# Structure of High Speed Turbulent Deflagrations

**Guillaume Simard[2], Matei I. Radulescu[1], Jean-Sebastien Grondin[2], John H.S. Lee[2],**

[1]Department of Mechanical Engineering, University of Ottawa, Ottawa, K1N6N5, Canada

[2]Department of Mechanical Engineering, McGill University, Montreal, H2V3W1, Canada

## 1 Introduction

Previous studies by Zhu, Chao and Lee indicated that upon reflection of a CJ detonation from a perforated plate, the detonation wave is quenched, and ignition of the mixture downstream occurs from the transmitted combustion products through the perforated plate [1]. A weak shock is also generated downstream driven by the transmitted products across the plate. Hence a high speed turbulent deflagration is generated which is observed to propagate at approximately the sound speed of the products into the unreacted mixture. It has been observed that depending on the sensitivity of the mixture (e.g., initial pressure, mixture composition) the deflagration either undergoes transition back to detonation or decays subsequently with complete decoupling of the shock from the reaction zone.

Typically, in mixtures for which the cellular structure of the detonations is very regular (we shall define this as a stable detonation), the transition is observed to occur either in the immediate vicinity of the perforated plate or decay with the complete decoupling of the precursor shock from the reaction zone. However, in mixtures for which the detonation's structure is very irregular (we shall define this as unstable detonation), the turbulent deflagration is observed to be able to maintain a more or less constant propagation speed for many tube diameters prior to transition back to detonation. When transition occurs near the plate, it is reasonable to assume that the turbulent characteristics of the flow through the plate to have an important influence on the transition processes. However, when transition occurs far away from the plate the influence of the initial turbulence is expected to be minimal. The basic question as to what mechanisms are responsible for maintaining the high speed propagation of the "metastable deflagration" and the eventual onset of detonation in these unstable mixtures is not clear. The present paper reports results of an investigation using high speed schlieren photography of the structure of these metastable deflagrations and the subsequent onset of detonation processes. For contrasting the difference in the mechanisms, the experiments are performed in mixtures with both stable (regular cellular structure) and unstable (irregular cellular structure) detonations.

## 2 Experimental details

The experiments were conducted in a rectangular channel, 1.1m in length, 50mm in width and 25mm in thickness. The perforated plate, situated approximately in the middle of the channel, had 18 equally spaced 5mm diameter holes, yielding an area blockage ratio of 70%. The mixtures investigated were $C_3H_8+5O_2$ and $C_2H_2+2.5O_2+70\%Ar$. These mixtures have similar detonation cell sizes at the same initial pressure, but significantly different cell regularities and reaction rate sensitivities to hydrodynamic fluctuations, the former being significantly more unstable[2].

**Correspondence to: matei@uottawa.ca** 

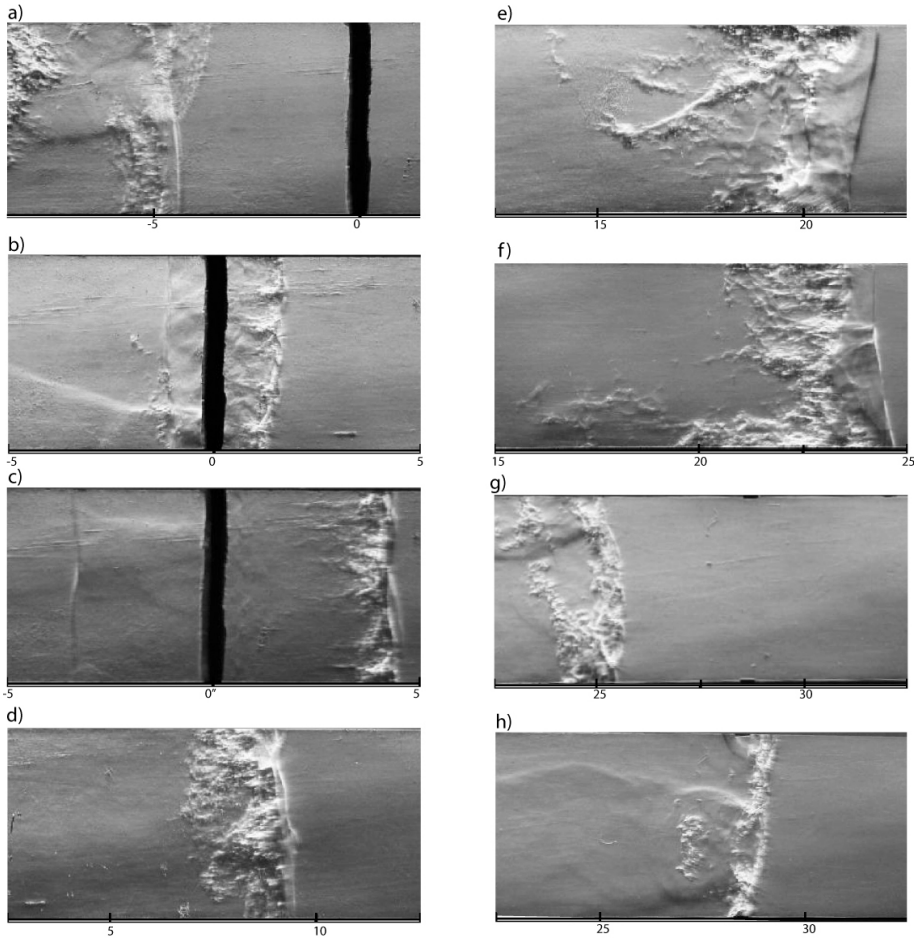


Fig. 1. Photographs illustrating the turbulent deflagration obtained after the interaction of a $C_3H_8$+$50_2$ detonation with a perforated plate, $p_o$ = 4 kPa; ruler shows distance from plate in centimetres.

In the experiments, a self-sustained detonation was initiated before the perforated plate by means of a powerful ignition by discharging a capacitor bank. Pressure transducers upstream and downstream of the plate were used to record the pressure and determine the wave speed. A conventional *Z* configuration was used for the schlieren visualization. Single frame photographs recorded digitally used a sub-microsecond spark unit as light source.

# 3 Results

Fig. 1 shows the propagation of an unstable single-head detonation through the perforated plate in propane-oxygen. The photographs are taken from different experiments, but it was found that they are quite reproducible in their global features, permitting a global reconstruction of the events. Fig. 1a shows a single headed detonation upstream of the perforated plate. The subsequent photographs illustrate the transmission through the plate and the ensuing turbulent deflagration wave downstream. Fig. 1b to 1f show the progressive broadening of the turbulent reaction zone with the precursor shock separating clearly from the reaction zone in Fig. 1e and 1f, at approximately 25 cm downstream of the plate, which is equivalent to 50 hole diameters. However, the propagation velocity remains approximately constant (hence metastable) throughout. Further downstream, transition to detonation occurs as shown in Figs. 1g and 1h.

The structure of the deflagration is seen to consist of a very broken up reaction zone structure of fine pockets of unreacted gas embedded in the products. Finite strength pressure waves, of similar

magnitude as the transverse waves in the original single headed detonation wave upstream of the plate can also be observed, most clearly in the shocked but as yet un-reacted gas behind the lead shock. The most noteworthy feature of Fig. 1 is the fact that the turbulent deflagration wave is maintained over a very long travel prior to transition to detonation. A cellular detonation (Figs. 1g and h) is re-established at approximately 5 channel heights or 50 hole diameters downstream of the perforated plate. At this length scale, it is reasonable to expect that the turbulence generated by the plate would have decayed, and that the turbulent deflagration relied on a self-generated mechanism for propagation.

In stark contrast, the same experiments conducted in the stable acetylene-oxygen-argon mixture, at a similar initial condition, showed substantially different features. Fig.2a shows a double headed detonation upstream of the plate and Fig. 2b and 2c show the transmitted deflagration downstream. In Fig. 2b, the structure of the deflagration is seen to be significantly less turbulent than those for the unstable mixture shown in Fig 1. In Fig 2c, the deflagration wave has decayed significantly with the reaction zone lagging behind at a great distance from the precursor shock. (Note that the curved waves behind the lead shock are reflections from a slight obstacle in the channel and do not play a role in the process).

Fig. 3 shows a stable detonation for the same mixture but at higher initial pressure. Again, rapid decoupling of the precursor shock from the reaction zone is observed and no metastable deflagration is observed. At still higher initial pressures, direct initiation occurs downstream in the vicinity of the perforated plate. Thus for stable detonations it appears that transition is governed by the characteristics of the plate.

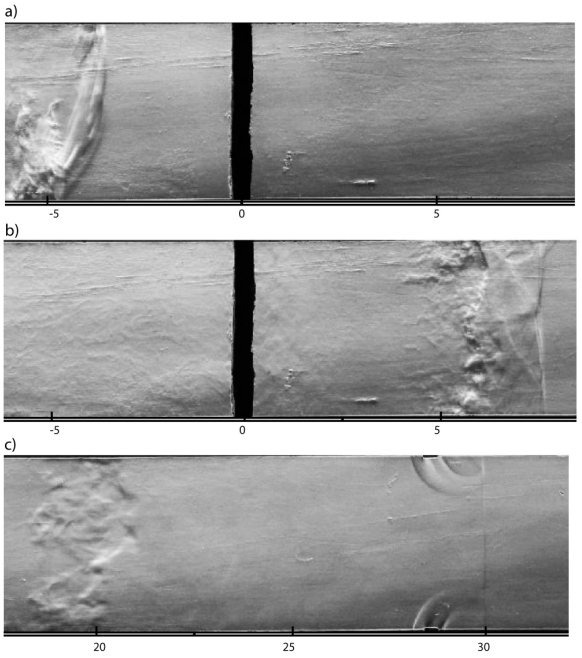


Fig. 2 The interaction of a stable $C_2H_2$+2.5$0_2$+70%Ar detonation with a perforated plate, $p_o$ = 3 kPa.

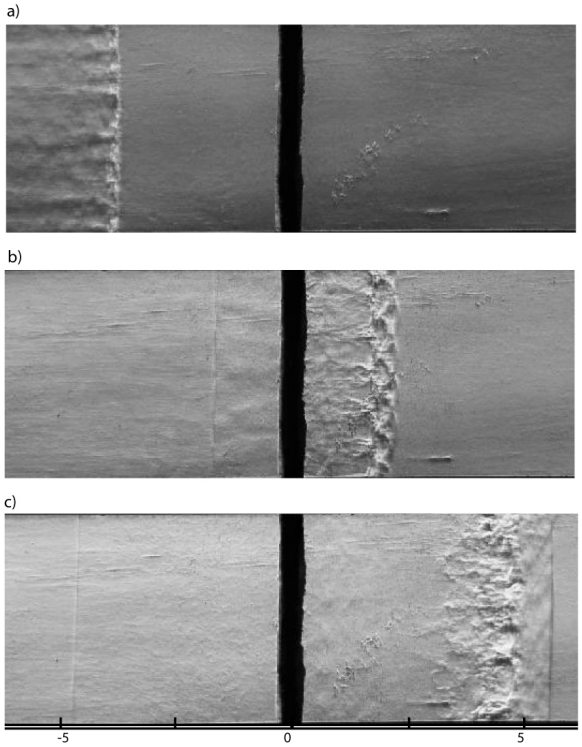


Fig. 3 The interaction of a stable $C_2H_2$+2.5$0_2$+70%Ar detonation with a perforated plate, $p_o$ = 12 kPa.

## 4 Discussions

The important finding in the present study is that re-initiation of a detonation wave downstream of the plate can occur in a much less sensitive mixture for the case where the detonation upstream is unstable than for the case of stable mixtures. This observation cannot be rationalized based

on 1D arguments of the changes in gas reactivity behind the transmitted shock. The unstable propane mixture has a much higher activation energy [2], and hence would be expected to be quenched more easily from temperature fluctuations than for the stable acetylene-argon mixtures. However, this is not the case as observed in the present experiments. This observation suggests that the lead shock wave does not play an important role in the re-initiation process for the unstable mixture and transition is probably due to the turbulent structure of the deflagration observed in the experiments.

We have also carried out numerical simulations and found that the structure of the reaction zone of the transmitted deflagration downstream of the perforated plate consists of an ensemble of interacting shocklets with pockets of unreacted and reacted gases embedded in the reaction zone. This is characteristic of highly compressible reacting turbulent flow. The numerical result is in very good accord with the present experimental observations (e.g. Fig. 3b, where alternating pockets of reacted and non- reacted gas are found as a consequence of initial wave interactions).

The results of the present experiments also show that the initial turbulization of the reaction zone by the perforated plate decays very rapidly in the more stable acetylene-argon mixture. However for the unstable propane mixture, the turbulence is sustained for a very long distance downstream leading to transition to a detonation.

The main difference between the two mixtures studied is the sensitivity of the reaction rates to perturbations in a hydrodynamic flowfield. In the unstable mixture, the chemical activation energy is significantly larger than in the acetylene-argon mixture [2]. Furthermore, the time scale over which the chemical energy is being released in a fluid element is a few orders of magnitude shorter in the unstable mixture than in the stable one [2]. For these reasons, it can be speculated that local hydrodynamic disturbances are likely to be amplified much more efficiently in the unstable mixture. Thus, in the propane-oxygen mixture, the very short reaction times in the scattered spots can locally build-up pressure fluctuations, since energy can be released faster than the acoustic expansion time scales of non-homogeneities. It is likely that these pressure fluctuations are responsible for the continuous self-turbulization of the mixture, although, clearly, more experiments are required.

However, it is well known that shock interactions with density gradients at a turbulent reaction zone gives rise to fine scale mixing by the Richtmyer-Meskov instability [3,4]. It is thus possible that our turbulent deflagration propagates by self-turbulizing its own structure via the scattered system of pressure waves it generates, and maintains its propagation via continuous turbulent mixing of the product gases with the shocked unreacted gas. This scenario, although highly speculative at the moment, is consistent with the present experimental observations of very fine turbulent structures and the presence of transverse shocks. We are planning future experiments to clearly identify the acceleration mechanism by generating controlled pressure waves and monitor their interaction with the metastable deflagration wave.

In conclusion, the present experiments confirm that high speed meta-stable waves downstream of the perforated plate are preferentially established in unstable mixtures whose reaction rates are more sensitive to hydrodynamic fluctuations. This is in stark contrast with what would be expected from 1D considerations. Such unstable mixtures can sustain a turbulent structure for distances much longer than in more stable detonations, and re-amplify back to detonation waves.

## References

[1] Zhu YJ et al. (2007) An experimental investigation of the propagation mechanism of critical deflagration waves that lead to the onset of detonation, *Proc. Combust. Inst.* 31(2): 2455.

[2] Radulescu MI (2003) The propagation and failure mechanism of detonations: experiments in porous walled tubes. PhD Thesis. McGill University.

[3] Thomas GO et al. (2001) Experimental observations of flame acceleration and transition to detonation following shock-flame interaction, Combust. Theory Modelling 5(4):573.

[4] Radulescu MI et al. (2007) The hydrodynamic structure of unstable detonations, J. Fluid Mech., 580:31