Experimental Detonation Propagation Under High Loss Conditions

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1 Introduction

In previous work, detonation propagation in tubes has been observed to occur at velocities well below the ideal Chapman-Jouguet velocity (U_{CJ}). Such velocity deficits are thought to result from the presence of nonideal boundary conditions, which are not typically accounted for in theory. The growth of viscous and thermal boundary layers serve to remove energy from the reacting flow through frictional dissipation and heat losses to the cooler tube wall. In situations where the reaction zone length is small relative to the tube radius, these losses have a limited effect on detonation, presumably because the sonic surface quickly isolates them from the chemically reacting gas driving the front. However, as mixture sensitivity decreases, the spacing between the shock front and the sonic surface grows and allows the loss mechanisms increased time to act on the reaction zone.

The resulting decreased detonation velocities, termed "sub-CJ detonations," are observed in marginal conditions and range from 0.8–$1.0U_{CJ}$ before failure of the detonation occurs. But in extreme cases, "low velocity detonations" with average velocities as low as $0.5U_{CJ}$ have been recorded [1, 2, 3, 4]. Other researchers have used microwave interferometry to obtain instantaneous velocity measurements showing that these low velocities are actually due to a combination of highly unsteady stuttering or galloping waves [2, 4]. However, due to the long wavelengths associated with these oscillatory modes, it is not clear if they are a persistent phenomena or simply a transient pathway to complete failure. Furthermore, the scaling of these modes is unknown since most measurements to date have been performed in tubes with identical 38-mm inner diameters (IDs).

To address these issues, we have performed studies of detonation propagation under varying conditions. Results are presented for detonations in propane and hydrogen mixtures with tube IDs ranging from 1.27–6.35 mm and tube length-to-diameter ratios (L/D) ranging from 194–10,350. Average velocity measurements obtained from transducer transit times and high-resolution velocity measurements obtained from a high-speed camera are reported.

2 Average Velocity Measurements

Detonations were initiated in a large-diameter tube and propagated into a test section consisting of small-diameter tubing. Two experimental configurations were used, a short-distance setup ($L/D = 194$

or 748) and a long-distance ($L/D = 5270$) setup.

In the short-distance setup, mixtures were initiated in a tube with a 38.1-mm ID and a length of 1.5 m using a 40-mJ spark. A Shchelkin spiral induced deflagration-to-detonation transition (DDT), which was verified by pressure transducers in the initiator tube. The detonation then entered a test section constructed of either 1.27-mm or 6.35-mm ID stainless steel tubing. The 1.27-mm-ID variant was 0.95 m in length and contained three pressure transducers spaced 32.8 cm apart, with the first transducer 29.1 cm from the downstream end of the test section. The 6.35-mm-ID variant was 1.23-m long and also had three transducers, but they were spaced 50.8 cm apart and the first one was 21.5 cm from the test section. For each experiment, the entire setup was evacuated and then filled with a stoichiometric propane-oxygen test mixture via the method of partial pressures. Mixing was accomplished by circulating the gases for 15 minutes.

In the long-distance setup, mixtures were initiated with either a 40-mJ spark or, for less sensitive mixtures, a 100-J exploding wire. Unlike the short-distance setup where the initiator volume was tens to hundreds of times the test section volume, the long-distance initiator volume was less than 10% of the test section volume in order to minimize any initiation transients and wave overdrive. The test section consisted of a 25-m length of 4.83-mm-ID copper tubing. Three pressure transducers measured wave arrival times and were spaced approximately 5.0 m apart. Ion probes and photodiodes were located opposite each transducer to detect the arrival of the reaction zone. In order to further minimize initiation transients and record steady-state operation, the length of tubing between the end of the initiator and the test section was increased to 15.4 m. Mixtures tested included stoichiometric propane-oxygen, propane-oxygen-40%nitrogen (C_3H_8+$5O_2$+$4N_2$), stoichiometric hydrogen-oxygen, and hydrogen-oxygen-40%argon ($2H_2$+O_2+2Ar). During testing, the setup was evacuated and filled with test gases that were premixed in a separate vessel.

As with previous research [1, 2, 3, 4], the average wave speed measurements for propane mixtures indicated that as mixture sensitivity decreased relative to the tube ID, the average wave velocity decayed from U_{CJ} to approximately $0.5U_{CJ}$ before quenching occurred. Little phenomenological difference was observed between the short-tube (Fig. 1) and long-tube (Fig. 2) data, indicating that steady state operation was reached early on. The propane-oxygen-nitrogen data is not shown here, but followed a similar trend. Figure 3 shows the short-distance velocity data plotted versus the log of induction length normalized by tube radius Δ/R, a nondimensional relationship intended to represent mixture sensitivity relative to the losses dependent on the tube length-scale; the average velocity is seen to smoothly decrease as the induction length grows large relative to the tube radius. Hydrogen mixture data, shown in Fig. 4, did not exhibit as significant of a velocity decay, instead quenching below $0.8U_{CJ}$, even when the exploding wire initiator was used. This indicates that the low velocity detonation mode may be unique to irregular (C_3H_8) mixtures and not supported by regular ones (H_2).

In the long-distance initiator, the slowest combustion waves were shock-driven and occurred at 0.06 bar in the propane-oxygen mixtures and 0.22 bar in the hydrogen-oxygen-argon mixtures. Below these critical pressures, no combustion whatsoever, including subsonic deflagration, was detected in the tube. It is believed that thermal quenching was responsible for this lower combustion limit. Studies of flame propagation in capillary tubes have shown that quenching occurs when the Péclet number Pe is less than 65. For both the propane and hydrogen mixtures used in this study, the critical pressure corresponded to $40 < Pe < 100$, supporting the conclusion that thermal quenching is responsible for the lack of combustion below this limit. Thus, the slowest combustion waves observed in this study were supersonic.

3 High-Resolution Velocity Measurements

High-resolution wave speed measurements were also obtained. A 30-m length of 4.83-mm-ID transparent plastic tubing was inserted in between the first and second pressure transducers in the long-distance setup, creating a continuous 50-m length ($L/D = 10,350$) of small diameter tubing. The tubing was wrapped in a spiral pattern (Fig. 5, insert). During testing with stoichiometric propane-oxygen mixtures, any chemiluminescence in the spiral was imaged with a high-speed CCD camera (Phantom V, 12,000 fps, 256 × 256 pixels), while pressure transducer measurements were also collected. Image processing then yielded high-resolution velocity versus time measurements over long distances ($L/D = 7500$). The results, shown in Figs. 5 and 6, indicate that the velocity deficits observed in the average wave speed tests are due to fluctuations in detonation velocity over a period of approximately 1 ms (∼400 IDs). Intermittent fluctuations seen at small average velocity deficits ($U/U_{CJ} = 0.8$ in Fig. 5) are similar to the stuttering mode observed by Lee et al. [2]. Large oscillations between $0.4U_{CJ}$ and $1.2U_{CJ}$ are observed at average velocities of $0.6U_{CJ}$ (Fig. 6) and correspond to the galloping mode seen by previous researchers [2, 4]. The slowest reaction zone speeds observed were consistent with the postshock velocity of the average wave speed, implying that when decoupling occurs the reaction zone exists in a shock-flame complex until DDT reoccurs. By using a much longer tube (in a nondimensional L/D sense), we were able to record up to 18 cycles of galloping, while previous studies with more conventional setups observed only a few cycles due to length limitations. Our results show that the galloping mode is a long-lived phenomena. Supporting observations were also obtained by high-speed imaging of straight lengths of tubing to obtain position-time plots, but are not discussed here due to space limitations.

4 Conclusions

For irregular mixtures detonated in tubes with large induction zone lengths relative to the tube diameter, we observe velocity deficits as large as $0.5U_{CJ}$. Such extreme deficits were not observed to occur with hydrogen mixtures, which exhibited no combustion waves slower than $0.8U_{CJ}$. High-resolution velocity data showed that the deficits were not due to boundary layer displacement effects smoothly slowing the detonation to a constant velocity, but rather from the wave propagation oscillating between a detonation and a coupled shock-flame complex in a stuttering or galloping fashion. With decreasing mixture sensitivity, the coupled shock-flame mode became more prevalent, although the oscillations persisted right up until total failure of combustion in the tubes tested.

The oscillatory mode is attributed to losses from viscous and thermal boundary layers growing significant relative to the amount of combustion energy released as the tube diameter and pressure decrease. For a specific regime, the high friction and heat losses push the detonation to failure. However, after failure occurs, these same effects paradoxically act to accelerate the flame and possibly carry pockets of unburned gas behind the front along the cold walls. This leads to DDT, and the cycle persistently repeats over the longest distances tested ($L/D > 10{,}000$). Decreasing the mixture sensitivity even further resulted in complete quenching of combustion. Our conclusion is that for these irregular mixtures in such a high-loss test geometry, there appears to be no stable or subsonic combustion mode available below the steady detonation regime.

References

[1] V.I. Manzhalei. Detonation regime of gases in capillaries. *Combustion, Explosion and Shock Waves*, 28(3):296–302, 1992.

[2] J.J. Lee, G. Dupre, R. Knystautas, and L.H. Lee. Doppler interferometry study of unstable detonations. *Shock Waves*, 5(3):175–181, 1995.

[3] V.I. Manzhalei. Low-velocity detonation limits of gaseous mixtures. *Combustion, Explosion, and Shock Waves*, 35(3):296–302, 1999.

[4] F. Haloua, M. Brouillette, V. Lienhart, and G. Dupre. Characteristics of unstable detonations near extinction limits. *Combustion and Flame*, 122:422–438, 2000.

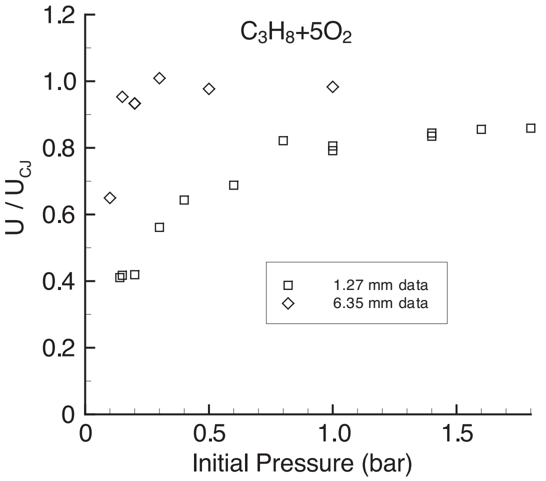

Figure 1: Short-distance C_3H_8+5O_2 data.

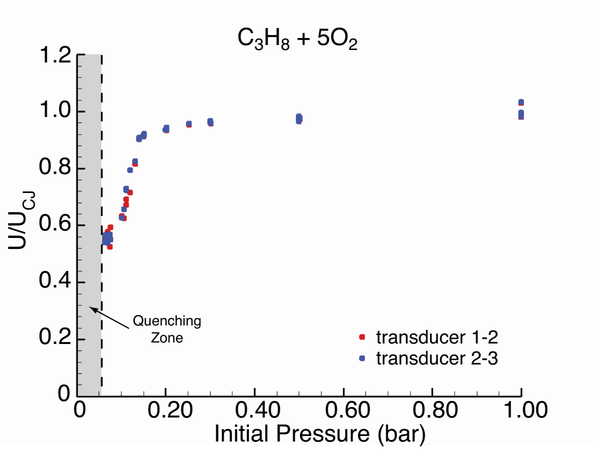

Figure 2: Long-distance C_3H_8+5O_2 data.

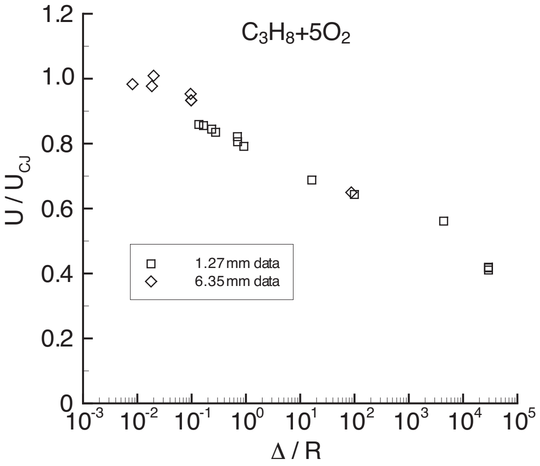

Figure 3: Short-distance C_3H_8+5O_2 data.

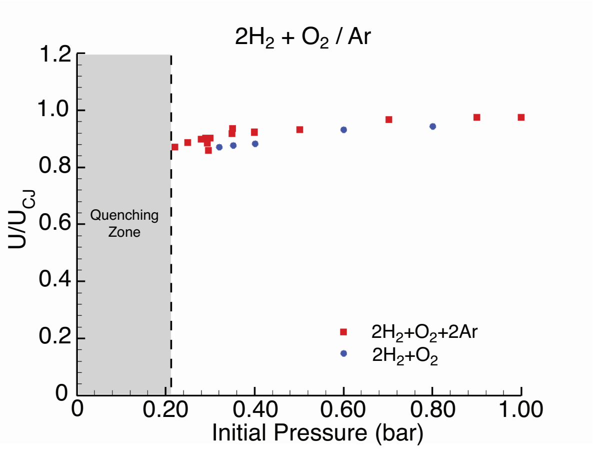

Figure 4: Long-distance hydrogen data.

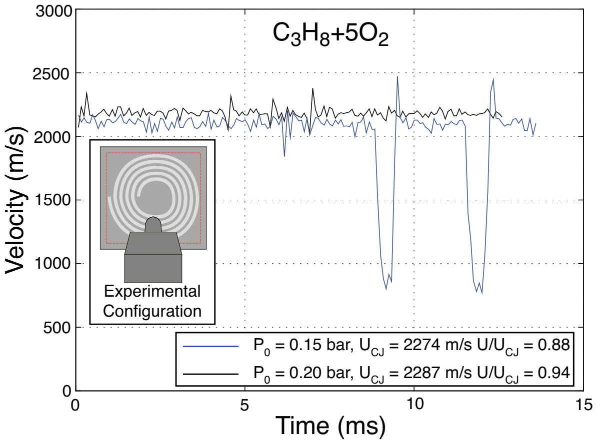

Figure 5: Steady and stuttering modes.

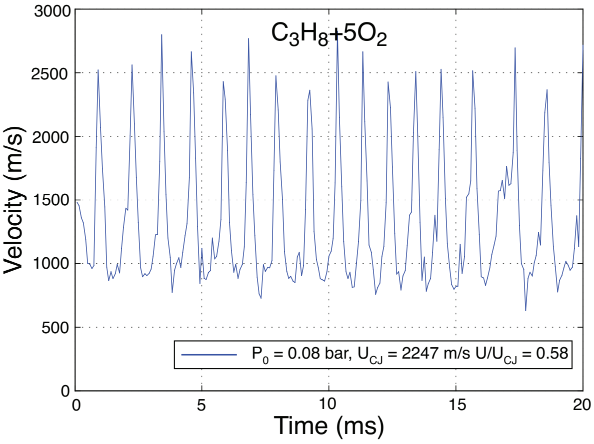

Figure 6: Galloping mode.