Structural Response of Tubes to Deflagration-to-Detonation Transition

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1 Introduction

An outstanding technical challenge in gaseous explosions [1] is the prediction of loads and deformations in the DDT regime, which is known to cause the largest pressure peaks and potentially can cause the largest structural damage. One common and particularly important situation is DDT in a tube with a closed end. In this case, there is the potential for development of extremely high pressures due to "pressure-piling" associated with DDT occurring within the compressed but unburned gas at the closed end of the tube [2, 3]. The DDT event and resulting detonation in the compressed gas can result in much higher pressure than direct (prompt) initiation of a detonation [4, 5]. Due to the complex nature of the DDT event, the prediction of the structural response poses a rich scientific problem. In order to examine this issue, we have experimentally studied the elastic structural response of a thick-walled tube to DDT events for four fuel-oxygen mixtures - hydrogen, methane, ethylene, and propane [6]. We report measurements of peak pressures and strains and make comparisons with predictions based on simple models of the explosion process. These results serve to guide the development of simple engineering models that are useful in analysis and design.

2 Experimental setup

The experimental facility (Fig. 1) consists of a 1.25 m long tube with an inner diameter of 127 mm and a wall thickness of 12.7 mm (0.5 in) closed with flanges at both ends. The tube and flange material is stainless steel, Grade 316L. The period of the fundamental hoop oscillation mode is 85 μs, corresponding to a frequency of 11.7 kHz. As the tube wall is sufficiently thick and the initial pressure (P_0 = 1 bar) sufficiently low, all deformations observed in the present experiment were elastic. The tube was instrumented with eight piezoelectric pressure transducers (P_1-P_8) and uni-axial strain gages (S_1-S_8), oriented to measure the hoop component. The mixture was initiated via a glow plug. We studied four fuels with varying stoichiometry and initial pressure but only the results for the ethylene-oxygen mixture at an initial temperature T_0=22-25°C, and an initial pressure P_0=1 bar are presented in this abstract.

3 Results for C_2H_4-O_2 mixtures

Pressure and strain traces (Fig. 2) were used to classify the combustion regime. The DDT location was determined by examining the pressure traces for the characteristic signatures of DDT. Near the DDT location, the pressure histories exhibit a sharp rise with peak pressures several times higher than the CJ pressure, P_{CJ}. Prior to the DDT event, pressure transducers show a gradual rise and in some cases, a series of shock waves created by a high speed flame. In Fig. 2, the DDT transition occurred close

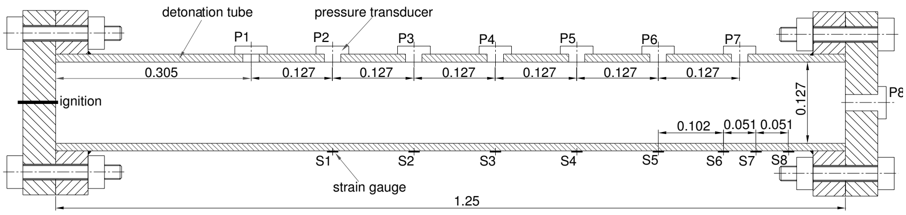


Figure 1: Experimental setup showing pressure transducer ports P_1-P_8 and strain gauge S_1-S_8 locations. The unit of length is meter.

to P_3 with a peak pressure of 10.4 MPa, almost 2.5 times larger than P_{CJ}=4.0 MPa. The detonation then propagated to the far end of the tube (P_8) and a reflected shock wave propagated back toward the ignition end. The peak pressure of the reflected shock wave is 29.8 MPa, about 3 times $P_{CJ,ref}$=10.0 MPa. The experimental peak pressures and strains, P_{max} and ϵ_{max}, shown as a summary in Fig. 3a and b, are the maximum measured pressure on any of the 7 transducers (P_1-P_7) and maximum strain recorded on any strain gauge (S_1-S_8). $P_{ref,\ max}$ is the measured maximum pressure on P_8 and is taken to be representative of the peak reflected pressure.

The DDT run-up distance (Fig. 3d) is determined as the location of the detonation onset ($P > P_{CJ}$), as derived from pressure traces. Within a wide range, $0.5 < \Phi < 2.7$, the DDT run-up distance is given as 300 mm (2.4D). Note the actual value may be smaller, as the location of the first pressure transducer (x=300 mm) is an upper bound for the DDT location. DDT events close to the far end of the tube were observed for $0.33 < \Phi < 0.35$ on the fuel-lean side, and $2.9 < \Phi < 3.0$ on the fuel-rich side. For $\Phi < 0.33$ and $\Phi > 3.0$, no detonation onset was observed in the tube as the critical run-up distance for these conditions exceeded the tube length.

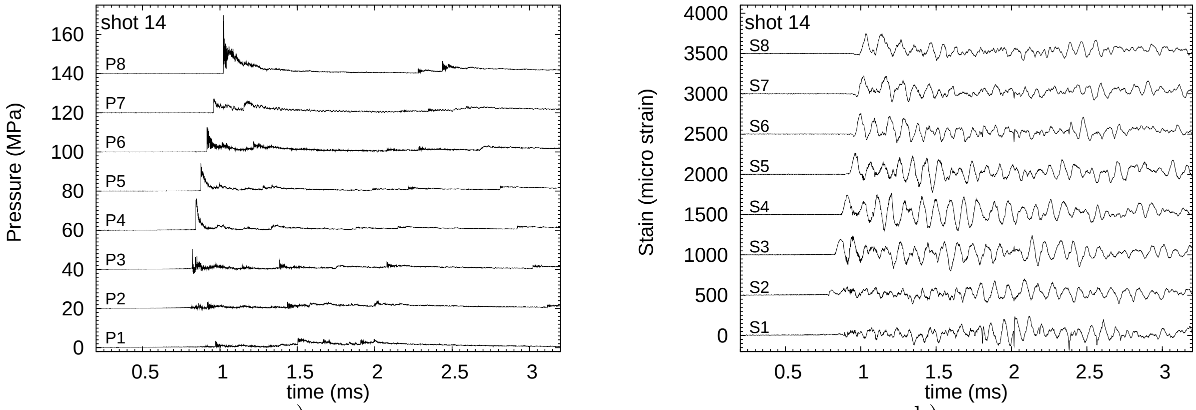
The peak value of the strain signals was analyzed via the concept of the dynamic load factor (DLF), the ratio of the measured peak strain to the peak strain expected in the case of quasi-static loading of an unconstrained tube segment

$$DLF = \frac{\epsilon_{max}}{\epsilon_{static}} \qquad \epsilon_{static} = \frac{\Delta PR}{Eh} \tag{1}$$

where E = 193 GPa, R = 69.5 mm (mean of inner and outer radius), h = 12.7 mm (wall thickness) and $\Delta P = P - P_{outside}$, the effective pressure loading on the tube ($P_{outside}$ = 1 atm). The reference strains ϵ_{CV}, ϵ_{CJ}, $\epsilon_{CJ,ref}$ shown as lines in Fig. 3a and b were obtained using the computed [7] pressure P for constant volume explosions (P_{CV}), CJ detonations (P_{CJ}), and reflected CJ detonations ($P_{CJ,ref}$) respectively. The DLF values shown in Fig. 3c were computed in two ways. The values for DLF_{exp} were based on the static strain that would be expected from the experimentally measured peak pressure ($P = P_{max}$) and the values for DLF_{CJ} were based on the calculated CJ pressure ($P = P_{CJ}$).

On the lean side of the DDT onset ($\Phi \approx 0.33$), peak pressures up to 5 times higher than P_{CJ} and peak strains up to 250 μstrain were observed, Fig. 3b. On the rich side of DDT onset ($\Phi \approx 2.9$), peak pressures up to 10 times higher than P_{CJ} and peak strains up to 400 μstrain were observed. The peak reflected pressure is 90 MPa, 10 times higher than $P_{CJ,ref}$. Close to the DDT thresholds, DLF_{exp} is smaller than 1. This is consistent with the very short duration of the measured pressure spikes associated with the highest pressures, indicating the impulsive nature of the loading regime in the transition regimes. The highest peak pressures correspond to the lowest values of $DLF_{exp} \sim 0.5$, for both regimes.

The dynamic load factor DLF_{CJ} is of practical interest, as it enables an easy estimation of the stresses in a DDT event, based on tube geometry and P_{CJ}. In the regime $0.5 < \Phi < 2.1$, DLF_{CJ} is on the order of 2, consistent with previous work on detonation loading at supercritical wave speeds [4]. In this regime, DDT is taking place between the ignition point and transducer P_1. The first strain gauge S_1 is located opposite of P_2, Fig. 1, and therefore only the tube section exposed to the fully developed and reflected detonation regime is captured on the strain gauge signals. DDT events close to the tube center ($L/D \approx 5$) are observed for $\Phi = 0.45$ and 2.5, Fig 3d, which result in DLF_{CJ} of 3.2 and 2.2 respectively, Fig 3c. For the critical regime in which the transition happens close to the tube ends, a value of DLF_{CJ}=4 appear to be appropriate. The highest values for DLF_{CJ} observed in this regime can be explained by the significant compression of the unburned gas section during the flame acceleration process prior to detonation onset.



a) b)

Figure 2: a) Pressure and b) strain gauge traces for C_2H_4-O_2 mixture at $\phi = 2.5$, $P_0 = 1$ bar and $T_0 = 295$ K. Note that S_1 is located opposite of P_2, Fig 1.

4 Summary

Tests with four fuel-oxygen mixtures and a wide range of fuel equivalence ratios have been performed to measure strain and pressure histories during DDT events. The highest strains and peak pressures were observed when DDT occurred close to the reflecting end. The peak pressure at the end wall was up to 8 times the calculated reflected detonation pressure, based on the initial pressure. However, the load is impulsive due to the short duration of the high pressure. The high pressure is caused by the compression of the unburned mixture through the flame motion prior to the onset of detonation. Using static deformation of a tube segment computed with P_{CJ} as a reference, we find a maximum dynamic load factor of 4 for DDT events, slightly smaller than the maximum of 5 expected for a reflected CJ detonation. Note that the tube in this study has an end flange assembly which is significantly stiffer than the main tube. This will result in lower peak strains than for an unconstrained tube segment (used for the DLF computation) or for a reflecting surface that is a solid or liquid blockage within the tube. When transition occurs away from the closed end of the tube, a maximum dynamic load factor (based on P_{CJ}) of two is measured. We conclude that although very high peak pressures can be obtained in DDT events, the impulsive nature of the load and the construction of the tube limit the resulting dynamic load factor.

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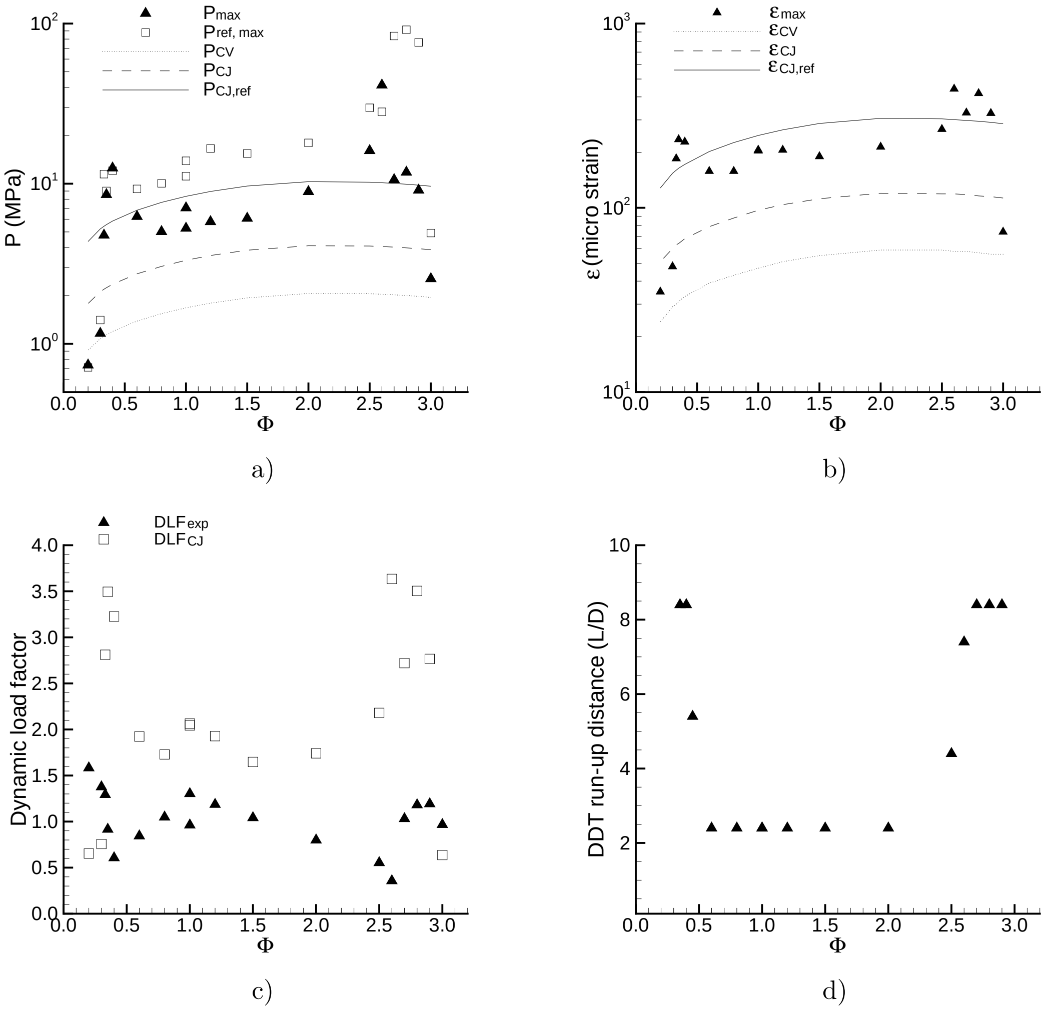

Figure 3: a) Experimental peak pressures (symbols) and calculated (lines) pressures, b) Peak strain ϵ. c) Dynamic load factors (DLF), and d) DDT run-up distance L/D (D is the tube diameter) vs. equivalence ratio Φ. $P_0 = 1$ bar and $T_0 = 300$ K.

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