An Investigation of the Conditions for Detonation Initiation at a 1D Turbulent Mixing Interface

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Introduction

Rapid turbulent mixing between reacting gas products and unburned reactants can lead to the onset of a detonation. This has been established by numerous experiments on DDT where the onset of detonation occurs at the turbulent flame brush [1]. Direct initiation by turbulent jets of products into reactants have also confirmed that rapid mixing can lead to the condition for the onset of detonation [2]. At present, relatively little is known about the mixing rate required for the onset of detonation. It is clear, however, that for a slow mixing rate such as that due to molecular diffusion (of heat and of chemical species) at an interface between hot products and reactants, a laminar flame would result. On the other hand, too rapid a mixing rate may lead to too low a temperature in the mixing zone for rapid chemical reactions to occur.

Previous studies on the SWACER mechanism indicate that a certain gradient field is required for detonation initiation. Past investigations prescribe the gradient field as the initial condition for the subsequent chemical reactions and pressure wave amplification [3]. For initiation via turbulent mixing, the gradient field itself is a consequence of the turbulent mixing. Thus, from physical considerations, it appears that there must be some critical mixing rate that provides a gradient field conducive for to the SWACER process to occur. The present study is aimed at elucidating the turbulent mixing parameters required for direct initiation. Experimentally, the critical conditions for initiation is systematically studied for a one-dimensional turbulent interface separating detonation products from reactants. The numerical simulation of the initiation due to turbulent mixing at an interface is given in a companion paper [4]. It is hoped that the present study, using more controlled mixing conditions will contribute towards the establishment of the critical conditions for the onset of detonation to occur.

Experimental Details

A 4.5 m long steel detonation tube 150 mm in diameter was used in the present study. The driver section upstream of the perforated plate is 3.4 m long, and the downstream test section is 1.1 m long. Perforated plates with two different hole sizes were tested (d = 8 and 15 mm). In both cases, the hole spacing to hole diameter ratio was maintained at l/d = 0.5. The downstream section was separated from the upstream section with a thin diaphragm placed ahead of the perforated plate, permitting the use of different mixtures in the upstream and downstream sections.

Either a H_2-O_2 or a H_2-air mixture was used upstream in the driver section. Downstream, mixtures of hydrogen with air were tested at different equivalence ratios. For any given experiment, the tube was initially evacuated to approximately 5 to 10 torr. It was then filled via choked orifice flow meters with the desired concentrations of fuel and of air to an initial pressure of 1 atm. A detonation was directly initiated using a high voltage spark.

Ionization probes were used to measure the time of arrival of the reaction zones, which permits the trajectory of the reaction fronts to be determined. PCB pressure transducers were used to measure the time of arrival of the shock fronts and the pressure rise behind the shock or detonation.

Results and Discussion

A successful case of detonation initiation is shown in Fig. 1. Subsequent to the reflection of the incident detonation from the perforated plate, the transmitted shock is measured to travel at 1176 m/s, giving a particle velocity behind it of 770 m/s. After a time delay of about 85 μs, a detonation is observed to form. It should be noted that successful initiation is always found to occur at a distance of the order of a tube diameter. This implies that the onset of detonation is not a result of flame acceleration as in DDT or due to shock reflections since the interface is essentially one-dimensional and fills the entire cross-section of the tube. The onset of detonation is observed to be very distinct, and successful and unsuccessful cases can be distinguished unambiguously. If initiation does not occur within a distance of about a tube diameter, then initiation does not occur at all. A reaction front will continue to propagate for the remainder of the tube (~ 8 tube diameters), which either decays or reaccelerates to form a detonation (in which case the mechanism would be one of DDT and not direct initiation due to rapid mixing).

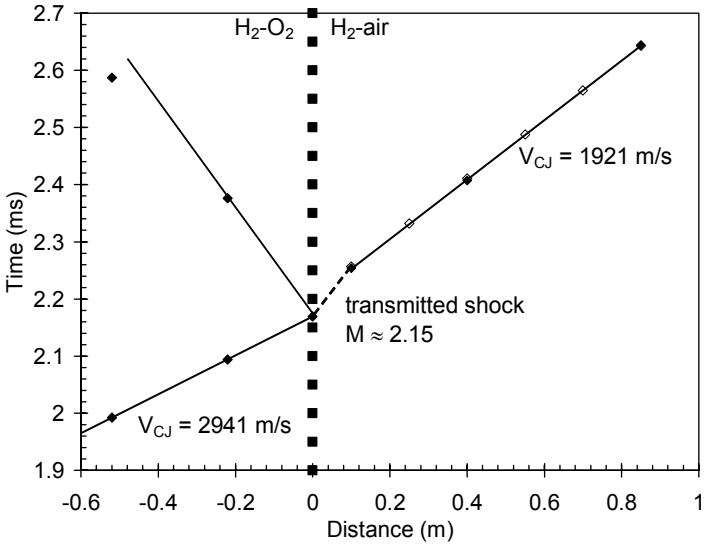

Fig. 1: Trajectory of successful case of initiation

Using a stoichiometric H_2-O_2 upstream of the perforated plate, we fixed the thermodynamic and chemical properties of the transmitted detonation products. Therefore, the conditions of the products at the mixing interface remain invariant. If the hole size and hole spacing for a given perforated plate are fixed, the turbulent scale (i.e. eddy size) in the mixing zone is fixed. We can then vary the mixture composition downstream to study the effect of equivalence ratio of the test mixture on direct initiation. The results for successful and unsuccessful initiation (for fixed

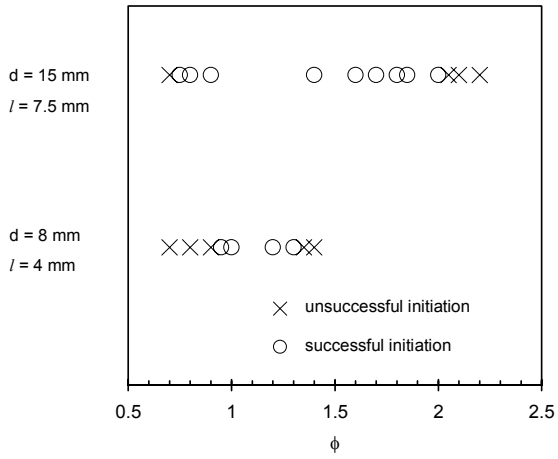

Fig. 2: Summary of results as a function of ϕ (H_2-O_2 driver)

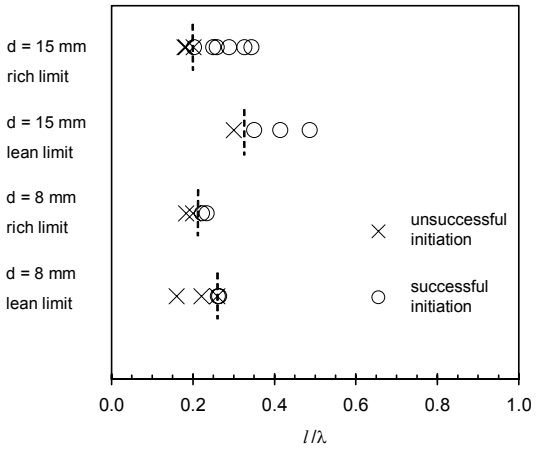

Fig. 3: Summary of results as a function of l/λ (H_2-O_2 driver)

upstream conditions) are shown in Fig. 2 as a function of the equivalence ratio of the downstream H_2-air mixture. It can be seen that for the plate with $d = 15$ mm, initiation occurs in the range $0.8 < \phi < 2$. For the plate with $d = 8$ mm, successful initiation occurs for $0.9 < \phi < 1.3$.

In previous studies of jet initiation, the critical limits between successful and unsuccessful initiation are correlated using the jet diameter and the detonation cell size, λ. In the present investigation, however, the mixing region spans the entire cross-section of the tube. It is more meaningful to represent the turbulence scale with the hole spacing, l, of the perforated plate, which should correspond to the turbulent eddy size. Correlation of the results (with the characteristic length scales of the turbulent mixing and of the sensitivity of the mixture) are shown in Fig. 3 as a function of l/λ. For the perforated plate with $d = 15$ mm, it can be seen that while initiation can occur at the rich limit ($l/\lambda \approx 0.3$), initiation is not possible for a lean mixture with an equivalent l/λ. The same is observed for the perforated plate with $d = 8$ mm. Initiation for rich mixtures is possible until a critical value of $l/\lambda \approx 0.3$. However, for lean mixture at this value of $l/\lambda = 0.3$, initiation does not occur. The different limits observed for rich and for lean test mixtures may be a result of the higher concentration of H radicals that are generated when rich test mixtures are used. As well, rich mixtures are more energetic than lean mixtures with equivalent cell sizes. For example, the CJ detonation velocity for a $\phi = 1.3$ H_2-air mixture (where $\lambda \approx 18$ mm) is about 2000 m/s. For a $\phi = 0.8$ mixture (also $\lambda \approx 18$ mm), the CJ velocity is about 1800 m/s.

Previous results reported by the authors [5] demonstrated the same results using lean and rich mixtures. However, in the authors' previous work, the driver mixture was varied for each experiment (the same mixture was used both upstream and downstream and the equivalence ratio was varied for each trial). It was not clear, however, if the results were due to variations in the properties of the transmitted detonation products or of the downstream mixture or both.

By using perforated plates with different hole sizes and hole spacing (keeping the H_2-O_2 driver fixed), the turbulent eddy size in the mixing zone can be varied. For the plate with $d = 15$ mm ($l = 7.5$ mm), it can be seen from Fig. 2 that the initiation is possible for a wider range of equivalence ratios compared to the plate with $d = 8$ mm ($l = 4$ mm) ($0.8 < \phi < 2$ for $d = 15$ mm and $0.9 < \phi < 1.3$ for $d = 8$ mm). By reducing the hole spacing, the eddy size is reduced and finer scale turbulence is generated in the mixing zone. Fine-scale turbulence can enhance turbulent mixing but cannot cause initiation alone as the turbulence decays too rapidly to promote mixing between the products and the reactants. This was also demonstrated by Knystautas *et al.* [2], although many factors were not controlled in their experiment (i.e., burning rate of the jet of combustion products, venting of unburned mixture ahead of the emerging jet).

By changing the upstream mixture from stoichiometric H_2-O_2 to H_2-air, the effect of the thermodynamic and chemical properties of the transmitted detonation products are examined. The results are shown in Fig. 4. For the $d = 15$ mm plate, successful initiation is only possible using a H_2-air drive for a more narrow range of equivalence ratios ($0.95 < \phi < 1.1$ compared to $0.8 < \phi < 2$ using the H_2-O_2 driver). For the $d = 8$ mm plate, initiation is not observed at all.

The results using the H_2-air driver are shown in Fig. 5 as a function of l/λ. Comparing the lean and rich limits for the $d = 15$ mm plate, it can be seen once again that initiation of rich test mixtures is possible for smaller values of l/λ (or larger values of λ). For products of a H_2-air mixture, the critical limit occurs at a value of about $l/\lambda \approx 1.0$. This differs from the critical limit of $l/\lambda \approx 0.2$ - 0.3 that is observed using products from a H_2-O_2 detonation (see Fig. 3). The difference between products of H_2-O_2 and of H_2-air is due to the higher temperatures and

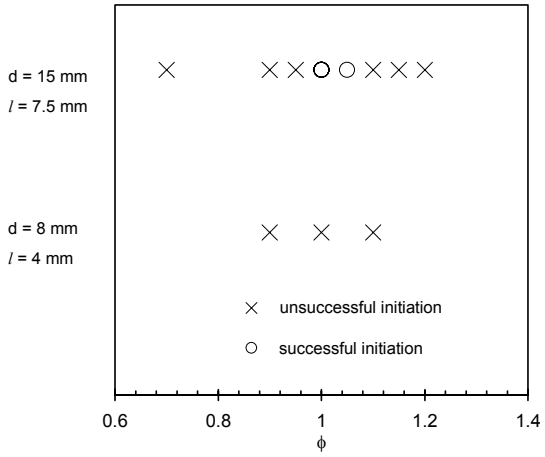

Fig. 4: Summary of results
as a function of ϕ (H_2-air driver)

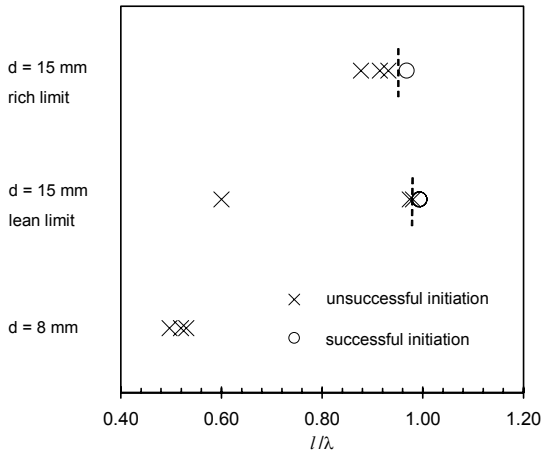

Fig. 5: Summary of results
as a function of l/λ (H2-air driver)

concentration of dissociated species for a H_2-O_2 detonation. Nonetheless, the present results indicate that the critical limit for initiation occurs when the detonation cell size of the test mixture is of the order of the turbulent eddy size generated by the perforated plate.

Concluding Remarks

The present investigation indicates that the initiation of a detonation via rapid turbulent mixing between hot products and reactants depends on the ratio of the turbulence scale to the cell size of the reactants. Without direct measurements of the integral length scale, we assume that the turbulence is characterized by the hole spacing of the perforated plate, which determines the largest turbulent scale in the mixing layer. It appears that the ratio of l/λ provides a better correlation of the critical condition than previous correlations based on the jet diameter or the tube diameter (which give a wider spread of the critical values for direct initiation). The thermodynamic state and the chemical properties of the products are also found to play a role in the initiation process.

References

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