Propagation of Gaseous Detonations in High Aspect Ratio Planar Curved Channels

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1 Introduction

Propagation of gaseous detonations through a planar curved channel has practical engineering applications including studying fundamental combustion initiation, investigating failure mechanisms that prevent stable propagation of detonations, and aiding in the design of rotating detonation engines (RDE's). The lack of laboratory experiments on a scale relevant to an air breathing rotating detonation combustor provide the opportunity for this work to study how the radius of curvature, channel width, and detonation cell size of a specified propellant mixture interact at these scales. Studying the fundamental mechanisms that lead to detonation suppression in a curved section is critical to begin to apply this knowledge to laboratory scale and eventually fielded applications of detonation driven combustion technology.

Kudo et al. [1] and Nakayama et al. [2] studied the stabilization of oblique detonation waves in a rectangular bent tube. These experiments involved varying the inner radius of curvature while fixing the channel width. A stoichiometric ethylene-oxygen gas was used at various initial pressures, and presented high-speed chemiluminescence images of their work. The results were organized as stable, critical, or unstable propagation, defined by geometry-to-detonation cell size ratios. This categorization showed that as inner radii were reduced, the detonation wave velocity would decrease. A numerical examination of the same physical configurations was done by Sugiyama et al.[3], which provided a detailed examination of the local shock-reflection structures that influenced the previously described propagation modes.

Short et al. [4] numerically studied circular arcs of high explosives, describing the wave structure and angular speed of the detonation as functions of the radius of curvature and channel width. Short et al. [5] also simulated gaseous detonations through circular arcs of similar geometries, finding that the wave was unstable with high propagation velocities for small arc widths. For sufficiently large widths, a hydrodynamically stable detonation formed.

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Frolov et al. [6] numerically and experimentally studied stoichiometric propane-air detonations through U-Bent circular tubes, similar to a pulsed detonation engine application. This study showed that some configurations of the U-Bends were able to produce a shock-induced initiation, while others produced temporary velocity attenuation or complete decay.

Olson et al. [7] studied the geometric parameters that best supported stable fuel-air detonation, using a rectangular curved channel with three defined ratios between inner and outer radii for various channel geometries. Reactant mixtures were controlled using the equivalence ratio. This study was completed using hydrogen-air mixtures, outlining the relationship between detonation stability and channel geometry.

The work being presented here will expand on the work of Olson et al. [7] by fixing the ratio between the inner and outer radii to three values, fixing the outer radius to three values, and then controlling the reactant mixtures using the equivalence ratio. Adjusting these variables will help cover the parameter space aiding in defining the boundaries of stable propagation and furthering the study of the mechanisms that lead to suppression of a detonation wave through a curved geometry. These studies are critical to informing the design of combustion initiation and power generation systems as they get closer to becoming an application and not just a laboratory experiment.

2 Experimental Set Up/Expected Results

The test section is supplied with metered and known reactants via the implementation of an Andrus Burner, or a pre-mixed pre-detonator. A detonation is then initiated and propagates through one of the straight legs in the test section, shown in Figure 1. The detonation then enters the curved section of the test section where it is diffracted at the inner radius of the channel and reinforced through compression along the outer radius.

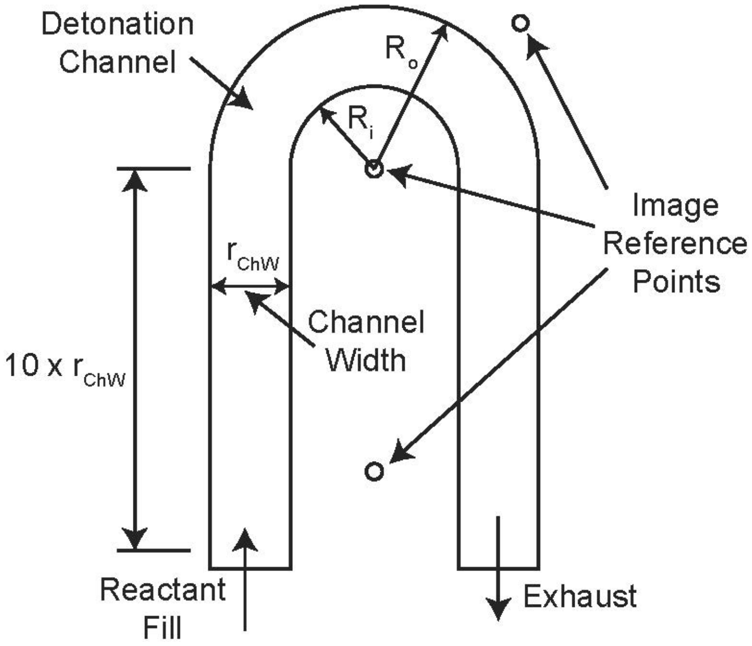

Figure 1: 2-Dimensional Test Section Schematic

Nine different test sections were tested, Table 1 contains the geometry of each configuration. Three outer radii were selected and fixed while the channel width, and ultimately the inner radii, were varied. An image of one of the installed test sections is shown in Figure 2.

Table 1: Compiled List of Test Section Geometry

Configuration Number	Channel OD	Channel ID	R = Ri/Ro
1	12	10.04	0.8367
2	12	9.3	0.7750
3	12	8.5	0.7083
4	18	15.06	0.8367
5	18	13.96	0.7756
6	18	12.74	0.7078
7	24	20.08	0.8367
8	24	18.6	0.7750
9	24	16.98	0.7075

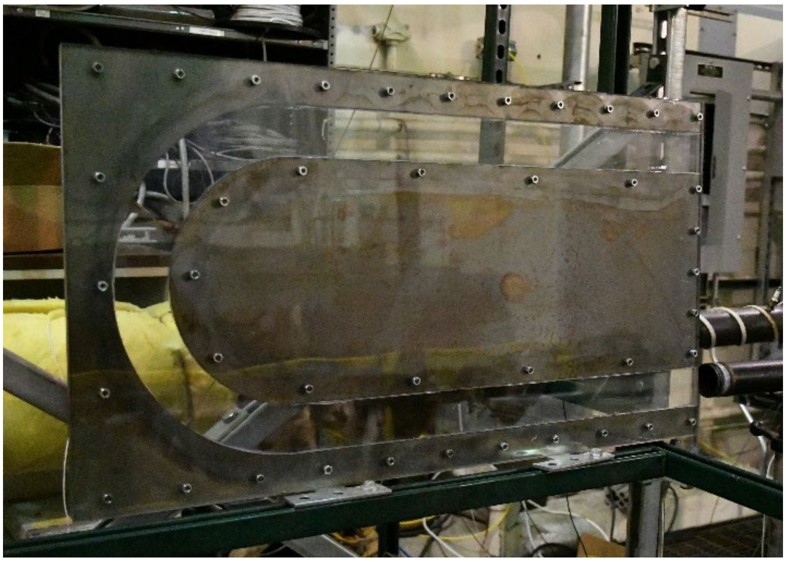

Figure 2: Test section installed

The use of an Andrus burner allows for different combinations of reactants to be used because of the burners variable gas flow ability. This provides the opportunity to control detonation cell size through the reactant combinations or the equivalence ratio. The test sequence begins by initiating air and fuel through a pair of thermal mass controllers, followed by the Andrus burner filling the test section and initiating detonation with a spark-plug at the exit of the burner flame arrestor upstream of the test section. Reactants for this work include gaseous hydrogen/air and gaseous ethylene/air detonated at atmospheric pressures. Detonation at atmospheric pressure was ensured through the low total reactant flow rates through the mass controllers and by leaving one leg of the test sections open to the atmosphere. The critical parameter ratio of inner radii to detonation cell size and its impact on stable propagation of detonation around a curved channel was explained by Nakayama et al. [2] The goal of this work is to provide structure for the necessary geometry and detonation cell sizes that promote stable wave propagation with a minimal drop in velocity or extinction of the wave.

Olson et al. [7] found that the most stable propagation of a detonation wave occurred when the test section had a large inner-to-outer radii ratio and the cell size of the reactant mixture was small. It was found that unstable detonations occurred at operating conditions near other test points that entered the curved test section as a detonation or test points that resulted in the detonation transitioning to deflagration in the curved test section.

High-speed chemiluminesence images of the detonation propagating through the curved test sections are the primary data collected during this experiment. A Phantom 711 using a 35mm or 24mm lens with an F-Stop of 1.4 and 2 respectively. Due to the size of the test sections and the exposure quality, video frame rate varied between 16,000 fps and 21,000 fps. The resolution of these captured images are a minimum 592x512, analyzed for outer and inner diameter position of the detonation wave.

3 Modes of Detonation Propagation

Prior work has shown that the propagation of a detonation wave through a curved channel is dependent on test section geometry and reactant mixture. The work done by Nakayama et al. [2] used a stoichiometric ethylene-oxygen mixture that was detonated through a test section that had a set outer radius and a varied inner radius. This particular experiment controlled the detonation cell size through its dependence on pressure. The work being presented here controls the cell size through the equivalence ratio of the reactant mixture, as all of tests are being conducted at atmospheric initial pressure conditions.

Three regimes of propagation; stable, critical, and unstable, were described by Nakayama et al. [2] A stable detonation propagation is shown below in Figure 3, which is a compilation of images into a 3x3 matrix. These images show the detonation wave progressing through one of the straight leg sections, entering into the curved test section where it maintains a geometrically consistent shape without diffracting or extinguishing along the inner radii.

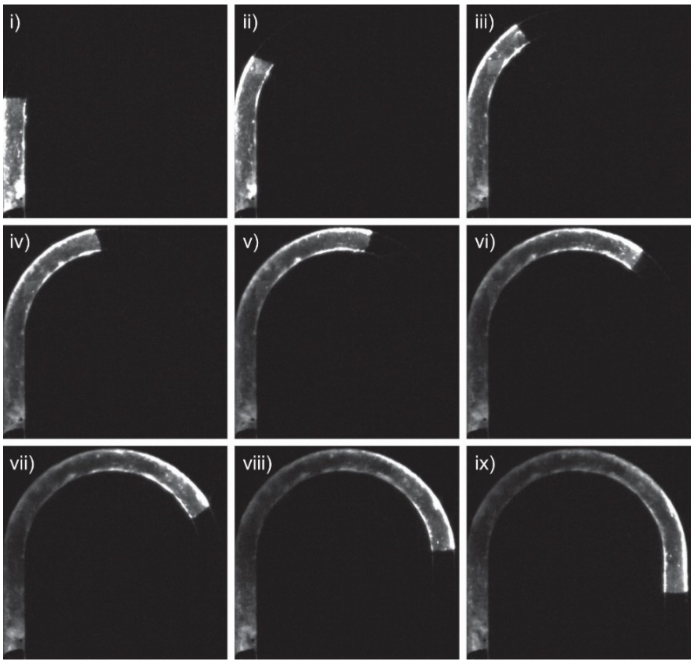

Figure 3: Stable Detonation Propagation - 3x3 Matrix of Individual Images [7]

Figure 4 shows an image of the wave fronts from a single test condition compiled into one picture. At the exit of the curve we notice the center of the wave front starts to distort, however the outer diameter and inner diameter location of the wave front are even.

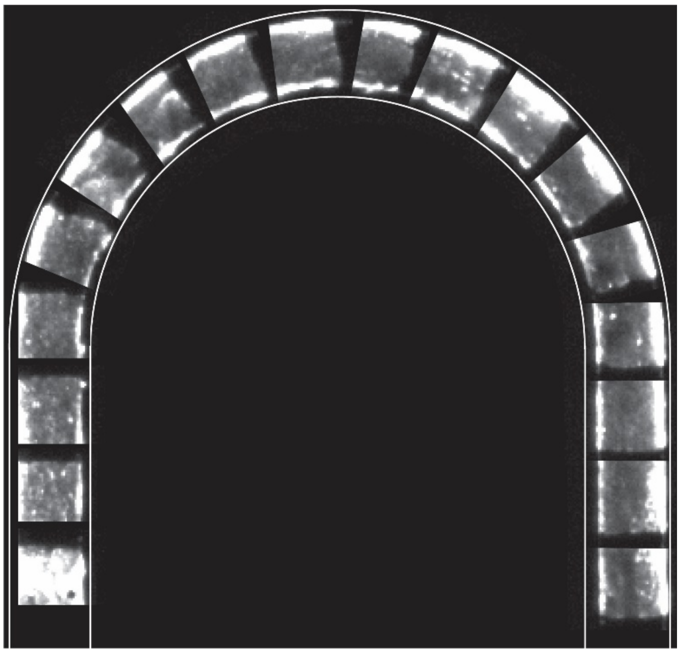

Figure 4: Compiled Images of Detonation Wave front [7]

The goal of the presented work is to outline the geometric requirements and detonation cell scales that promote a stable propagating detonation wave. This stable propagating wave is to have minimal velocity deficit and/or no extinction of the wave as it travels through the test section. Successful design of a detonation driven combustor is dependent on understanding how the detonation wave and the geometry of the combustor interact with one another.

References

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