Critical Parameters for Pulse Detonation Engine Predetonator Tubes

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INTRODUCTION

There has recently been considerable interest in the concept of pulse detonation engines (PDEs). From a practical perspective, it is highly desirable that PDEs use combustible fuels which have already been approved by the aviation industry (e.g., JP-10 or Jet-A). However, one drawback to the use of these fuels in PDEs is that the resulting fuel-air mixtures are relatively difficult to detonate.



One initiation scheme receiving considerable attention involves the use of a 'pre-detonator' or 'driver' tube [1,2]. In this concept, a detonation is first formed in a sensitive fuel-oxygen mixture by spark ignition followed by rapid deflagration-to-detonation transition. The established wave is then used to initiate the less sensitive fuel-air mixture contained in the main combustion chamber. It is desirable from both safety and performance points of view to keep the volume of the pre-detonator as small as possible. Therefore, the efficiency of transmission from the driver to the main chamber is an important issue. Very little published information is available about this topic despite its importance to the PDE community.

In a previous report [3], the transmission of detonation from a fuel-oxygen driver to a larger, co-axially aligned receptor tube containing fuel-air mixture was investigated. This geometry is considered to be the simplest generic predetonator concept. The results showed that both the power of the driver tube mixture and the confinement provided by the receptor tube walls play an important role in determining the overall effectiveness of detonation transmission. For example, a driver tube containing stoichiometric C_2H_2 - O_2 was found to be capable of initiating lean C_2H_2 -air in a receptor tube nearly three times larger in diameter. In the limit, the driver tube diameter was approximately 24 times smaller than the critical tube diameter for the C_2H_2 -air mixture being initiated. The results were even more impressive for an equimolar C_2H_2 - O_2 driver because of its higher detonation velocity and correspondingly stronger transmitted shock wave. Using the same set-up, the driver tube was found to be nearly 40 times smaller than the critical tube diameter for the C_2H_2 -air mixture being and correspondingly stronger transmitted shock wave.

In the present paper, additional results are presented for a smaller-scale apparatus which confirm that the previously proposed scaling relationship is applicable. The

minimum driver tube length is also investigated in experiments employing a variable-length driver section.

EXPERIMENTAL DETAILS AND RESULTS

The test set-up is shown in Figure 1. The previously reported large apparatus consisted of a closed receptor vessel 21.6-cm inside diameter by 6.1 meters long and having three interchangeable driver tubes of 5.08, 7.37, and 10.2 cm inside diameter. The driver tubes were 1.25 meters in length. A smoke foil 0.66 meters long and covering the full periphery of the receptor was positioned downstream of the driver tube exit to capture the details of the reinitiation process. The current smaller apparatus was similar, consisting of a 8-cm diameter receptor 3.5 meters long connected to various driver tubes of 4 cm diameter. The smoke foil section in this apparatus was 0.29 meters in length. Driver tubes were available in various discrete lengths up to 1.5 meters. A variable-length driver containing a moveable piston was also built which allows its effective length to be accurately varied over the range from 3 to 63 cm. The



piston was connected to a threaded rod which passed through a threaded hole in the end wall of the driver. All tubes were fitted with a combination of pressure transducers and ionization gap probes. Stoichiometric acetylene-oxygen was used as the driver gas. The receptor gas was lean acetylene-air except in selected tests where stoichiometric propane-air was used. All mixtures were prepared in a separate vessel using the method of partial pressures with the exception of the fuel-air mixtures used in the large receptor. The larger volumes in that case mandated that the mixtures be prepared directly in the receptor. The method of partial pressures was again used and a re-circulation system was employed to guarantee homogeneity. A thin polyethylene diaphragm (0.025 mm thick) was used to separate the driver and receptor gases. Initiation of detonation in the driver tubes was achieved using a commercially-available capacitor discharge system and an exploding wire. Smoke foils were not routinely employed in the driver tubes. However, a number of tests with smoke foils were carried out early in the program specifically to confirm that initiation was occurring promptly; i.e., in the immediate vicinity of the exploding wire. All experiments were carried out at atmospheric conditions except where noted otherwise.

Transmission Details

Figure 2 is a collection of smoke foils from experiments in the large apparatus in which C_2H_2 - O_2 drivers were used to initiate lean acetylene-air mixtures. The receptor fuel concentrations for (A) through (D) were 5.0%, 4.25%, 4.125%, and 4.0% acetylene, respectively. The foils show that the number of reinitiation sites decreases as the limit is approached. Two reinitiation mechanisms likely exist; one mode for normal shock reflection at early times, and a second Mach reflection mode at later times. Away from the limit, the reinitiated waves are initially overdriven and take some time to equilibrate as evidenced by the increasing cell size in the direction of propagation. As the limit is approached, the cells also become quite large. Both factors render the equilibrium cell size difficult to measure on the smoke foil. A suitable reference cell size λ can be estimated using the critical tube diameter data of Moen et al. [4] and the correlation $\lambda = d_c/13$ where d_c is the critical tube diameter. This gives values for λ of 5.08 cm, 14.0 cm, 17.3 cm, and 21.6 cm in (A) through (D), respectively. The corresponding values of D/ λ are 4.25, 1.54, 1.25, and 1.0, where D is the receptor diameter.

Transmissibility Scaling Relationship

In our previous work [3], it was proposed that the transmissibility be defined by $\beta = d_c/D_0$ where D_0 is the driver tube diameter and d_c is the critical tube diameter for the fuel-air mixture being initiated. When defined in this manner, $\beta = 1$ (by definition) for the classical critical tube diameter scenario in which a detonation wave in a tube transmits to the same mixture in unconfined half space. Values of β greater than unity signify more effective transmission. In the present apparatus, the increased transmissibility is due to two factors. Firstly, a fuel-oxygen driver is more powerful than a fuelair driver and can deliver a correspondingly stronger transmitted shock wave to the receptor gas. For example, the



respective detonation velocities for stoichiometric C₂H₂-air, stoichiometric C₂H₂-O₂, and equimolar C₂H₂-O₂ are 1865 m/s, 2425m/s and 2937 m/s (for initial conditions of 1 atm and 300 K). In experiments where acetylene-oxygen drivers were used to initiate unconfined acetylene-air (i.e., for D/D₀ $\rightarrow \infty$), it was determined that $\beta = 1.4$ and 3.4 for

stoichiometric and equimolar C_2H_2 - O_2 drivers, respectively. The second factor affecting transmissibility is the confinement provided by the receptor tube walls. When the shock wave from the driver transmits to the receptor, it initially diffracts at the abrupt area change, but later reflects from the side wall. The smoke foils in Figure 2 confirm that the reflected shock is responsible for reinitiating detonation in the receptor. The strength of the reflected shock is a function of D/D₀. Reinitiation becomes more difficult with increasing values of D/D₀.

Figure 3 is a plot of β versus D/D₀ which compares the data for the large apparatus (D/D₀ = 2.93 and 4.25) and the small apparatus (D/D₀ = 2). Stoichiometric C₂H₂-O₂ drivers were used in all experiments shown in the figure. In the limit of large D/D₀ (i.e., transmission to unconfined space), β must approach the value of 1.4 noted above. In the other limit of D/D₀ = 1, the receptor diameter D is equal to the driver diameter D₀ and critical conditions are characterized



by the onset of single-head spin in the receptor (see [5] for a review). Under these conditions, the cell size is equal to the receptor periphery; that is $D = D_0 = \lambda/\pi$. Substituting $d_c/13$ for λ gives $D_0 = d_c/13\pi$. After rearranging, $\beta = d_c/D_0 = 13\pi$ or a value of about 40.8. The data in Figure 3 are consistent in describing the variation of β with D/D_0 . The data also appear to approach the expected limits for small and large values of D/D_0 . These observations suggest that the scaling relationship proposed in the earlier work is valid.

Minimum Driver Tube Length

Additional experiments were conducted to elucidate the factors governing the minimum length of driver required to initiate detonation in the receptor. These tests were done using the small apparatus and employed only one geometry $(D/D_0 = 2)$. Most tests employed the variable-length driver described previously. Again, stoichiometric C_2H_2 - O_2 was used in the driver and lean C_2H_2 -air was used in the receptor.

Figure 4 shows the variation of critical driver length as a function of acetylene concentration in the receptor. As expected, the critical driver length increases as the receptor mixture is made leaner. Figure 5 shows the data after being normalized by the cell size for the receptor gas. The cell size for the driver gas is exceedingly small (about 0.1 mm based on the critical tube diameter data of Matsui and Lee [6]) and is likely irrelevant in the present problem. The interesting observation about Figure 5 is the fact that the critical scaled driver length actually increases as the number of cells in the receptor increases. This would at first appear to be counter intuitive but can be explained by the fact that a second important factor plays a role in the reinitiation process. The points at the left side of Figure 5 correspond to a receptor acetylene concentration of about 4.5%, while the points at the right side correspond to stoichiometric acetylene-air. The respective detonation velocities for these two mixtures are approximately 1655 and 1870 m/s. When compared to the detonation velocity of 2425 m/s for the driver gas, it becomes evident that the driver delivers a relatively stronger transmitted shock wave to lean mixtures versus stoichiometric mixtures. A similar observation was made by Kuznetsov et al [7]. In their study, a stoichiometric fuel-air detonation in the driver was used to initiate lean fuel-air mixtures in a receptor of the same diameter. These investigators calculated the strength of the transmitted shock across the driver/receptor interface and used the ratio of the transmitted pressure to the receptor detonation pressure as a measure of the degree of overdrive.

The approach of Kuznetsov could be applied in the present work although the shock diffraction and subsequent reflection processes would have to be taken into account. In our case, the pressure behind the reflected shock wave is likely the most suitable for characterizing the driver strength. In order to estimate this pressure, a CFD calculation was carried out using the IFSAS code in which a stoichiometric C_2H_2 - O_2 detonation in a 4-cm diameter driver was allowed to transmit into a half space containing air. The calculation indicated that the shock wave arrived at a radius of 4 cm in 19 μ s. The pressure behind the shock wave was calculated to be 3.4 atm. The corresponding reflected shock pressure was calculated using the reflected shock relations to be about 9.5 atm. Figure 6 shows a plot of normalized driver length as a function of relative driver strength where the latter is denoted by the ratio of the reflected shock pressure to the detonation pressure of the receptor gas. The plot clearly shows that the critical driver length decreases as the relative driver strength increases. Additional tests were conducted using the same driver gas but a stoichiometric propane-air receptor gas. This scenario was of interest because stoichiometric C_3H_8 -air has the same cell size as 4.75% C_2H_2 -air but a detonation velocity 125 m/s higher. In the first test at atmospheric pressure, the driver failed to initiate the propane-air mixture as expected because of the lower relative driver strength. Subsequent tests at elevated initial pressures of 2 and 3 atm produced the same result. Note that elevating the pressure reduces the C_3H_8 -air cell size but leaves the shock

dynamics relatively unchanged. Finally, successful reinitiation was observed for an initial pressure of 4 atm. The results of these tests, included in Figure 6, are consistent with the correlation for the acetylene-air system. The cell sizes for propane-air were again based on the critical tube diameter data of Moen and the 13λ correlation. An inverse pressure dependence for cell size was assumed for elevated pressures.

CONCLUSIONS

This study has confirmed the previously proposed correlation between driver performance and receptor-todriver diameter ratio for the case of a stoichiometric C₂H₂-O₂ driver initiating C₂H₂-air. It has been shown as well that driver performance depends not only on the cell size of the mixture being initiated, but also on the relative strength of the reflected shock wave in the receptor gas compared to its detonation pressure. The strength of the reflected shock is clearly a function of the transmitted shock strength across the driver/receptor interface and the ratio of diameters D/D_0 .

The data obtained to date, although limited to a single value of D/D_0 , have suggested a generalized iterative approach to pre-detonator design. For a given design problem, the engine diameter D, as well as the driver and receptor gases, would necessarily be specified. The objective would then be to calculate the driver dimensions D_0/λ and L/λ . This would be done as follows. The designer would first guess at the driver diameter D_0 . Knowing the gases and D/D_0 , it would then be possible to calculate the reflected shock pressure P_{R} . Data of the type shown in Figure 6 would then yield the normalized driver length L/λ . Likewise, knowing the receptor gas and engine diameter D, data of the type shown in Figure 5 would yield an independent value for L/ λ . The two values of L/ λ will only be identical if the initial guess for D₀ was correct.

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