X-Ray Radiographic Studies of the Deflagration to Detonation Transition in Porous Beds of Explosives

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1 Introduction

The deflagration to detonation transition in explosives is an important phenomenon impacting the safety and performance of explosives. Deflagration refers to the sub-sonic burning of explosives and detonation to the supersonic energy release. Deflagration can be started by thermal or mechanical means and with appropriate conditions of material and case confinement, can propagate to a detonation. The transition between the sub- and super-sonic regimes is referred to as the DDT transition. Mechanisms for the transition have been posited to include conductive and convective burning of porous beds leading to pressurization of the bed ahead of the burn front and formation of a compacted plug of material which initiates an SDT event. Indirect observations of these steps have been made[1-4]. However, no direct observation of the compacted plug has been made to date. It is a goal of this work using continuous x-ray transmission imaging to observe the compacted plug mechanism. In this paper, we describe work developing x-ray radiographic diagnostics to follow the transition between sub-sonic deflagration and super-sonic detonation. Work to date on porous beds of HMX will be described and future directions outlined.

2 Experimental Methods

We have developed a DDT experiment capable of sufficient confinement to enable the evolution of a deflagration to detonation transition, but with sufficient x-ray transmission to enable continuous x-ray radiography of the event. For this work, the DDT tube contains a low density porous bed of HMX powder in a lexan cylinder, as shown in Fig. 1. The HMX column is ¼” diameter and 4” long packed with approximately 4g of bimodal class 3.1 HMX powder gently tamped into the cylinder. The confinement is a ½” wall thickness lexan tube which has been polished to provide clear optical imaging. The bottom of the cylinder is sealed via an o-ring to a steel holder with a commercial glow plug embedded. The glow plug is used as a simple means to ignite the HMX column at one end. A power supply run at 48V and approximately 30A is used to heat the glow plug to initiate the burning of the HMX column. The top cap on the cylinder is another steel plate also o-ring sealed against the lexan tube. The steel top and bottom plates are bolted to each other to hold the entire assembly together. The assembly is then placed in the confinement vessel in the x-ray radiography experimental setup as shown in Fig. 2. [5] The total areal density imaged through the ½” wall thickness lexan tube at ~ 1.2 g/cc and the ¼” of HMX at 40% TMD and ~ 1.9 g/cc is ~3.5 g/cm^2. This is imaged using our dynamic x-ray radiography apparatus (REF RSI) operating at 100 kVp and ~ 1 Amp with a frame rate of 120,000 frames per second and frame integration time of 7.8 μs. Dynamic x-ray radiographs are divided by static radiographs taken before the glow plug is ignited. This yields an image of the change in x-ray transmission with dark indicating a decrease in transmission caused by an increase in density and white indicating an increase in transmission due to a decrease in density. A visible light image of self-light in the explosive is simultaneously recorded on a second axis orthogonal to the x-ray line of sight. The visible imaging is collected using an ultrafast framing camera run at 300,000 frames per second with 400 ns exposure time.

3 Results

There are several diagnostics utilized to understand the burn velocity and whether or not a transition from deflagration to detonation occurs in these experiments. The steel endcap serves as a witness plate indicating the ultimate energy release rate, or reaction violence of the event. Spall on the witness plate is indicative of a transition to detonation. Both the visible and x-ray images give information about the burn velocity. Supersonic velocities indicate a transition to detonation. What we observe in these experiments is that there is a transition to detonation as indicated by the steel witness plates. There are several velocities observed in the x-ray and visible light images. The visible light images shown in Fig. 3 part B illustrate the heterogeneity of the event. There is not a simple flat front propagating along the full diameter of the column. The x-ray radiographs shown in Fig. 3 part A also indicate a spatially heterogeneous event. The frames progress in time from left to right and capture the region closest to the glow plug at the bottom and approximately 1.6” from bottom to top. The full HMX column is 4” long, so this is only a fraction of the column. The images in this experiment are taken of the central 1.6” section . This is an experimental limitation which will be addressed in future iterations of the work. It is not a fundamental limit of the technique. The initial x-ray frames show a darkening above the glow plug which propagates up the tube. A few frames later (~ 20 microseconds), a white band is observable moving up the edge of the HMX column. This white band is caused by the lexan tube inner diameter expanding due to the pressurization from the HMX burning. The band propagates at approximately 1 km/s and means that the one dimensional nature of the front is lost as confinement fails. The loss of confinement allows hot gases to propagate up the tube at the HMX/tube interface rather than through the HMX column. This flame front can complicate the interpretation of visible light images as it is not a uniform front but occurs at the tube interface. Both the densified plug and the tube wall expansion propagate up the full length of the image before breakup of the dense plug is observed as well as lightening at the glow plug ignition end of the tube indicating a loss of density. In later frames, a tube expansion propagating from the top of the tube is observed to propagate back down the tube towards the initiation end. This indicates a second reaction outside the x-ray field of view propagating back down the tube and greatly expanding its diameter and consuming the HMX.

4 Discussion

We interpret the images from this experiment as demonstrating a DDT event occurring outside the field of view of our images. The velocities we directly measure in both X-ray transmission and visible light imaging are all sub-sonic. However, the steel witness plates bear evidence of a transition to detonation. The observation of a reaction front propagating from above the field of view back down the tube indicates a second higher order reaction occurs in the top portion of the column. We believe this is the detonation wave propagating back down the tube and consuming the remainder of material that has been sub-sonically burning. It is clear from these results that a longer aspect ratio x-ray transmission measurement is needed and modifications are underway to enable this.

The results shown here are from a single DDT tube experiment. To date, we have conducted 8 of these experiments and found repeatability in the generation of a DDT in ¼ diameter HMX powder beds confined by ½” wall lexan tubes. The location of the transition to detonation, however, has been found to be poorly reproducible. In some experiments, the transition to detonation was near the end of the 4” tube, and in one case, it was near the initiation end. A second type of confinement using an aluminum wall with carbon fiber reinforcement was also attempted and a very different type of behavior observed. While the lexan tube confined experiments showed a run distance before detonation of inches, the carbon fiber overwrapped aluminum confined case showed a transition to detonation in the field of view below the x-ray imaging window, ie, very near to the ignition location. The x-ray images from this experiment show simultaneous tube diameter expansion along the fully image length, indicating reaction run velocity fast compared to the few microsecond interframe time. This is consistent with a detonation wave, although it is not a resolved velocity. To date, we have only run a single experiment in this configuration and thus can not yet comment on its reproducibility. Previous work by Parker et al in heavy steel confinement showed significantly higher reproducibility in run to detonation for porous HMX beds.[6] We attribute the high variability in the lexan confined tubes to the loss of 1-d confinement early in these events. In comparison, previous series of experiments run in heavily confined steel tubes showed DDT with much more reproducible run distances to detonation.

5 Conclusion

We conclude that it is possible to generate deflagration to detonation transitions in systems with sufficiently low areal density confinement to enable continuous x-ray radiography during the full duration of the event. However, we also find that the ½" wall thickness lexan tubes provided confinement which failed early in the deflagration event causing a loss of 1-dimensionality in the experiment and causing low reproducibility in the run to detonation. The early expansion of the inner wall diameter allows convective flame propagation at the interface between the HE and the case wall which will cause difficulties in interpretation of visible light imaging from this type of experiment. We are continuing our efforts on these experiments and will improve the measurements by expanding our x-ray transmission field of view to match the HMX column length. We will also look at other x-ray compatible case materials such as thin steel and aluminum in an attempt to make a more reproducible x-ray transparent run to detonation experiment.

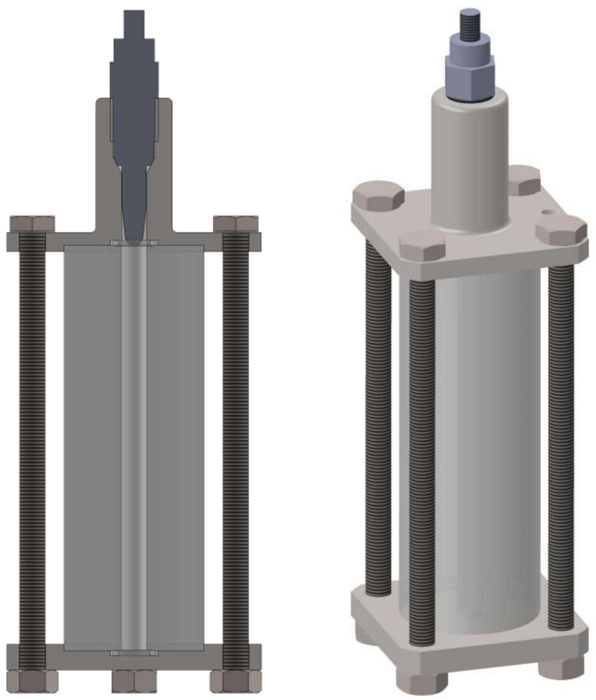

Figure 1. Schematic of DDT tube. Left panel shows cutaway view and right panel external view.

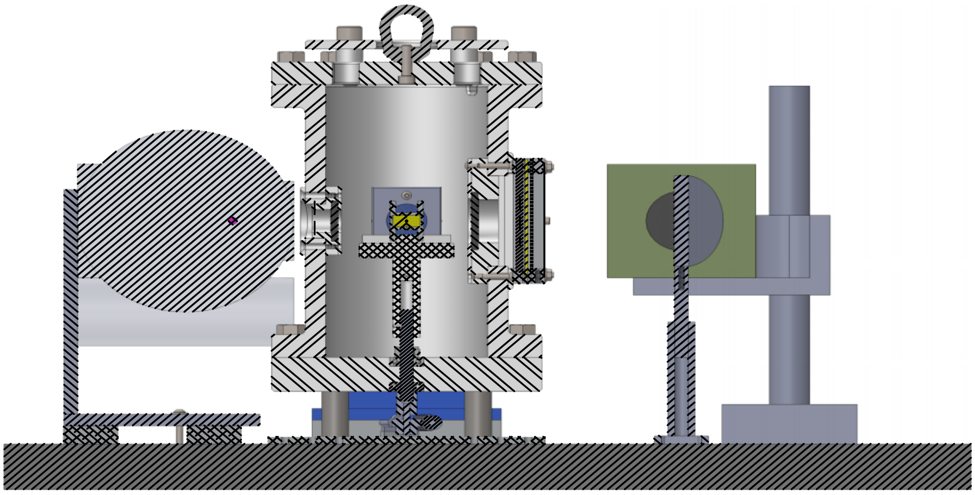

Figure 2. Schematic of x-ray experiment. From left: x-ray source, explosive chamber, scintillator, Turning mirror to camera.

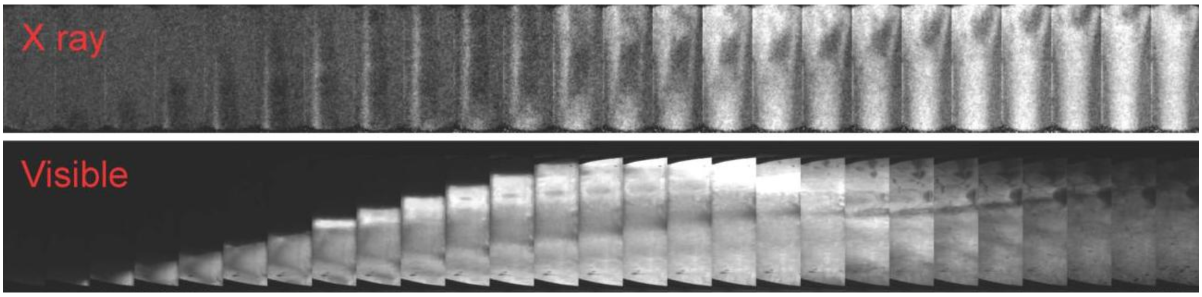

Figure 3. X-ray and visible light frames from videos taken during DDT event.

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