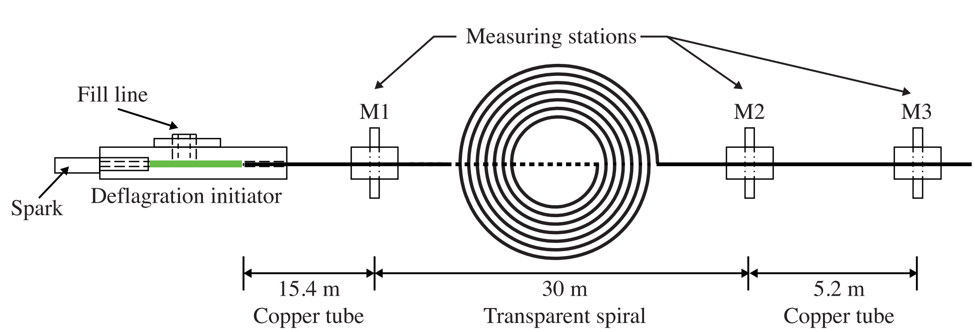

Fig. 2. The experimental geometry.

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