Detonation Propagation over a Surface of Water in Oxyhydrogen Mixture

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1 Introduction

Detonation phenomena play a significant role in various engineering fields, including aerospace propulsion, industrial safety, and nuclear power plant safety. Despite its significance in various industrial applications, propagation of detonation waves over liquid surfaces is a largely unexplored phenomenon. During catastrophic incidents like the Fukushima Nuclear Power Plant Accident in 2011 [1], hydrogen detonation highlighted the risk of transition from deflagration to detonation (DDT). Since nuclear reactors use water as a coolant, understanding the interaction between detonation waves and water surfaces is essential in improving the safety protocols and risk assessment models.

Previous studies on detonation wave propagation have focused on gas-phase detonations either in confined or unconfined environments. While some research has considered the effects of a liquid boundary, the complexities introduced by liquid surfaces remain not fully understand [2-5]. Unlike solid surfaces, liquid surfaces can deform and cause additional effects such as splashing, vaporization, ripple effect, hydrodynamic instabilities, and shock reflection, all of which have the potential to change the behavior of detonation waves.

This study aims to investigate detonation propagation over a water surface in different fuel-oxygen ratios, including stoichiometric and non-stoichiometric mixtures, under controlled laboratory experiments. A custom-fabricated stainless-steel detonation channel is used to analyze key parameters such as the DDT run-up distance, detonation velocity, pressure variations, and visual observations of the flame behavior using a high-speed camera.

2 Theoretical Background

Combustion waves can be classified into deflagration or detonation based on their propagation mechanism. Deflagration is a subsonic combustion process that spreads via heat conduction and diffusion whereas detonation is a supersonic process triggered by shock waves and chemical reactions. The transition from deflagration to detonation is (DDT) influenced by many factors such as turbulence,

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confinement, and initial mixture pressure. The distance required for DDT to occur after ignition is called DDT run-up distance and it is a critical parameter in detonation dynamics research.

3 Experimental Setup

A stainless-steel detonation channel has been designed and manufactured to conduct experiments for investigating detonation propagation over water. The experimental setup consisted of three main sections: an ignition section, a test section, and a dump section. The ignition section contains obstacles with blockage ratio of 0.5 which promote turbulence and help reducing the DDT run-up distance. The test section is installed with a transparent acrylic window for visualization. It also includes a water layer to analyze detonation interactions with the liquid surface. The dump section is designed to safely dissipate the detonation energy. Overall, detonation waves propagate within a 40×40 mm cross-section, with a 20 mm water pool present only in the test section.

Experiments were conducted under three different conditions: a water-filled channel, a smooth channel with a metal block replacing the water, and an empty channel. Figure 1 shows the schematic diagram of the experimental setup. The detonation tube is equipped with multiple pressure sensors (PCB $2-11$). The triggering of the spark is controlled via an Arduino UNO circuit board after the detonation channel is filled with a fuel mixture. Each pressure sensor is amplified by an amplifier which sends data to the data acquisition system. High-speed Schlieren imaging has been used to capture the detonation wave dynamics at $290{,}000$ fps. The high-speed camera captures the area between PCB $5-7$. Multiple experiments have been conducted with the initial pressures of H_2-O_2 mixture, P_{ini} in the range of $20-86$ kPa and video image analysis has been done to calculate the detonation velocity.

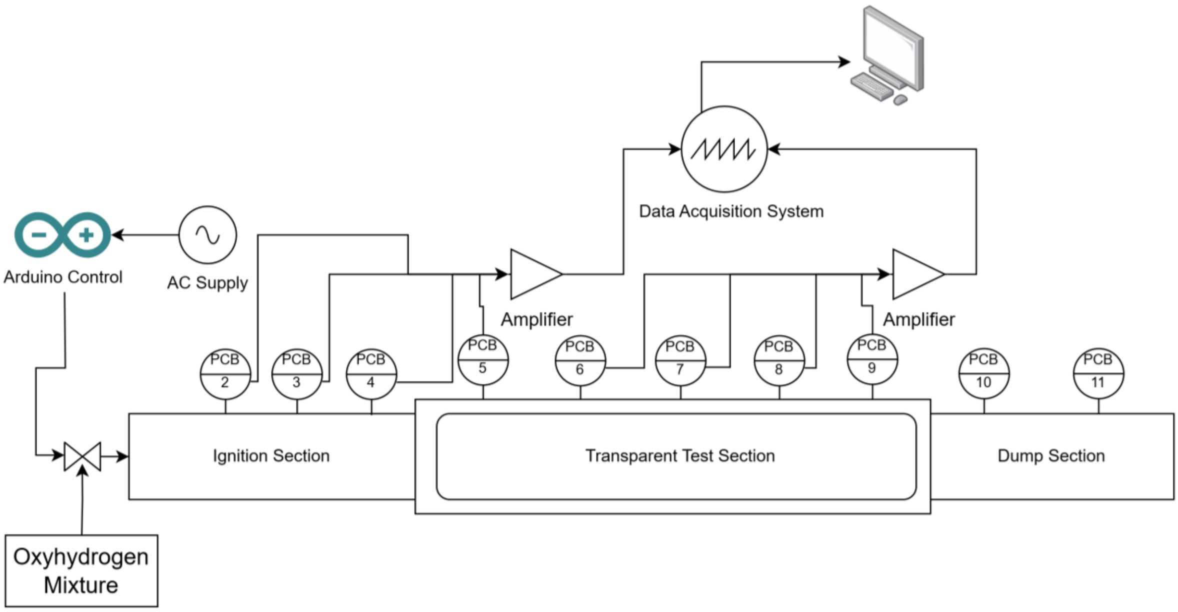

Figure 1: Schematic diagram of detonation channel

4 Results and Discussion

The high-speed video recordings revealed significant differences in detonation behavior under different experimental conditions. In Figure 2, the high-speed images of the test section at P_{ini} is 70.0 kPa and water presence is shown at the bottom of the test section. The image clearly shows the moment of DDT occurrence at $t = 79.31$ µs above the water surface and compression waves appear as distinct gradient bands in the water surface. At $t = 93.10$ µs the transition from deflagration to detonation occurs with a sudden intensification and flash in the wavefront. At $t = 124.14$ µs the wave moves forward and interacts with the water surface. The velocity of the detonation front is calculated by high-speed analysis, approximately 1864 m/sec where was the CJ velocity is approximately 2808 m/sec for this mixture. This reduction in velocity suggests that the presence of water inhibits detonation process which is likely due to energy loss from wave reflections and hydrodynamic instabilities.

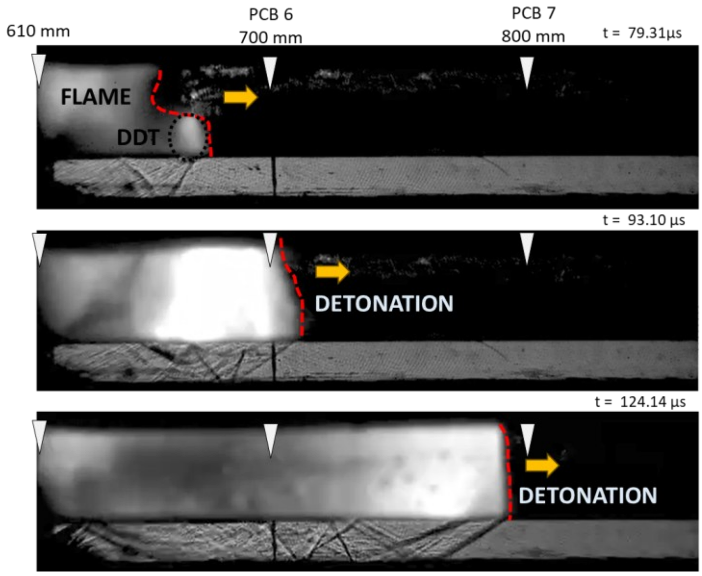

Figure 2: High-Speed Imaging Case: 72 ($P_{ini} = 70.0$ kPa, water)

Figure 3 shows the pressure measurement reading for the initial pressure of 70.0 kPa. It can be clearly seen that pressure at PCB 6 rises abruptly which confirms the occurrence of DDT. The sharp and sudden rises in pressure readings are consistent with the detonation phenomenon, however, PCB $7 - 9$ shows a drop in pressure readings which is due to the water interactions. This interaction causes damping of the detonation wave resulting in faster decay.

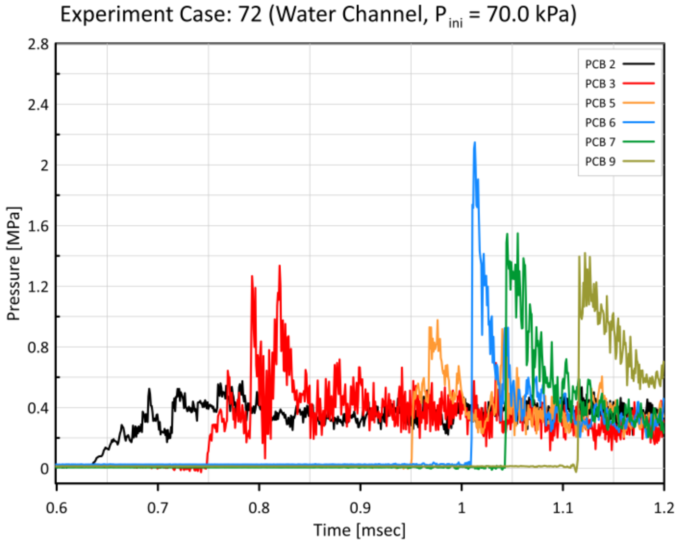

Figure 3: Pressure Fluctuations, Case: 72

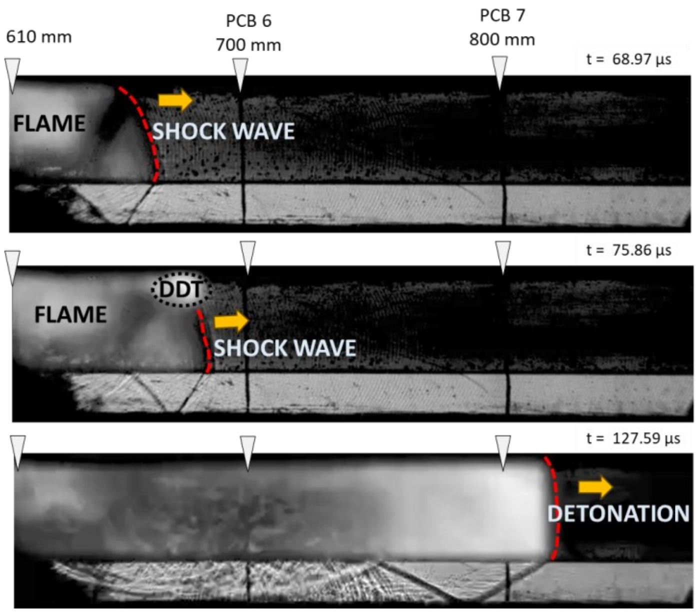

Figure 4: Video images of experiment 75 (P_{ini} = 50.0 kPa, water)

Figure 4 shows the high-speed images of the test section at P_{ini} is 50.0 kPa along with water at the bottom. At t = 68.97 μs it can be seen that a shock front moves forward and a t = 75.86 μs there is gradient intensification at the top of the test section indicating DDT occurrence, along with a reflected shock front in the water surface. At t = 127.59 μs detonation wave moves forward interacting with the water surface, where multiple ripples and reflected waves can be observed.

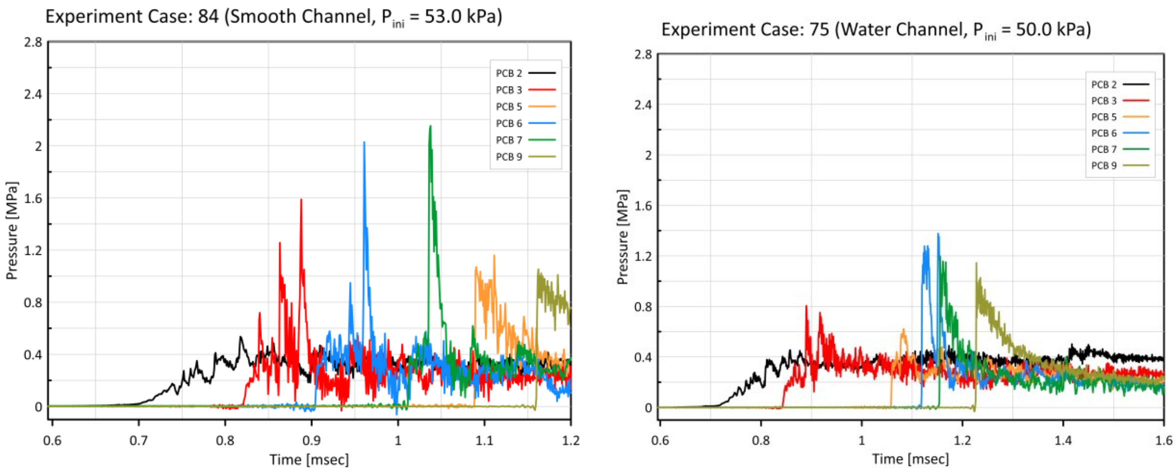

Figure 5: Pressure fluctuations (P_{ini} = 50.0 kPa): (a) Case: 84 Smooth Channel; (b) Case: 75 Water

Figure 5(a) – (b) shows the pressure fluctuations when the initial pressure (P_{ini}) of the fuel mixture is 50.0 kPa. Case 84 and Case 75 represent the test section with a metal block in place of water (referred to as a smooth channel) and the test section filled with water, respectively. It can be observed in Fig. 5(a) that the detonation phenomenon occurs somewhere near the location of PCB 5 as there is a sudden rise in the pressure peak whereas in Fig. 5(b) pressure fluctuation at PCB 5 is lower which can be due to the interaction of the wave with water. Figure 4 confirms the onset of DDT even when there is water present in the test section, however, the pressure fluctuations indicate damping of the detonation wave as it moves forward possibly due to energy transfer with the water surface.

Figure 6 compares the propagation velocities in different cases at different pressures and test section conditions. This velocity was determined by analyzing video images frame by frame. In the smooth channel cases, the propagation speed nearly reached the CJ velocity, confirming successful detonation. However, when water was present in the test section, the propagation speed was lower, which, under certain conditions, prevented the transition to detonation. At an initial pressure of 30 kPa, detonation did not occur in any case, and the propagation speeds were similar. However, at 40 and 50 kPa, detonation was observed only in the smooth test section while the presence of water suppressed detonation.

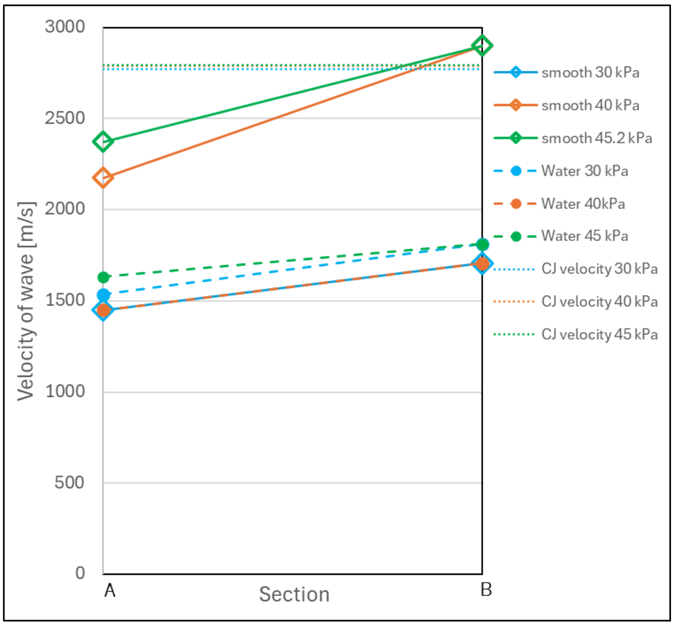

Figure 6: Propagation velocity of in different cases

5 Conclusion

This study provides new insights into the interaction between detonation waves and water surface. The experimental results confirm that the presence of water increases the DDT run-up distance, thereby delaying the detonation initiation process. The high-speed image analysis also confirms that DDT process can occur from both the top and bottom of the channel which means multiple initiation points are possible in confined geometries.

We are currently in the middle of experimental investigations and data analysis. Furthermore, we are going to continue to investigate additional cases, including varying fuel-oxygen ratios and different initial pressures. The results of this research contribute to improving safety measures in nuclear power plants, and detonation dynamics.

References

[1] International Atomic Energy Agency (IAEA). (2015). The Fukushima Daiichi accident: Report by the Director General. Vienna, Austria: IAEA.

[2] A. A. Borisov, S. M. Kogarko, and A. V. Lyubimov, "Sliding of Detonation and Shock Waves over Liquid Surfaces," Combustion, Explosion, and Shock Waves, vol. 1, pp. 19–23, 1965.

[3] F. Holt, "Shock Wave Interactions with the Ocean Surface," 1982.

[4] A. Teodorczyk and J. E. Shepherd, "Interaction of a Shock Wave with a Water Layer," Explosion Dynamics Laboratory Report FM2012.002, 2012 (revised in 2015).

[5] V. Rodriguez, G. Jourdan, A. Marty, A. Allou, and J.-D. Parisse, "Interaction of a Planar Shock Wave with a Water Surface," 31st International Symposium on Shock Waves, vol. 1, pp. 429–434, 2019.