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Detonation diffraction in a circular arc geometry of the insensitive high explosive PBX 9502

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ABSTRACT

We describe the details of an unconfined insensitive high explosive (PBX 9502) circular arc section experiment, in which, after a transient period, a detonation sweeps around the arc with constant angular speed. The arc section is sufficiently wide that the flow along the centerline of the arc section remains two-dimensional. Data includes time-of-arrival diagnostics of the detonation along the centerline inner and outer arc surfaces, which is used to obtain the angular speed of the steadily rotating detonation. We also obtain the lead shock shape of the detonation as it sweeps around the arc. Reactive burn model simulations of the PBX 9502 arc experiment are then conducted to establish the structure of the detonation driving zone, i.e. the region enclosed between the detonation shock and flow sonic locus (in the frame of the steady rotating detonation). It is only the energy released in this zone which determines the speed at which the steady detonation sweeps around the arc. We show that the sonic flow locus of the detonation driving zone largely lies at the end of, or within, the fast reaction stage of the PBX 9502 detonation, with the largest section of the detonation driving zone lying close to the inner arc surface. We also demonstrate that the reactive burn model provides a good prediction of both the angular speed of the detonation wave and the curved detonation front shape.

1. Introduction

A detonation is a shock driven region of chemical reaction. The coupled shock-reaction zone complex can propagate at speeds of 5–8 km/s in solid, condensed-phase high explosives (HE), and generate shock pressures in the range of 10–40 GPa [1]. The minimum self-sustaining speed of a steady one-dimensional detonation is known as the Chapman–Jouguet (CJ) speed, wherein the flow at the end of the reaction zone is sonic in a frame of reference traveling with the detonation shock. The energy released between the detonation shock and sonic plane determines the Chapman–Jouguet speed for a given explosive. Divergently curved detonations run at speeds less than CJ, where the motion of the curved, steady propagating detonation is determined by the energy released within a structure known as the detonation driving zone, or DDZ [2,3]. The DDZ is the region bounded by the non-planar detonation shock and sonic flow locus, again defined in the frame of the steady traveling detonation shock. As recently reviewed by Short and Quirk [3], the structure of the DDZ is heavily influenced both by the explosive geometry and the properties of materials providing confinement of the HE. This includes the significant effect of detonation diffraction [4].

A two-dimensional circular arc of HE provides an ideal geometry for the study of a steadily propagating, diffracting detonation. The flow dynamics and DDZ structure of a detonation propagating in a circular arc has recently been studied computationally by Short et al. [5] using a reactive burn model approach. Short et al. [5] considered an ideal condensed-phase detonation model [6] where the reaction rate was pressure sensitive. They also considered a fixed radius of the inner arc surface, inside which was a low-impedance (weak) confinement material. Variations in the DDZ structure were then explored as a function of the arc thickness and the properties of the confiner material around the outer arc surface (either low-impedance or high-impedance (strong confinement) materials). For sufficiently thin arcs relative to the inner arc surface radius, the DDZ structure was found to extend across the arc thickness, and consequently the angular speed of the detonation sweeping around the arc was found to be influenced both by the outer arc confinement material properties and the arc thickness. Beyond a critical arc thickness, the angular speed is found to limit to a constant value independent of either further increases in the arc thickness or the type of confinement on the outer arc surface, confirming earlier results found by Short et al. [7] based on a Detonation Shock Dynamics (DSD) surface evolution analysis.

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Short et al. [5] found that this behavior was a consequence of the evolution of the DDZ structure. For weak confinement on the outer arc surface, the configuration studied in the current paper, beyond a critical arc thickness, the DDZ is found to detach from the outer arc surface with the flow being supersonic outside the DDZ region. At this point, the DDZ region consisted of a sonic locus which intersected the detonation shock both at the inner arc surface and at a fixed constant radial position internal to the outer arc surface. With the DDZ region now fixed in shape as the arc thickness increased further, and since it is only energy released in the DDZ that drives the detonation around the arc, the angular speed was found to not vary with increasing arc thickness.

For sufficiently thick arcs, the DDZ was found to consist of a small area near the inner arc surface, with most of the reaction in the arc configuration occurring in supersonic flow [5]. Consequently, the inner arc region is found to play a disproportionate role in the flow dynamics of a detonation in a thick arc [4,5]. An asymptotic study by Short et al. [7] based on a DSD surface evolution model lead to further insights on the dynamics that control the motion of a detonation in a circular arc configuration for thick arcs. The DSD surface was found to consist of a layer away from inner arc surface in which, to leading order, the normal surface speed was equal to the CJ speed, with surface curvature effects being weak. However, at the inner arc surface, a thin boundary layer structure was present where curvature and inner arc surface confinement effects became important. Solution of the boundary layer structure, and matching to the outer layer structure, determined the influence of both the detonation curvature in the inner arc region and the confinement properties on the inner arc surface on the angular speed of the detonation wave.

The circular arc configuration has been studied previously both in condensed-phase and gas-phase [8–11] explosive systems. Here we are concerned with condensed-phase systems. The speed of a detonation and its front shape in an unconfined circular arc of the insensitive high explosive PBX 9502 (95 wt% TATB (2,4,6-triamino-1,3,5-trinitrobenzene)/5 wt% Kel-F 800 (poly(chlorotrifluoroethylene-co-vinylidene fluoride))) have been experimentally measured and partially reported by Bdzil et al. [12]. The arc section extended 135 degrees, had an inner radius of 65 mm, an outer radius of 90 mm and was 200 mm wide (Figs. 1–3). The inner and outer arc surface circumferential distances were 153.2 and 212.1 mm. Based on a previous study of PBX 9502 in a slab geometry [13], where the head of a side rarefraction originating from the explosive edge was observed to propagate into the lead detonation shock at an angle of ≈ 15 degrees, the flow along the centerline of the arc should therefore remain two-dimensional given an arc width of 200 mm (Section 2). For the 212.1 mm outer arc surface circumferential distance, the edge rarefractions would need to propagate in from the sides at an angle of ≈ 25 degrees to destroy the two-dimensionality of the flow along the arc centerline, an angle significantly larger than that observed for PBX 9502 [13].

The angular speeds of detonation in circular arc sections of a polymer-bonded TATB explosive, confined on both the inner and outer arc surfaces either by PMMA (acrylic) or by steel, have been described by Lubyatinsky et al. [14]. The arcs were 60 mm wide and extended 180 degrees. The outer arc radius was 60 mm in all cases, while the inner radii considered were 30 mm, 40 mm and 50 mm, with corresponding inner arc surface circumferential distances of 94.2 mm, 125.7 mm and 157.1 mm and an outer arc surface circumferential distance of 188.5 mm. The speed of detonation propagation in 95 wt% TATB based explosive arcs confined by steel were reported by Zhao et al. [15]. Each arc had an inner radius of 70 mm and an outer radius of 100 mm. The arcs were 50 mm wide and extended either 60, 90 or 125 degrees (giving inner arc circumferential distances of 73.3 mm, 110.0 mm and 152.7 mm and

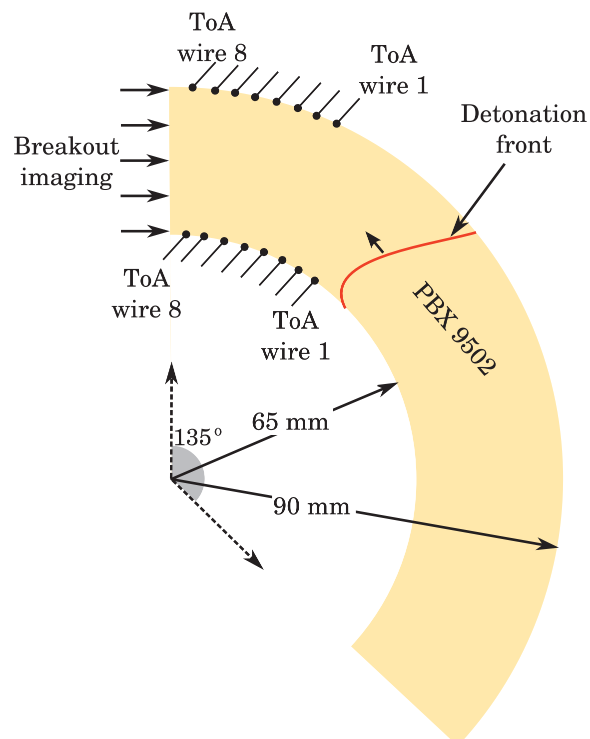

Fig. 1. Dimensions of the 2D plane section of the arc centerline. Also shown is a schematic representation of the positions of the ToA wires on the outer and inner arc surfaces.

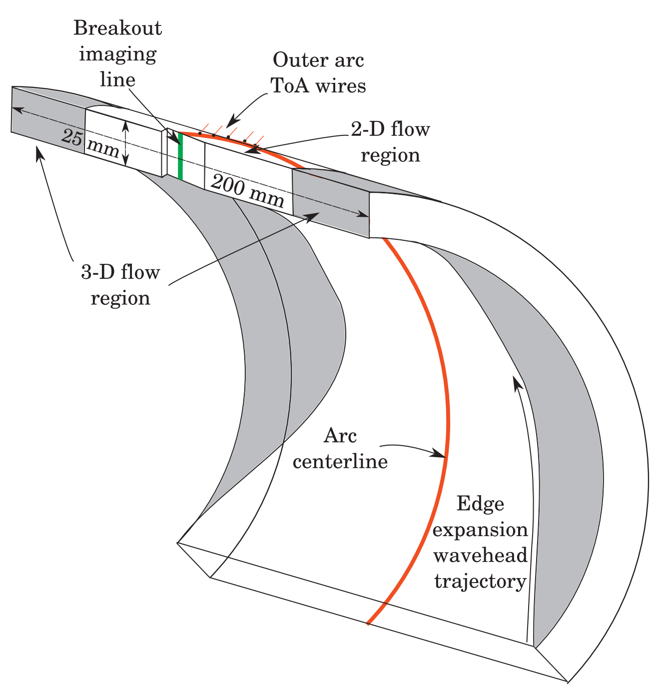

Fig. 2. A schematic of the 3D arc section showing the location of the surface used for imaging the detonation shape. Also shown are ToA wires along the centerline of the outer arc surface. A region of 3D flow propagates toward the arc centerline, but the dimensions of the arc section have been chosen such that the flow will remain two-dimensional in the central region of the arc, where the ToA and detonation front shape measurements are taken.