Shock Transmission from Detonating Mixtures in Open Tubes

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1 Introduction

Transmission of a shock wave from a steady-state detonation inside of a tube into an open atmosphere is an engineering problem relevant to many applications ranging from fundamental research experiments to pulse-detonation engines. Texas A&M University (TAMU) is currently developing an open-ended detonation tube (ID~2 m, L~200 m) for large-scale experimentation purposes including studying low-reactive fuel mixtures where the detonation dynamics are not geometrically constrained. Accordingly, we were motivated to gain a better fundamental understanding of the conditions outside of the open end of the tube when steady-state detonation waves propagate from it and into the surrounding atmosphere. Three lab-scale detonation tubes were designed and built to evaluate the underlying physical phenomena and potential scaling problems associated with these conditions, ultimately leading to the prediction of large-scale facility behavior. Provided in this abstract is a summary of the experiment details and methods, followed by a presentation and brief discussion of the results.

2 Experimental Methods

A new experimental facility consisting of three detonation tubes with various inner diameters and the associated infrastructure was developed for the current study and is described by the authors in detail elsewhere [1]. A schematic overview of the experimental setup is shown in Fig. 1. The experiment consists of several interchangeable, open-ended detonation tubes which are connected to a gas delivery system, instrumentation, and a DAQ/control box. The detonation tubes have inner diameters of 0.5, 1, and 2″ (1.27, 2.54, and 5.08 cm) with corresponding maximum lengths of 5, 11, and 15 ft (1.52, 3.35, and 4.57 m). The detonation tubes are constructed from flanged sections, such that their total length can be tailored to any 1-ft (0.3-m) increment. The end of each tube is terminated with a blind flange that includes a pressure-sealed insert housing a Nichrome-wire ignition system. The tubes are secured on top of leveled cinderblocks during experiments, such that their outer diameter rests approximately 1 ft (0.3 m) above the ground. The lengths of the detonation tubes contain ports along their centerline for instrumentation purposes with an inter-port spacing of approximately 3″ (7.6 cm). A 30″ (76-cm) long pressure transducer rake (Fig. 2) is mounted at the tube exit, flush with the exit's outer diameter, and can house up to 19 sensors. High-frequency, high-resolution, ground-isolated, ablative-coated piezoelectric pressure sensors (PCB #CA102B) were utilized to measure transient pressures behind the detonation wave inside of the tube and behind the shock wave propagating into the atmosphere. Additionally, 4 free-field, pre-polarized, pre-amplified microphones (PCB #377C01) were deployed in the field away from the detonation tube to measure acoustic wave strength behind the wave propagating into the atmosphere. The typical instrumentation configuration utilized in the current study consisted of 4-6 dynamic pressure transducers mounted along the length of the detonation tube, 10-12 dynamic pressure transducers mounted in the rake, and 4 free-field microphones deployed in the field at various distances (2.5-25 m) from the detonation tube. In addition, a standard video camera and a high-speed camera were utilized to capture shock wave transmission and jet flames in select experiments.

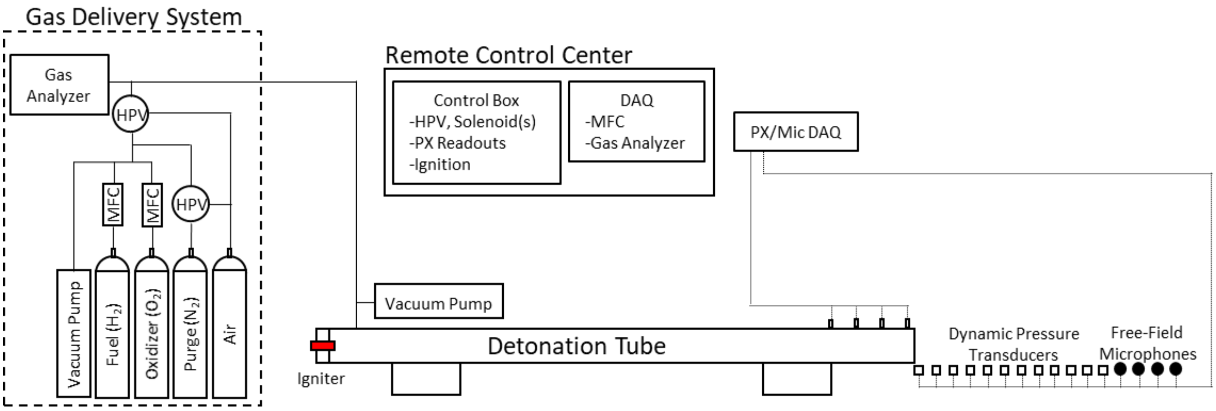

Figure 1: Overview of the experiment including a single detonation tube, the gas delivery system, instrumentation, and control and DAQ systems. Key diagnostics include 4-6 in-tube and 14-16 out-of-tube piezoelectric pressure transducers, and 4 free-field microphones.

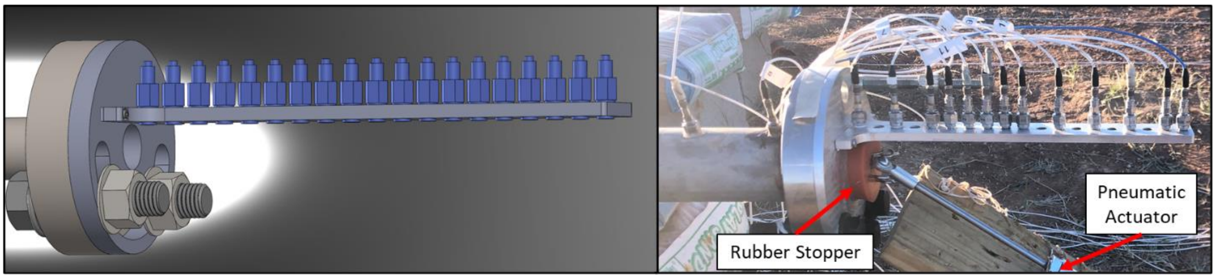

Figure 2: (left) CAD representation and (right) image of the pressure transducer rake utilized to secure piezoelectric pressure transducers near the exit of the detonation tubes.

Prior to testing, the open end of the detonation tube was plugged with a tapered rubber stopper that minimally (< 1 cm) penetrated the inside of the tube. A pneumatic linear actuator was secured to the stopper to hold it in place (Fig. 2). The gas manifold, detonation tube, and associated piping were vacuumed down to a value of 0 psia (pressure readout resolution is 0.1 psia), and a vacuum was continually pulled for an additional 10 minutes. The detonation tube was filled with reactive gas up to atmospheric pressure and then sealed off from the rest of the system. The gas manifold and connecting piping were vented, purged with N_2 gas, and vacuumed down to isolate the reactive gas mixture in the detonation tube. The experiment was initiated by removing the rubber stopper by triggering the pneumatic linear actuator and subsequent application of an electrical current to the Nichrome wire igniter. Representative transient data traces for a stoichiometric H_2/O_2 detonation experiment are shown in Fig. 3.

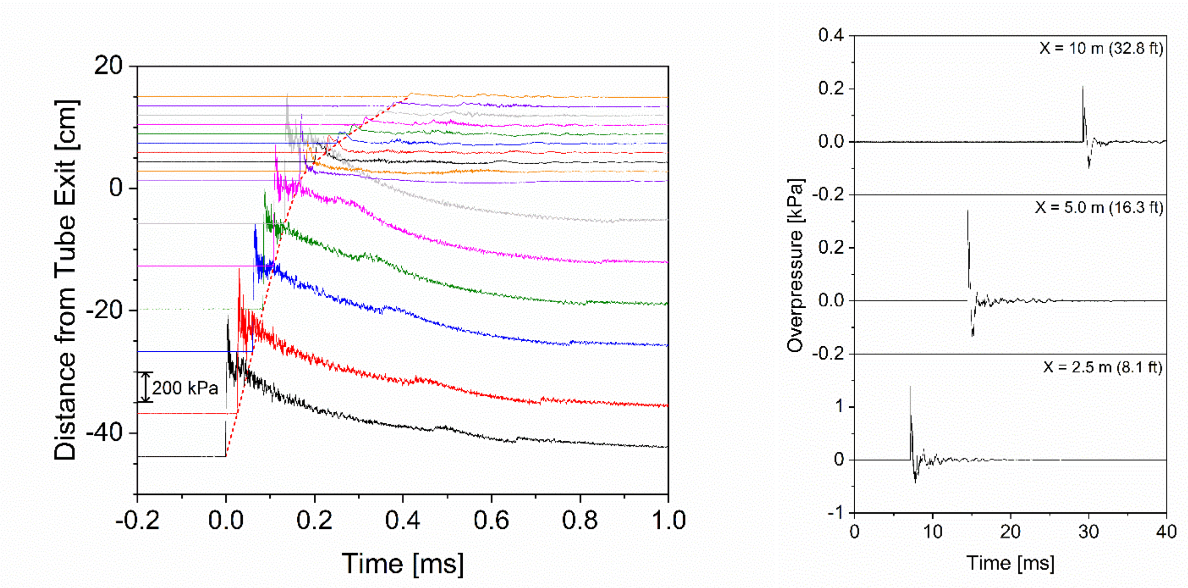

Figure 3: Representative 2D representations of the (left) PZT pressure and (right) free-field microphone data collected during a stochiometric H_2/O_2 detonation tube (ID=1.27 cm, L=1.52 m) firing.

3 Experimental Results

In a smooth tube, a flame acceleration phase followed by the onset of detonation and subsequent decay of an overdriven detonation to a steady-state CJ detonation is expected [2]. To verify the presence of a steady-state detonation wave at the detonation tube exit, the tube length of each tube was varied, and dynamic pressure transducers (0-3.45 MPa, 0-500 psi) were moved along the length of the tube between experiments. The maximum raw overpressure data collected during these experiments for the smallest tube (d =1.27 cm) are shown in Fig. 4a as a function of distance from the ignition location (i.e., the closed end of the tube). Similarly, the average wave velocity measured between sensors is shown in Fig. 4b. Each of the nine sets of symbols corresponds to a separate experiment. The different symbol shapes represent duplicate experiments, while different filling patterns represent different tube lengths. The dashed lines in Fig. 4 correspond to the steady CJ detonation values for stoichiometric H_2/O_2. For the maximum overpressure values reported for sensors near the ignition source (e.g., the first two sensors), care was taken to report the pressure associated with the pre-DDT deflagration and not the retonation wave. The anticipated trend is observed, where DDT occurs near the closed end of the tube after an acceleration phase, yielding an overdriven detonation that decays to steady-state CJ conditions. Stable conditions, with pressures and wave velocities near the expected CJ conditions, are observed at the open end of the detonation tube.

The detonation wave exiting the tube transmits a shock wave into the surrounding medium which ultimately decays into an acoustic wave far from the tube exit. The authors suggest the pressure decay data (Fig. 5) can be represented by an oblique asymptote in x-t space:

$$D(t) = (ct + D_0) - \left\{\frac{D_0^2/(V_e - c)}{t + [D_0/(V_e - c)]}\right\} \tag{1}$$

where D is the distance from the detonation tube exit, t is the time passed since the detonation wave reached the tube exit, c is the speed of sound in the local atmosphere, D_0 is termed the decay coefficient, and V_e is the initial speed of the shock wave transmitted to the atmosphere by the detonation wave.

Equation (1) can be differentiated with respect to time to yield the decaying velocity of the acoustic wave:

$$V(t) = \frac{\partial D}{\partial t} = c + \frac{D_0^2(V_e - c)}{[D_0 + (V_e - c)t]^2} \tag{2}$$

The speed of sound in the local atmosphere (c) can be determined prior to experiments based on local conditions (pressure, temperature, and humidity), but is directly measured herein by fitting a line through the time-of-arrival data collected with the far-field microphones. It is worth noting that the local speed of sound varied between testing days throughout the year, and measured values generally agreed well with theoretical values computed according to recorded ambient conditions. The exit velocity of the wave can be computed from relative acoustic impedances of the reactive gas mixture and atmosphere [3]. The decay coefficient is empirically determined from time-of-arrival data. The prescribed analytical treatment of the transient wave velocity allows for application of the 1D normal shock equations to predict the conditions behind the wave, and this modeling approach is described further by the authors elsewhere [1].

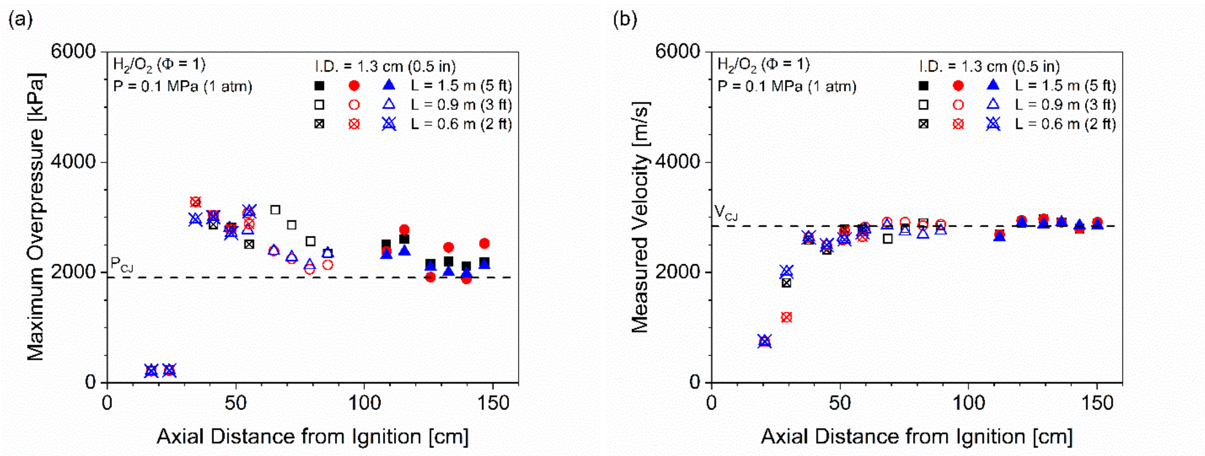

Figure 4: (a) Maximum overpressure data and (b) computed wave velocities inside of the detonation tube (ID=1.27 cm, L=0.6, 0.9, or 1.5 m) for a total of nine experiments conducted with stoichiometric H_2/O_2 (P=0.1 MPa). Symbol shapes represent replicate experiments, while different filling patterns represent different tube lengths.

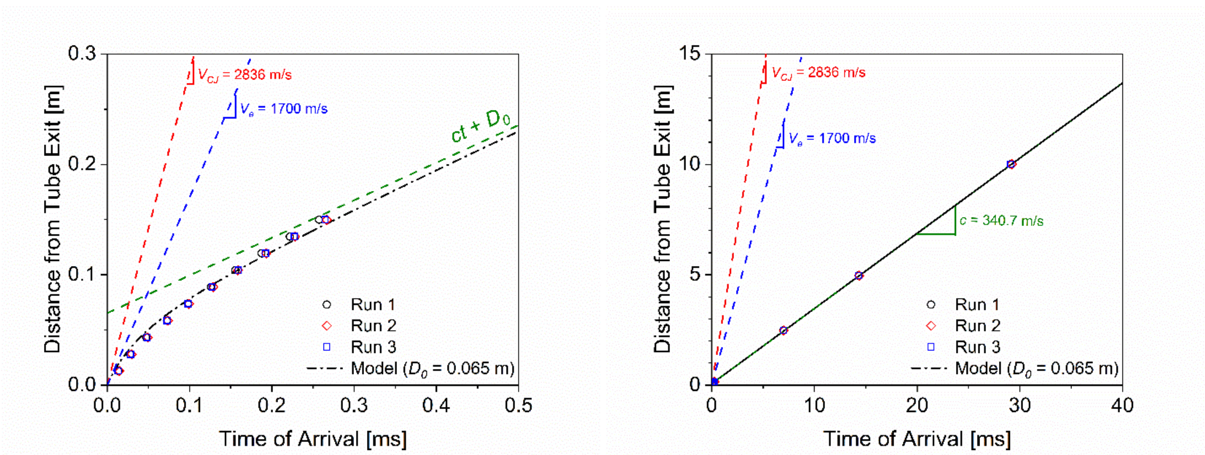

Figure 5: (left) Near- and (right) far-field pressure decay data collected for a shock wave transmitted into ambient air from a stochiometric H_2/O_2 detonation inside of a tube (ID=1.27 cm). Points correspond

to experimental measurements with (left) piezoelectric pressure transducers and (right) free-field microphones. The black dash-dotted line corresponds to the decay model.

The overpressure data outside of the detonation tube (Fig. 6) have been normalized herein to allow for comparison to similar datasets available in the literature [4-8]. In addition, the Sach's scaled distance ($R = X/(E/P_0)^{1/3}$) is utilized for this comparison. Sochet et al. [9] refined the surface energy model detailed by Lee [2] to estimate the energy at the surface of a blast produced by a detonation wave at the tube exit:

$$E = \frac{4\pi}{3} E_v d^3 = \frac{4\pi}{3} \rho_0 Q d^3 \quad (3)$$

where E_v is the chemical energy released per unit volume of the reactants and d is the tube diameter, and this method is implemented herein. The experimental overpressure data collected for stoichiometric H_2/O_2 detonations in all three tube sizes (d =1.27, 2.54, and 5.06 cm) are shown in Fig. 6a alongside available literature data which span a range of tube sizes (d =2.54–10 cm) and various fuel/oxidizer combinations. The data are compared to various modeling approaches in the literature in Fig. 6b including standard TNT air blast correlations [10-11], a coupled strong/weak shock approximation adopted by Allgood [12], and a blast decay model proposed by Jones [13], but poor agreement is observed between all of these approaches and the data. The 1D normal shock model developed by the authors [1] and described herein exhibits good agreement near the tube exit but under-predicts overpressures away from the tube. The data are correlated well (R^2=0.9) with an offset power law:

$$\frac{\Delta P}{P_0} = 2.5\ (R + 0.15)^{-1.434} \quad (4)$$

The authors suggest adoption of the 1D normal shock model near the tube ($R \leq 1$) and enforcement of the empirical decay coefficient (-1.434) at further distances ($R > 1$).

4 Conclusion

A new experimental apparatus consisting of three open-ended detonation tubes was utilized herein to evaluate the transmission of a shock wave from a steady-state detonation inside of a tube into an open atmosphere. Steady-state detonation conditions at the tube exit near the anticipated CJ condition were verified. Overpressure data collected outside of the tubes collapse upon each when scaled appropriately and agree well with data available in the literature. Several historical modeling approaches were applied, but exhibited poor agreement. An analytical expression for the decaying wave velocity was proposed and coupled with 1D normal shock equations, exhibiting good agreement in the near-field. In addition, an empirical correlation was developed and exhibited good agreement across the range of scaled distances. The results presented herein ultimately enable the capability to predict overpressure decay outside of open-ended detonation tubes under a wide range of conditions (e.g., tube size and reactive mixture).

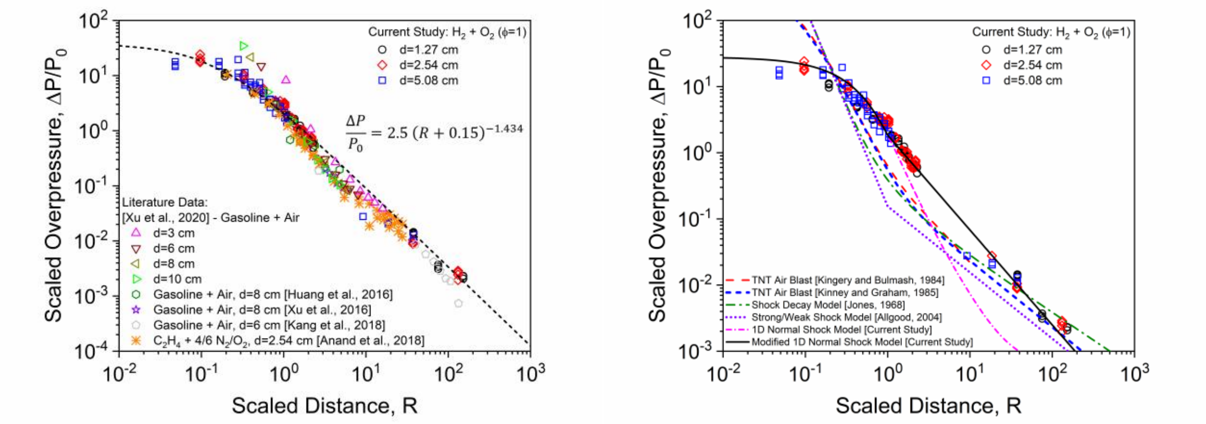

Figure 6: (left) Comparison of experimental overpressure data collected herein and the available literature [4-8]. (right) Comparison of modeling approaches to the experimental overpressure data.

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