Detonation wave attenuation by a cylinder and the subsequent re-initiation régimes

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1 Introduction

Detonation waves exhibit a complex cellular structure involving compressible turbulence interactions within the reaction zone. Recent studies have suggested that the traditional assumption of an inviscid flow may be inaccurate, as mechanisms generating turbulent mixing within the reaction zone may significantly affect the bulk reaction rates within the detonation structure. [1]

Unfortunately, the detonation structure is highly stochastic and the flowfields are not reproducible from experiment to experiment. For this reason, the different physical phenomena occurring within the structure cannot be studied in detail. The present study attempts to provide a canonical problem offering the same complexity as the detonation problem, but for which the flow field is much more reproducible than in cellular detonations. Such a flow field can then serve for detailed comparison with numerical results, and can serve to isolate modelling shortcomings.

The flow field suggested is the interaction of detonation waves with an opening between a cylinder and flat wall. Preliminary numerical results have been obtained by Radulescu and Maxwell [2], which show the richness of the problem, and the well-posedness of the initial strong perturbation by the cylinders, that eventually sets a reproducible sequence of phenomena. In the present study, detailed experimental visualization experiments are performed in order to shed light into the complex wave interactions and hydrodynamic instabilities and preliminary numerical analyses have also been carried out, for a specific case, to gauge our current ability to predict numerically.

2 Experimental setup

The experiments were performed in a rectangular channel with a cross section of 19.1 mm by 203.2 mm. The tube is 3.4 m long and consists of three sections of equal length. The first section served as a reactive driver, utilizing an oxi-acetylene detonation driver. The second and third sections were the test or ”driven” sections, with the third section having an unobstructed field of view of the entire channel. A half cylinder, 305 mm in diameter was placed in the last section. All experiments were performed in a stoichiometric methane-oxygen mixture, known for its highly turbulent detonation structure. All pressure traces were recorded by pressure transducers positioned along the top wall of the shock tube.

Schlieren visualization was achieved with a novel technique of utilizing a PIV camera, delivering two frames with an interframe time delay of less than a microsecond, coupled with a two-spark light source (PalFlash 501).

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This setup permitted excellent time resolution and the capability to conduct detailed velocimetry on all features observed in the flow field (shock waves, contact surfaces, unreacted pockets, etc.). Note that each experimentally obtained image, shown below, is considered as a "single frame" with two pictures (top and bottom) seperated by a time difference of 11 microseconds; the bottom picture is taken 11 microseconds after the top picture.

Preliminary experiments were also carried out to study the effects of channel roughness on a fully decoupled detonation wave behind the half-cylinder obstacle. To simulate the channel roughness in our experiments, a thin plate with two dimensional ridges, or "rectangular cuboid teeth", of length 428.6 mm, total height 10 mm and width 19.1 mm was designed to lie along the bottom of the channel. Each rectangular tooth has a length and height of 3.2 mm each and the gap between each tooth is 3.2 mm as well. This rough plate is manufactured from the same material as the obstacle to ensure consistency. The rough plate was placed at the foot the half-cylinder to ensure that the diffracting detonation wave immediately encounters the rough plate.

3 Experimental results

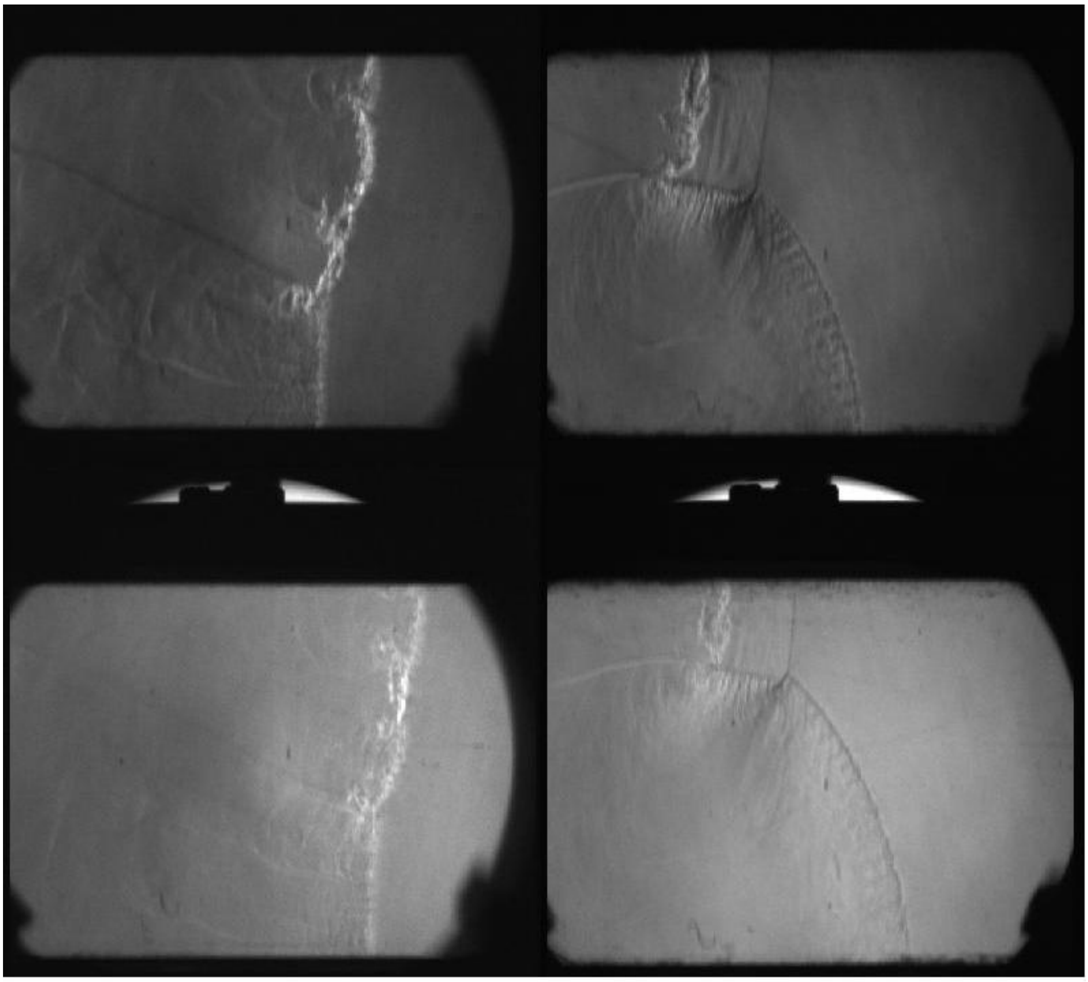
Since the mixture sensitivity of the driven gas (stoichiometric methane-oxygen mixture) is strongly dependent on its initial pressure, the initial pressures studied in our experiments were varied from 5 kPa to 16 kPa; in decreasing order of initial pressures of the driven mixture, the five cases studied are presented below. The schlieren images, shown below, were taken at different length scales downstream with respect to the half-cylinder obstacle. The approximate distance, in terms of multiples of obstacle diameter, is quoted below for each case.

a) **Case 1 - Direct Transmission (Supercritical case)**: Based on preliminary tests, this case corresponds to an initial pressure of 17.6 kPa and 300K for the driven section. Figure 1(a), which was captured between 1 and 2 diameters downstream of the cylinder, shows distinctly large cellular pattern along the shock front, with the reaction zone not fully de-coupled from the shock front. Also observed, closer to the bottom wall, are new cell formations and at the junction between the larger course cells and the smaller fine cells is a reflected wave travelling transversely upwards towards the top wall.

b) **Case 2 - Re-initiation along Mach stem and Transverse Wave (Critical case)**: This case corresponds to an initial pressure of 11.9 kPa and 300K for the driven section. Figure 1(b), which was captured between 1 and 2 diameters downstream of the cylinder, clearly shows re-initiation of the Mach stem and the transverse wave because of the: distinct "ripple pattern" trailing behind both waves; new triple points formation; no tongue of unburnt gases behind the mach and transverse front. Also noticeable is the marked difference in appearance between the Mach stem and the incident shock front (along top wall) which clearly appears to be de-coupled from its reaction zone. We notice the transverse wave to be re-initiated into a detonation wave, or "super detonation wave", propagating upwards and burning the shocked unburnt gases trapped between the incident shock front and the trailing reaction zone.

c) **Case 3 - Transition from Subcritical (Case 4) to Critical case (Case2)**: Based on preliminary tests, this case corresponds to an initial pressure of 10.3 kPa and 300K for the driven section. Figure 2(a), which was taken between between 1 and 2 diameters downstream of the center of the cylinder, shows a de-coupled incident shock front and reaction zone along the top wall. We also see that the reaction zone, behind the Mach stem, has an induction length relatively shorter than the induction length between the incident shock front and its reaction zone. This is considered as a "transitional case" because: the reaction zone is decoupled from the incident shock, along the top wall; occasionally, there is no re-initiation into a detonation wave, characterized by no new cellular formation, along any shock front. However, from Figure 2(a) the induction length of the Mach stem, along the bottom wall, for this case is relatively shorter as compared to case 4; in case 4 we notice this induction length growing with time whilst here it appears to trail relatively closely to its respective shock front.

d) **Case 4 - Full decoupling of diffracting Detonation Wave (Subcritical case)**: This case corresponds to an initial pressure of 5.5 kPa and 300K for the driven section and is shown in both Figure 2(b) and Figure 3; Figure 3 show the evolution of a fully decoupled, or "failed", detonation wave between 1 and 2 diameters away from the obstacle. In Figure 3(a), the slip line curves forward forming a wall jet near the bottom wall, which eventually disappears as the triple point continues to evolve; the wall jet feature was explained in [3]. In Figure 3(b) a new triple point, formed due to the collision of the reflected wave with the top



(a) (b)

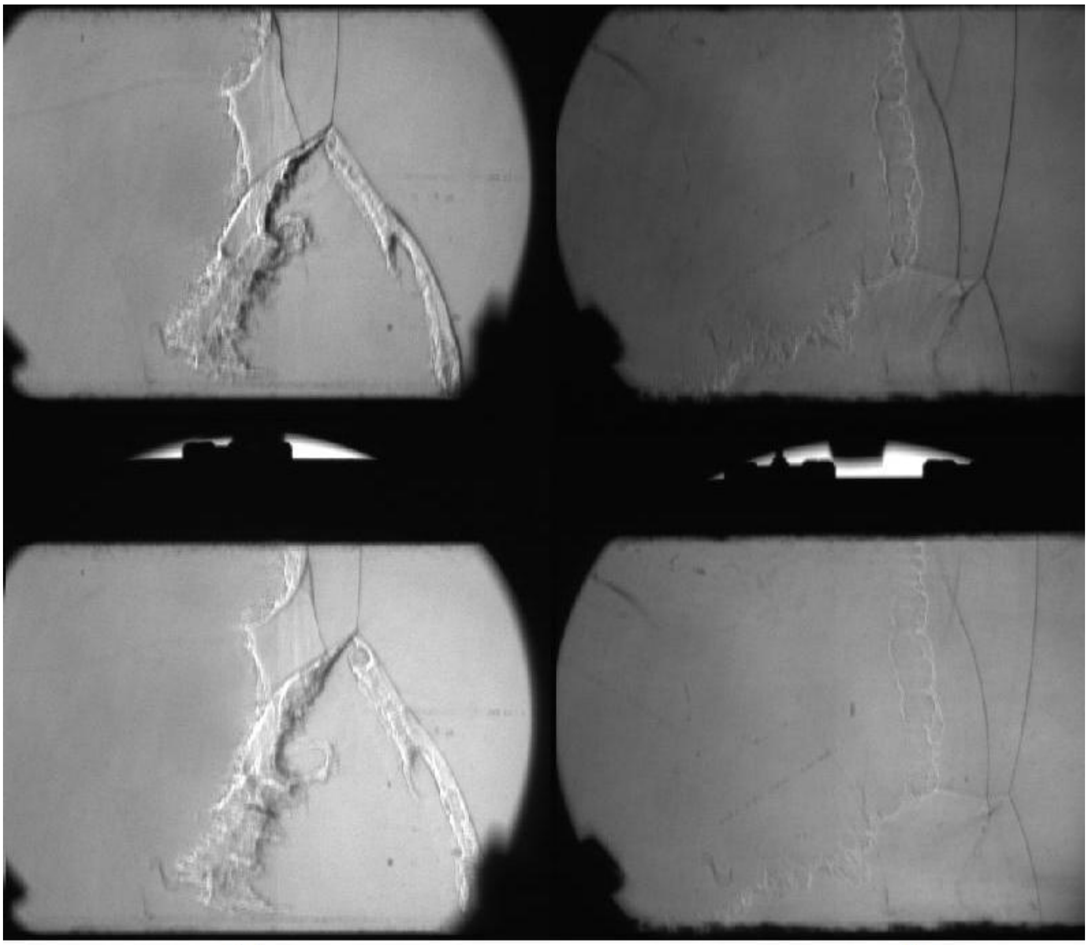
Figure 1: Complex wave structures of a detonation wave diffraction, behind the half-cylinder obstacle, for: (a) Case 1(17.6 kPa); (b) Case 2(11.9 kPa)

wall, progresses downwards and right. Another interesting phenomena observed in this figure is the Kelvin-Helmholtz instability shown forming along the slip line, lengthening and weakening as time progresses.

e) **Case 5 - Effect of Surface Roughness on Re-initiation**: As mentioned before, the effect surface roughness has on an attenuated detonation wave behind the cylinder was studied at the preliminary level. This case corresponds to the same initial conditions used in the subcritical case i.e case 4. Figure 5, showcases the flow field of a fully decoupled detonation wave over the rough plate; these images were captured roughly within one to two diameters from the obstacle. Figure 5(a) shows the attenuated wave propagating along the rough surface. A Mach reflection is seen forming in front of the incident shock wave at the bottom wall. Along the rough surface, the induction zone length was found to be smaller than at any other point in the wave structure. Figure 5(b) shows the wave approaching the end of the plate with a small channel of burnt gas sitting above the surface, trailing the Mach shock. Lastly, Figure 5(c) shows the wave at the end of the plate. Here, a vortex of burnt and unburnt gases is found within the Mach reflection.

4 Numerical results

The numerical simulations assume inviscid, non-heat conducting reactive gases undergoing a single Arrhenius step chemical reaction. The numerical simulation technique, involving an adaptive grid refinement technique, is



(a) (b)

Figure 2: Complex wave structures of a detonation wave diffraction, behind the half-cylinder obstacle, for: (a) Case 3(10.3 kPa),(b) Case 4(5.5 kPa)

described in detail elsewhere [2]. In order to simulate the methane-oxygen mixture, the parameters obtained in Ref. [1] have been used; the heat release Q and the activation energy E_a, normalized p_0/ρ_0, were respectively 43 and 63.7, where p_0 is the initial pressure and ρ_0 is the initial density. The isentropic exponent was $\gamma = 1.24$. For the methane mixture investigated, the chemical reaction length of the ZND detonation was $\delta = 9mm$ [1], hence the simulations were set such that the channel dimensions corresponded to 24δ. The simulations were initialized using the ZND structure, placed upstream of the cylinder. The maximum resolution used corresponds to 64 grid points per induction length δ. Only priliminary numerical results for case 5 are provided here.

The evolution of the flow field obtained is shown in Figure 6 at successive time steps. The successive plots illustrate the flow density field evolution.

5 Discussion

For case 1 to case 3, at present no preliminary numerical computations were carried out. However, the experimentally obtained schlieren images look very promising, due to its richness in information, thereby setting a benchmark for future numerical analyses using reactive flow analyses.

As mentioned earlier, the highly stochastic gas dynamic behaviour of detonation waves poses an interesting challenge in reproducing the same results for a given set of initial conditions. While this problem was overcomed for cases 2 and 4, cases 1 and 3 however are still, strictly speaking, at present not entirely reproducible and hence the

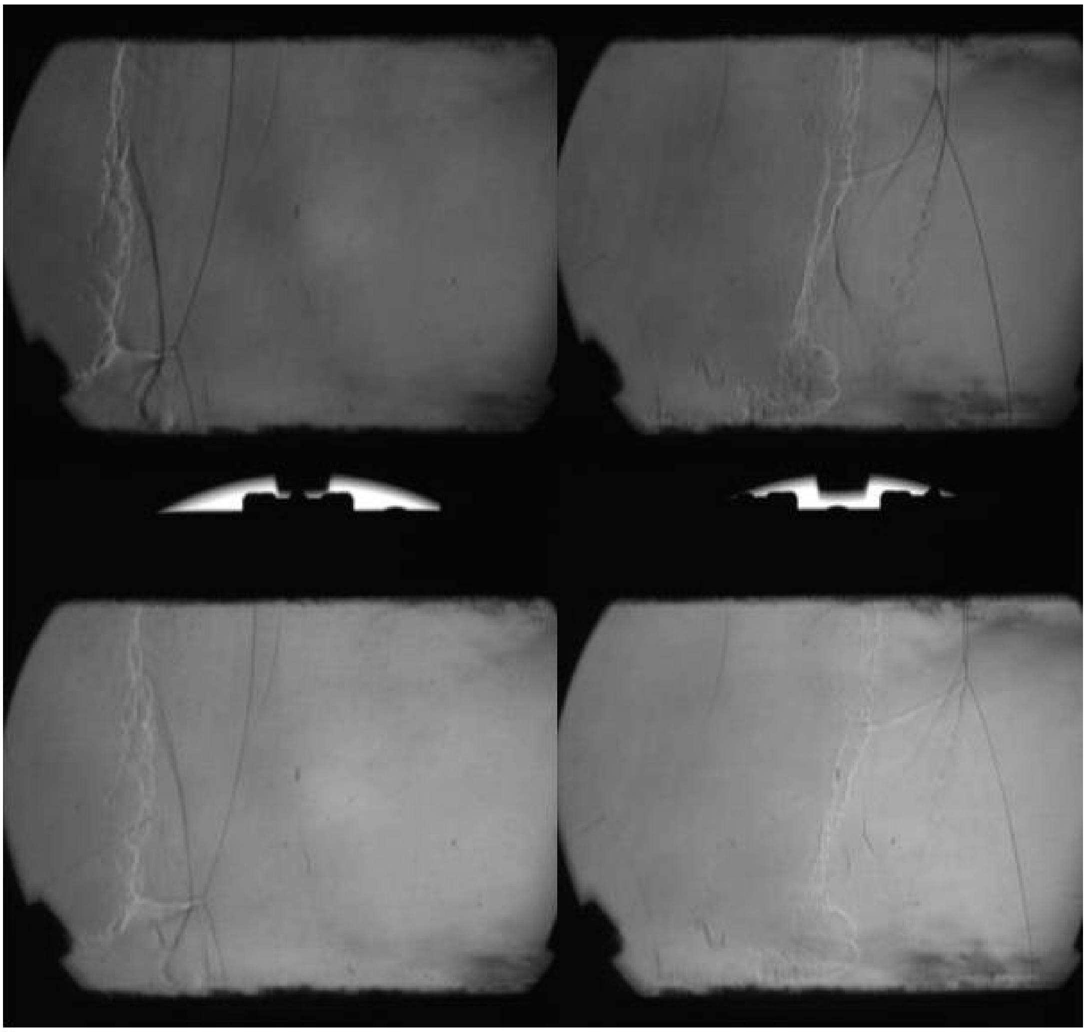
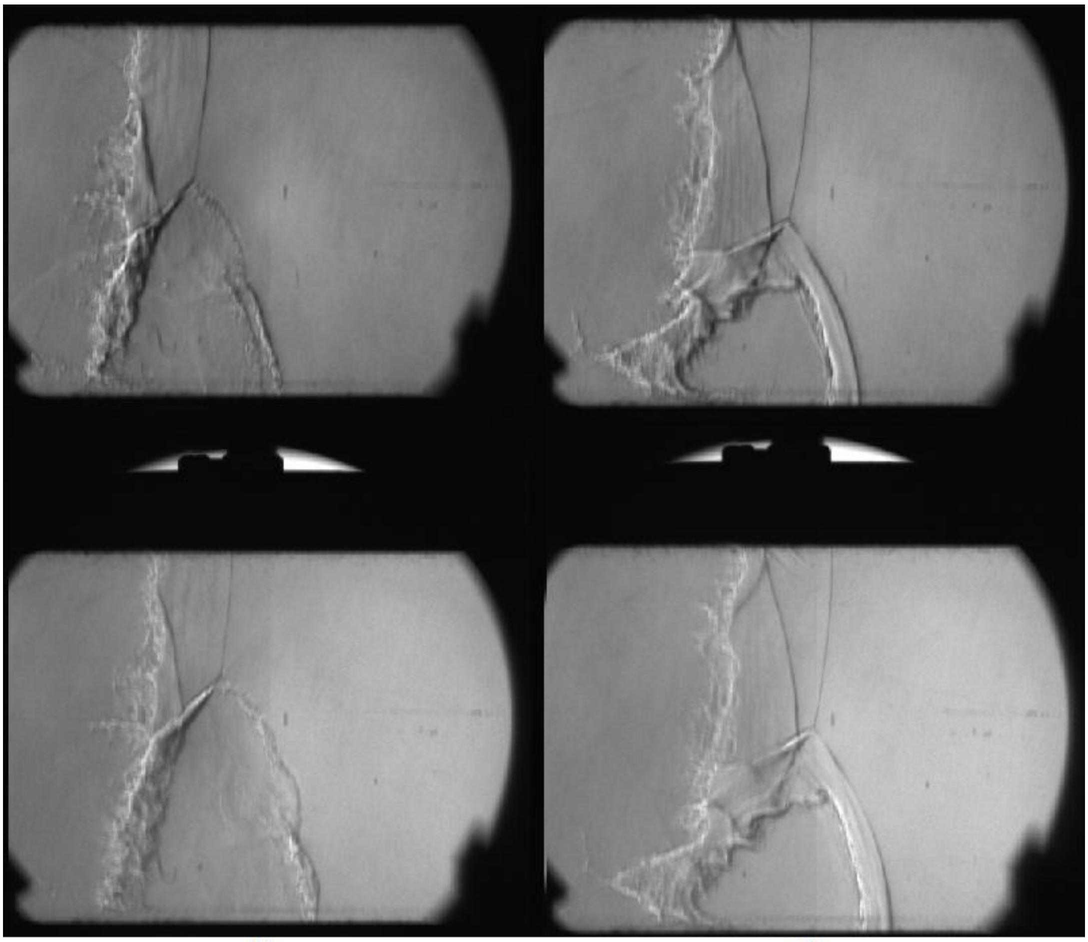


Figure 3: A fully decoupled detonation wave showing the forward jet and KH instability for Case 4(5.5 kPa)

initial conditions presented here are only preliminary; they are subject to change. Citing case 3 as an example to demonstrate this point, as illustrated in Figure 4(a) and Figure 4(b), both tests were carried out at the same intial conditions and both were captured at exactly the same distance from the half-cylinder. Despite this, Figure 4(a) shows re-ignition into detonation only along the Mach stem because of the: new cells being formed, clearly, along the Mach stem; very small induction length, which is similar to re-initiated detonation waves, as shown in Figure 1(a). Figure 4(b) on the other hand does not show any re-ignition as pointed out in the previous section. Since cases 2 and 4 are fully reproducible, it is speculated that additional tests, at different initial pressures, are required to obtain reproducible results for cases 1 and 3. Furthermore, due to the transitional nature of case 3, more tests are needed to possibly bifurcate case 3 into two sub-cases - (i) where there is re-ignition into detonation wave only along the Mach stem and;(ii) were there is no re-initiation for the same length scale.

For case 4, if we compare the experimental data with the numerical simulations, evidence appears identifying variation between the numerical simulation and its experimental counterpart: in the numerical simulation, the forward jet continues to grow while it is absent in the experimental results and; the numerical simulation shows no sign of the Kelvin-Helmholtz instability along the slip line. At present, this can only be attributed to the numerical resolution adopted in our non-reactive Euler model. Due to the relatively low resolution, the induced artificial numerical viscosity appears to dampen out the KH instability in the numerics. However, suprisingly, the same numercially induced viscosity does not have any dissipational effects on the forward jet whereas in



(a) (b)

Figure 4: Highly stochastic gas dynamic behaviour of detonation waves diffracting behind a half-cylinder obstacle for Case 3(10.3 kPa)

our experiments the forward jet dissipates faster. Thus, increasing the numerical resolution may yield the KH instability but could also potentially eliminate any presence of a forward jet along the bottom wall.

For case 5, our premilinary studies on evaluating the role of surface roughness on the ignition process by use of a ribbed plate, indicate that local hotspots are formed due to the presence of multiple wave reflections within the grooves between each tooth. These wave reflections promoted faster burning rates along the surface possibly due localized hotspots. The rapidly ignited pockets of gas expanded into the flow above the plate inducing turbulent mixing with unburned gases above. The mixing of these gases led to the formation of a large, expanding vortex trailing the Mach shock, which may lead to shock strengthening and detonation re-initiation. Further investigations are required to identify the validity of this theory. Additional details of the analyses conducted can be found in [4].

6 Conclusions

The experimentally obtained schlieren images for the case 1 through 3 shed light on the vast complexity of the gas dynamic behaviour of the diffraction of a detonation wave behind a half cylinder in a stoichiometric mixture of methane-oxygen. These new cases show very interesting and distinct features, one of which is the re-ignition into a detonation wave along the Mach stem and transverse wave. Thus, these results can be used as a stepping stone for advanced numerical analyses using reactive flow models.

For case 4, the comparison between the experiments and numerics have shown excellent agreement, with the

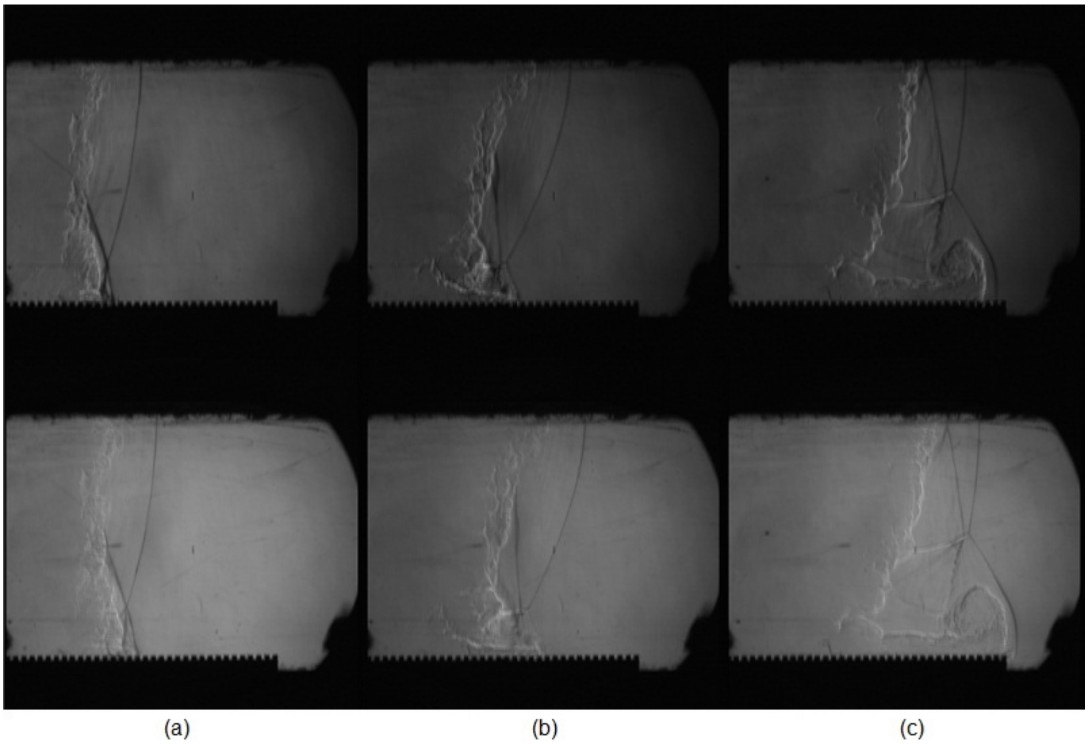


Figure 5: A fully decoupled detonation wave travelling over the rough plate for Case 5(5.5 kPa)

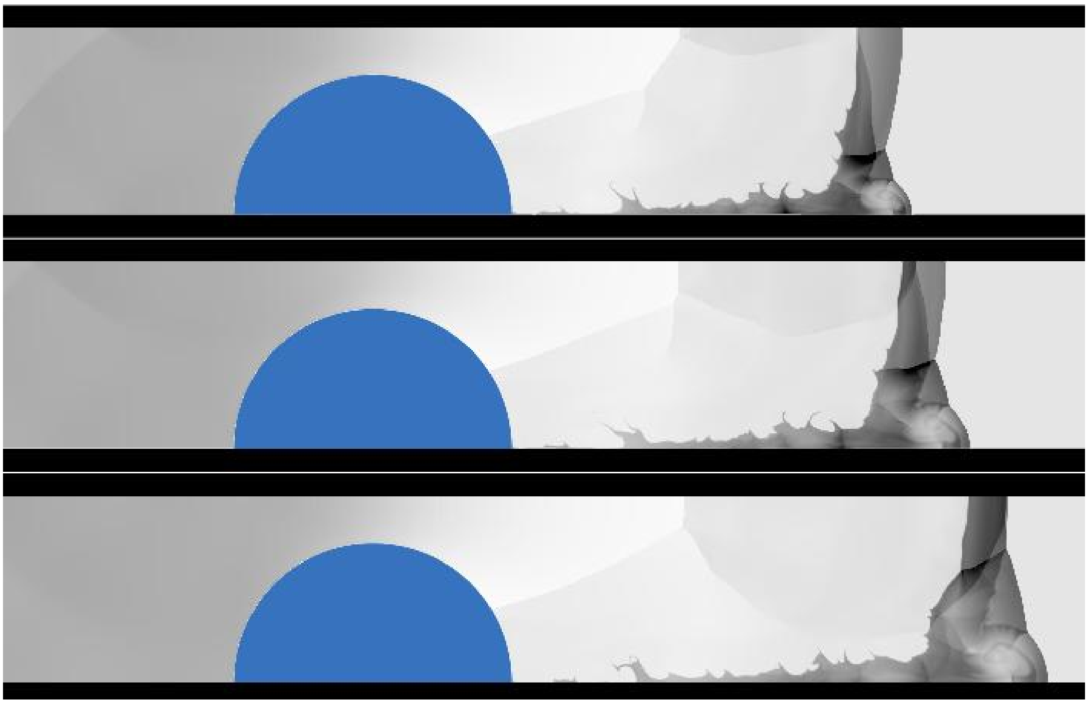


Figure 6: Evolution of the density field obtained numerically

exception of the wall jet formed behind the Mach shock and the Kelvin-Helmholtz instability at the slip line. In the experiments, the wall jet appears to be much weaker, and can no longer be observed immediately after its formation. It appears that this feature, along with the Kelvin-Helmholtz instability along the shear layers, is the missing physics in the numerical calculations.

Finally for case 5, using the same initial conditions as case 4, rapid ignition of pockets of gas behind the Mach stem occured along the rough bottom surface while it did not occur along the smooth surface, suggesting that surface roughness may aid in the re-ignition of the decoupled detonation. This is based on our preliminary studies and a more detailed investigation is required.

Acknowledgements

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References

[1] M. I. Radulescu, G. J. Sharpe, C. K. Law, and J. H. S. Lee, “The hydrodynamic structure of unstable cellular detonations,” *Journal of Fluid Mechanics*, vol. 580, pp. 31–81, 2007.

[2] M. I. Radulescu and B. M. Maxwell, “The mechanism of detonation attenuation by a porous medium and its subsequent re-initiation,” *Journal of Fluid Mechanics*, vol. 667, pp. 96–134, 2011.

[3] M. I. Radulescu, A. Papi, J. J. Quirk, P. Mach, and B. M. Maxwell, “The origin of shock bifurcations in cellular detonations,” 22nd International Colloquium on the Dynamics of Explosions and Reactive Systems, Minsk, Belarus, p. 4, July 27-31 2009.

[4] G. C. Maines, “Detonation re-initiation in the wake of a cylinder,” Bachelor of Applied Science (B.A.Sc) degree thesis, Mechanical Engineering, University of Ottawa, p. 4, May 2011.