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Detonation Initiation at a Turbulent Interface

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Introduction

It has been shown experimentally that direct initiation of a detonation wave can result from the rapid turbulent mixing of a jet of combustion products with an unreacted explosive mixture [1-7]. In the original experiments of Knystautas *et al.* [1], high pressure combustion products of a stoichiometric acetylene-oxygen mixture were discharged from a precombustion chamber through an orifice into a test chamber. Direct initiation of a detonation was observed in the jet. Despite demonstrating that direct initiation can be achieved by turbulent mixing, the critical conditions for successful initiation were not established. The initiation of a detonation by a so-called "flame-jet" was also investigated [2-5]. It must be borne in mind that a "flame-jet" is not truly an underexpanded jet; it is a turbulent flame that is first accelerated in a tube to a high velocity and then suddenly emerges into an unconfined test section. Therefore, the formation of a detonation in these experiments was a result of the mechanisms of DDT (deflagration to detonation transition) rather than of intense turbulent mixing. In the later jet initiation experiments of Carnasciali *et al.* [6] and Inada *et al.* [7], a diaphragm was used to separate the precombustion chamber from the test section in order to obtain controlled stagnation conditions (corresponding to a constant volume explosion) upstream of the jet.

One of the difficulties in past experiments to conclusively correlate a characteristic length scale of the jet to a parameter that characterizes the sensitivity of a mixture arises from the difficulty in controlling initial conditions in the turbulent mixing zone of the combustion products and the unburned mixture. If a diaphragm is not used, the pressure rise in the precombustion chamber can not be controlled and the upstream stagnation conditions of the jet depend on the burning rate in the precombustion chamber. Unburned reactants can also start to vent into the test chamber and establish a turbulent flow prior to the emergence of the combustion products. On the other hand, when a diaphragm is used to control upstream stagnation conditions, the ruptured fragments of the diaphragm influence the turbulence parameters in the mixing region at the head of the jet.

In the present study, a simple "one-dimensional" geometry is used to investigate the problem of detonation initiation at a turbulent interface. A detonation tube is divided into two sections by a perforated plate. In the section upstream of the perforated plate, a Chapman-Jouguet (CJ) detonation is generated. As the detonation is reflected from the perforated plate, the flow through the plate becomes choked and the combustion products are transmitted downstream into the test section. Since the plate is perforated over the entire cross-sectional area, there is no lateral expansion of the transmitted combustion products and no entrainment of reactants from the sides of a jet. Therefore, mixing occurs only at the interface between the transmitted products gases and the unburned mixture, and therefore, detonation initiation can be investigated at the turbulent interface.

Experimental Details

A 5.5 m long 300 mm × 300 mm nominal square cross-section steel tube was separated into two sections by a perforated plate. The upstream section is 3.7 m long, and the test section downstream of the perforated plate is 1.8 m long. A 1.1 m long ignition tube 150 mm in diameter lined with obstacles and was used to facilitate the formation of a detonation in the upstream section. A schematic of the experimental set-up is shown in Fig. 1a. The perforated plate consisted of a

25.4 mm thick steel plate perforated over the entire cross-sectional area. Two perforated plates with different hole sizes ($d = 5$ mm and $d = 8$ mm) were used. The ratio of hole spacing to hole diameter, l/d, was about 1.5 for both plates. A photograph of the two perforated plates is shown in Fig. 1b.

Mixtures of ethylene-oxygen and propane-oxygen with varying amounts of nitrogen dilution were tested at atmospheric pressure. For any given experiment, the tube was first evacuated and then filled by the method of partial pressures to achieve the desired composition. Uniform mixing was effected by a bellows-type recirculation pump. Ignition of the mixture (in the ignition tube) was achieved by means of an electric match. In all the cases studied, steady detonations (propagating at velocities within 2% of the theoretical CJ detonation velocity) were established prior to reflection from the perforated plate. The time of arrival of the flame front was monitored by ionization probes. Pressure transducers were also used to monitor pressure profiles and the time of arrival of precursor shock waves.

Theoretical Considerations

The gasdynamic flow fields resulting from the interaction of a shock wave with a wire mesh in a non-reacting medium have been previously investigated [8-10]. Subsequent to the collision of an incident shock wave against a wire mesh, a shock is reflected upstream. Downstream, a transmitted shock is formed and is followed by a contact surface. For cases where the flow is choked at the plate, a backward facing auxiliary shock is formed in order to match the pressure and the particle velocity of the flow exiting the plate with those across the contact surface behind the transmitted shock. Since the flow is choked, the properties of the flow immediately upstream and downstream of the plate can be determined uniquely as functions of the ratio of the total cross-sectional area to the total hole area by assuming isentropic expansion.

For a combustible mixture, the downstream wave processes can be determined in the same manner if it is assumed that there is no heat released downstream of the perforated plate. For an ethylene-oxygen mixture with a nitrogen dilution of $\beta \approx 2.5$, the interface velocity is calculated to be about 940 m/s, which is roughly the sound speed of the combustion products. The transmitted shock velocity is determined to be about 1100 m/s, corresponding to a shock strength of $M_T \approx 3.24$. Assuming that $\gamma = 1.38$ for this particular ethylene-oxygen-nitrogen mixture, the temperature behind the shock is calculated to be around 850 K. This is insufficient for auto-ignition by adiabatic shock compression; therefore, it seems unlikely that a detonation can form spontaneously as a result of shock heating.

Results and Discussion

A typical trajectory for successful initiation downstream of the perforated plate with 5 mm holes is shown in Fig. 2 for an ethylene-oxygen mixture diluted with nitrogen ($\beta \approx 2.5$). Upstream of the perforated plate ($x < 0$), a detonation can be observed to propagate at a velocity within 2% of the theoretical CJ detonation velocity (≈ 1800 m/s). Subsequent to the collision of the detonation with the perforated plate, it appears that a combustion front propagates downstream at a velocity of about 940 m/s. After a time delay of about 0.2 ms, a detonation is observed to form at a distance 0.2 m downstream of the plate. This newly formed detonation continues to propagate downstream at a velocity within 1% of the CJ detonation velocity. A typical trajectory for unsuccessful initiation is shown in Fig. 3. For this particular run, the same ethylene-oxygen mixture with nitrogen dilution ($\beta \approx 2.5$) was tested using the same perforated plate (5 mm holes). Once again, upstream of the perforated plate, a detonation propagates with a velocity within 2% of the CJ velocity. After the detonation is reflected from the perforated plate, a combustion wave traveling at about 820 m/s is now observed downstream. Ahead of the combustion wave, a precursor shock wave is driven at a velocity of about 900 m/s (or $M_T \approx 2.62$). In comparison to the theoretical results, the experimental velocities are slightly slower, which may be because it was assumed that the flow expands isentropically through the perforated plate. Nonetheless, it appears that when ignition occurs of the flame occurs at the interface, the flame is actually driven by the interface rather than transport mechanisms of premixed flames. Therefore, it seems likely that when detonation initiation does occur, it occurs at the turbulent interface where combustion products are mixed rapidly with the unburned shocked mixture. A summary of the results for successful and unsuccessful detonation initiation in terms of nitrogen dilution, β, is shown in Fig. 4a. Although repeated shots were conducted at different β, only one data point is shown for clarity. An open circle represents successful detonation initiation; unsuccessful initiation is denoted by an "x." It can be seen that an ethylene-oxygen mixture with greater nitrogen dilution can be initiated using the perforated plate with larger diameter holes. The critical limit between successful and unsuccessful initiation for the 8 mm hole plate occurs at $\beta \approx 3.2$ whereas the critical limit occurs at $\beta \approx 2.5$ when the 5 mm hole plate is used. For propane-oxygen with nitrogen dilution, the critical limit occurs at $\beta \approx 2.2$.

In previous investigations, the critical limits between successful and unsuccessful initiation were correlated with the critical tube diameter ($d_c \approx 13\lambda$). This was meaningful since the combustion products were transmitted through an orifice (with or without turbulence generators like wire meshes or perforated plates) that was smaller than the dimension of the test section. Thus, the global mixing region was characterized by the jet diameter. In the present investigation, however, the mixing region spans the entire cross-section of the tube. Therefore, the two meaningful length scales are the hole size, d, and the hole spacing, l, of the perforated plate. The dimension of the tube is much larger and should not play a significant role. The results for successful and unsuccessful initiation are plotted in Fig. 4b in terms of d/λ where λ is the characteristic cell size of the mixture. It must be borne in mind that the l/d ratio for both plates are equivalent so that the effect of hole spacing can not be gleaned from the experimental results at present. It is of interest to further investigate the effect of the hole spacing. Nevertheless, it can be seen that for the mixtures and the perforated plates tested, a critical value of $d/\lambda \approx 0.4$ is required for successful initiation. In the pioneering experiments of Knystautas *et al.* [1] where a perforated plate with a similar l/d ratio of 1.7 was used, the critical limit between successful and unsuccessful initiation was found to occur at $d/\lambda \approx 5.7$ for an equimolar mixture of acetylene-oxygen. The large discrepancy between these results may be due to the difficulty in previous investigations to control stagnation conditions upstream of the turbulent mixing interface.

Concluding Remarks

The present results seem to indicate that detonation initiation is not effected by adiabatic shock compression. Instead, a flame is driven by the turbulent interface between the combustion products and the unburned reactants at a velocity close to the sound speed of the combustion products. Detonation initiation occurs at the interface where intense turbulent mixing occurs. For the mixtures and the perforated plates tested in the present investigation, the criterion for successful detonation initiation is $d/\lambda \approx 0.4$. The effect of hole spacing, however, remains to be investigated.

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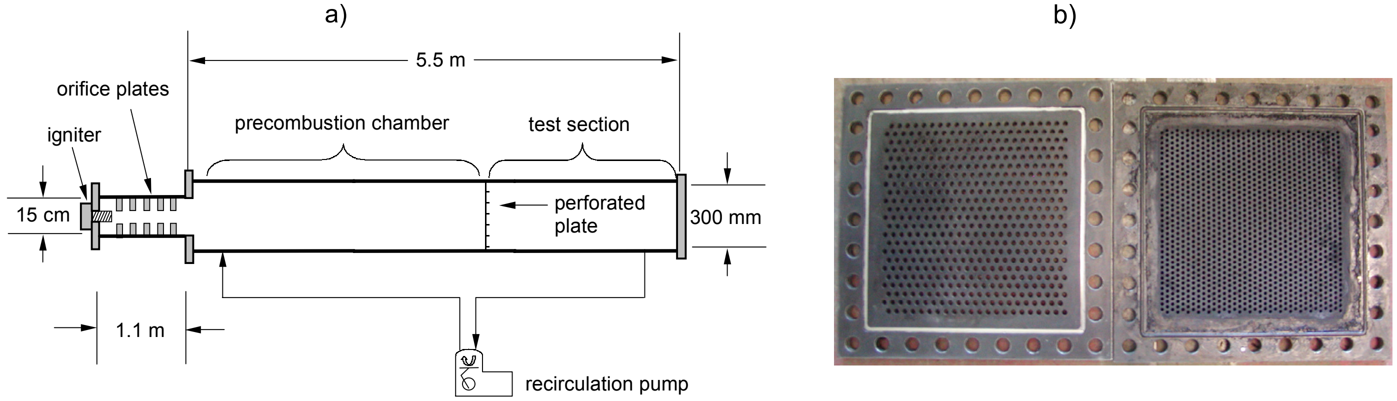

Fig. 1: a) Schematic of experimental apparatus; b) photograph of perforated plates

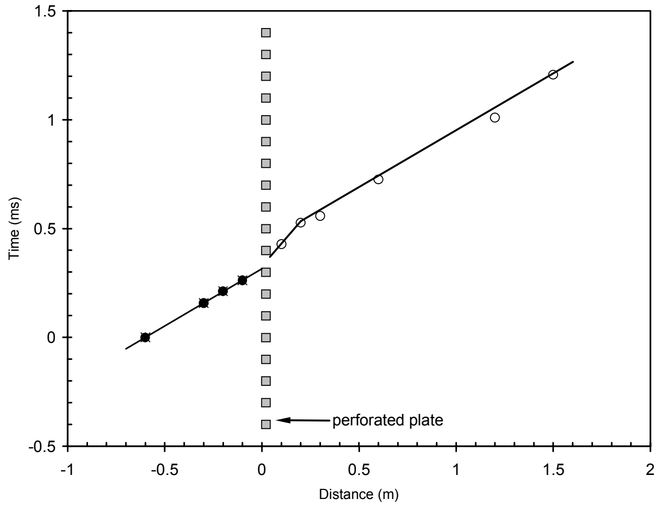

Fig. 2: Trajectory for C_2H_4-O_2-N_2 with $\beta = 2.5$; successful initiation (5 mm hole plate)

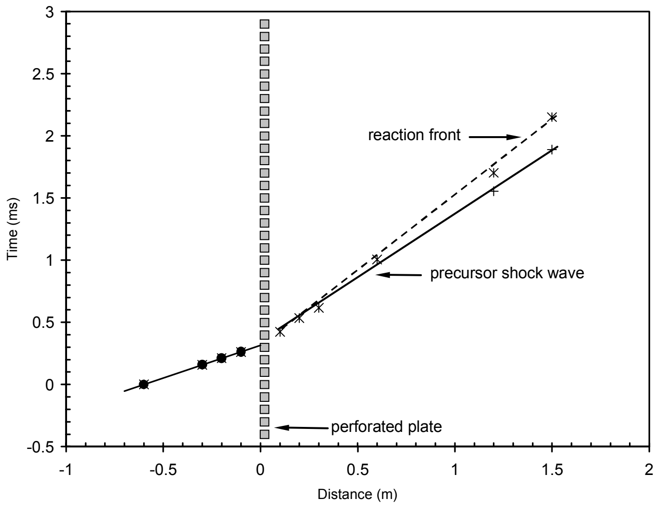

Fig. 3: Trajectory for C_2H_4-O_2-N_2 with $\beta = 2.5$; unsuccessful initiation (5 mm hole plate)

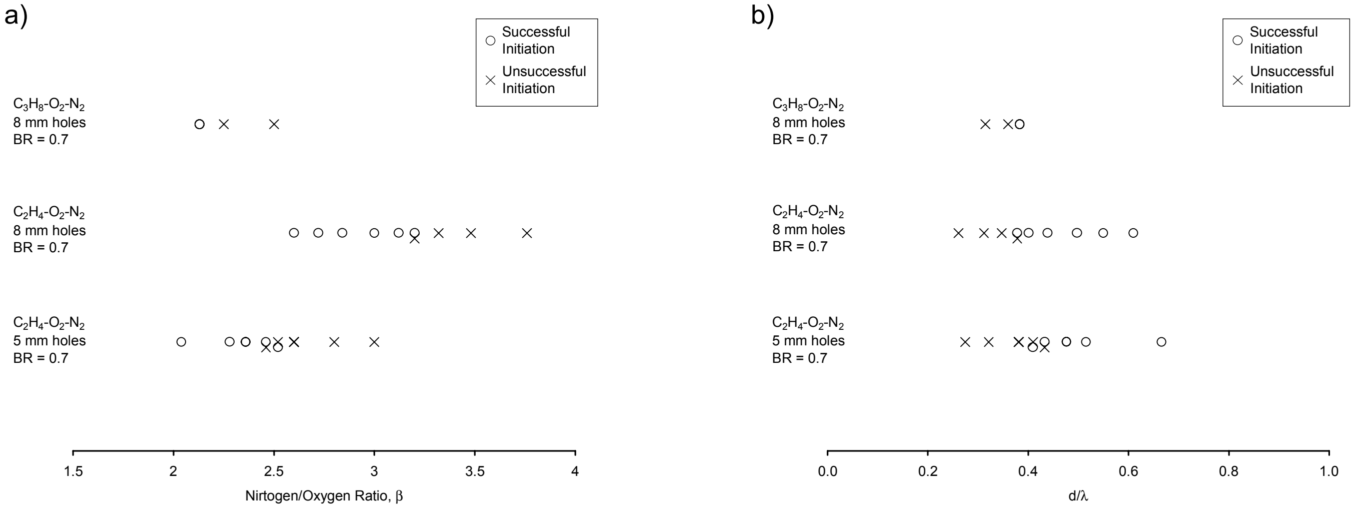

Fig. 4: Summary of results in terms of a) nitrogen dilution, β, and b) d/λ