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Direct impulse measurements were carried out for detonations and deflagrations in a tube closed at one end by using a ballistic pendulum arrangement. Three tubes with length to internal diameter ratios of 8, 13, and 40 were tested with stoichiometric propane- and ethylene-oxygen-nitrogen mixtures. Results were obtained as a function of initial pressure and percent diluent. The effect of internal obstacles on the transition from deflagration to detonation was studied. Three different extensions were tested to investigate the effect of exit conditions on the ballistic impulse for ethylene-oxygen mixtures as a function of initial pressure and percent nitrogen.

Nomenclature

c_2	sound speed of burned gases just behind detonation wave
c_3	sound speed of burned gases behind Taylor wave
d	inner diameter of detonation tube
g	gravitational acceleration
I	single-cycle impulse
I_{sp}	mixture-based specific impulse
I_V	impulse per unit volume
L	length of detonation tube filled with charge
L_p	length of pendulum arm
L_t	overall length of detonation tube and extension
m	pendulum mass
P_1	initial pressure of reactants
P_2	Chapman-Jouguet pressure peak
P_3	pressure of burned gases behind Taylor wave
S	wetted surface area of tube's inner diameter
T_1	initial temperature of reactants
u_2	flow velocity just behind detonation wave
U_{CJ}	Chapman-Jouguet detonation velocity
V	inner volume of detonation tube
β	ratio of N_2 to O_2 concentration in initial mixture
Δx	pendulum deflection
γ_2	ratio of specific heats in combustion products
λ	cell size
ρ_1	initial density of reactants
τ	wall shear stress

Introduction

IMPULSE per cycle is one of the key performance measures of a pulse detonation engine. In order to evaluate the performance of an engine concept, it is necessary to have reliable estimates of the maximum impulse that can be obtained from the detonation of a given fuel-oxidizer combination at specified initial temperature and pressure. Of course, the overall performance of an engine will depend strongly on a number of other factors such as inlet losses, nonuniformity of the mixture in the detonation tube, and the details (nozzles, extensions, coflow, etc.) of the flow downstream of the detonation tube exit. In order to make some progress on this issue without considering a specific engine configuration, we have examined the idealized problem of the impulse created by detonating a uniform mixture in a constant-area tube that is closed at one end and open at the other.

Direct impulse measurements were made for single-cycle detonations initiated in three detonation tubes with different length to internal diameter (L/d) ratios. Each tube was hung from the ceiling in a ballistic pendulum arrangement. The effect of various obstacles on the transition to detonation and the measured impulse was examined for propane- and ethylene-oxygen-nitrogen mixtures with varying initial pressure and dilution amounts. Deflagration-to-detonation transition (DDT) distances and times were obtained for these mixtures. The measured impulses were used to validate an analytical model[1] that provides estimates for the impulse per unit volume and specific impulse of a single-cycle pulse detonation engine for a wide range of fuels (including aviation fuels) and initial conditions. Additional experiments were carried out to investigate the effect of three types of extensions to the tube.

Experimental setup

Direct measurements were made of the impulse delivered by a DDT-initiated detonation or a fast flame in a tube (see Figure 9). The impulse was determined by measuring the displacement using a ballistic pendulum that consisted of a tube suspended from the ceiling by four steel wires (Figure 1). The combustible mixture, initially contained in the tube by a thin diaphragm sealing the open end, was ignited by a spark at the closed end of the tube. Combustion products were free to expand out from the tube into an unconfined volume. Pressure histories were recorded, including the pressure at the thrust surface as shown in Figure 2, which is formed by the interior of the closed end of the tube. Ionization gauges were used to determine the time-of-arrival of the wave.

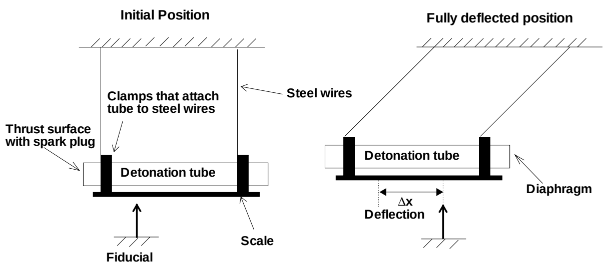

Fig. 1 Ballistic pendulum arrangement for direct impulse measurement.

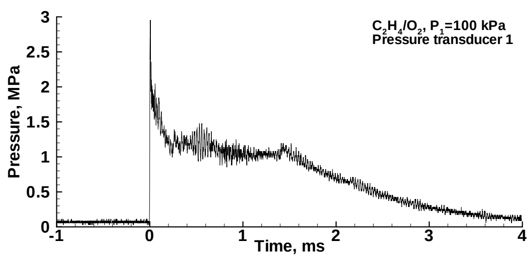

Fig. 2 Sample pressure trace recorded at thrust surface.

The three detonation tubes tested had the following dimensions: (1) 76-mm diameter by 0.609 m long (L/d = 8), (2) 76-mm diameter by 1.016 m long ($L/d = 13$), and (3) 38-mm diameter by 1.5 m long ($L/d = 40$). Several obstacle configurations were investigated, including two spirals, blockage plates, and orifice plates. All obstacles tested had a blockage ratio of 0.43. The blockage ratio is defined as the ratio of unblocked area to the total area. The choice of blockage ratio was based on work by Lindstedt et al., who cite 0.44 as the optimal configuration.[2]

The tube with $L/d = 8$ contained four ionization gauges and three PCB pressure transducers positioned along the tube's length. An additional PCB pressure transducer was positioned on the thrust surface. Two spirals (pitch 28 and 51 mm) extending the length of the tube were used to induce DDT in ethylene- and propane-oxygen with increasing nitrogen dilution up to the amount equivalent to that in air. Initial pressures ranged from 50 to 100 kPa. Different regimes of detonation, DDT, and fast and slow flames were observed with varying nitrogen dilution and some examples of pressure histories are given in Figures 3, 4, 5, and 6.

The tube with $L/d = 13$ contained ten ionization gauges and three pressure transducers positioned along the tube's length. An additional PCB pressure transducer was located at the closed end of the tube. Measurements were carried out in stoichiometric ethylene-oxygen mixtures with nitrogen dilution in a tube free of obstacles and with three different obstacle configurations: blockage plates spaced at one tube diameter were suspended along the centerline of the entire tube by a single threaded rod, and orifice plates were spaced at one tube diameter both along the entire length of the tube and along half the length of the tube in the upstream portion.

The tube with L/d of 40 contained a 0.305-m long Shchelkin spiral of 11-mm pitch in the upstream portion. Experiments were carried out for propane-oxygen with varying nitrogen dilution.

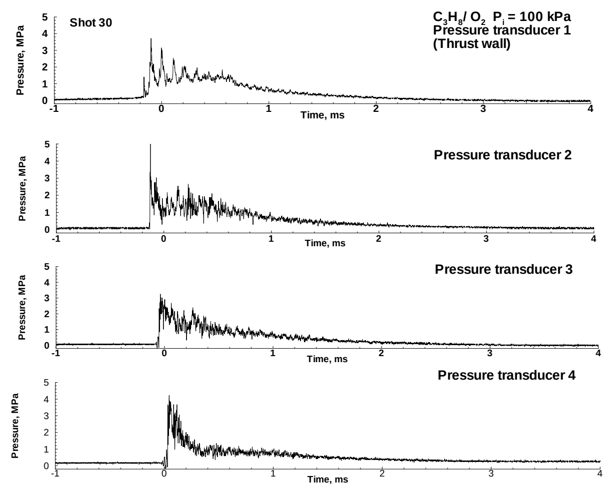

Fig. 3 Pressure history recorded in stoichiometric C_3H_8-O_2 in the tube of $L/d = 8$ illustrating the detonation case.

Results on detonation initiation

The inclusion of obstacles in the tube dramatically reduced the DDT time for ethylene-oxygen-nitrogen mixtures. The effectiveness of obstacles for reducing DDT time is well known and has been extensively studied, however, the role of obstacles in determining impulse has, to our knowledge, not been previously studied. The DDT time was determined by measuring the combustion wave velocity, defined as the ratio of the distance between ionization probes to the time it took the reaction zone to pass from one ionization probe to the next. The combustion wave is said to have undergone DDT when this average velocity is equal to or greater than the Chapman-Jouguet detonation velocity, U_{CJ}. At 30 kPa initial pressure, the obstacles reduced the DDT time by an average of 65%, as

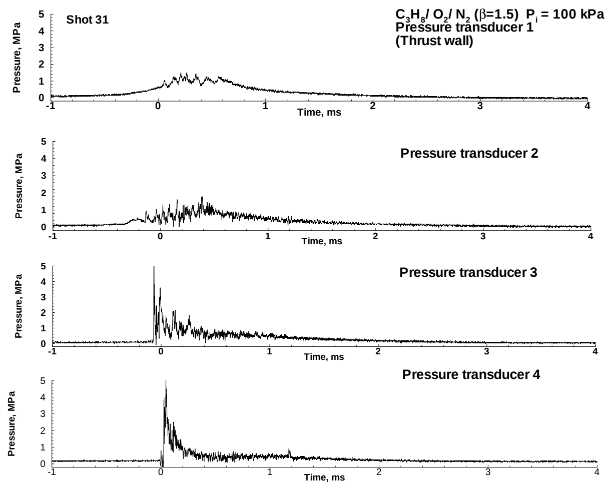

Fig. 4 Pressure history recorded in C_3H_8-O_2-N_2 with $\beta = 1.5$, $L/d = 8$, illustrating the deflagration-to-detonation case.

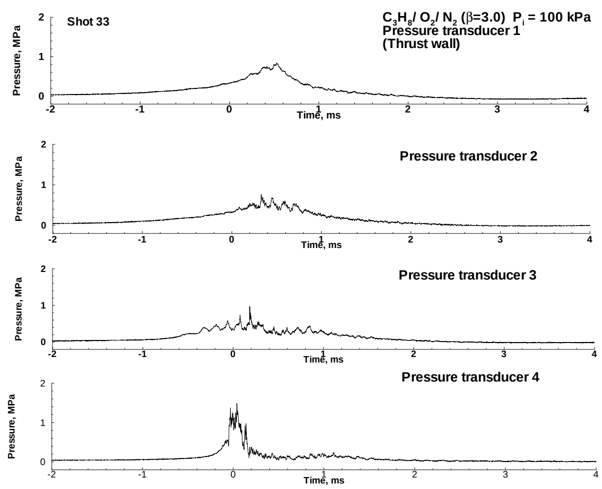

Fig. 5 Pressure history recorded in C_3H_8-O_2-N_2 with $\beta = 3$, $L/d = 8$, illustrating the fast flame case.

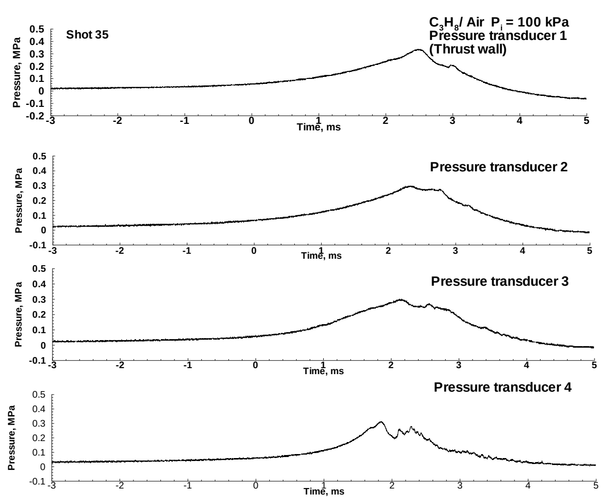

Fig. 6 Pressure history recorded in C_3H_8-air, L/d = 8, illustrating the slow flame case.

shown in Figure 7. The obstacles allowed DDT to occur in mixtures composed of up to 60% nitrogen (see Figure 8). Comparatively, with no obstacles present, DDT was not achieved in mixtures with more than 30% nitrogen. Only a fast flame could be initiated in ethylene-air.

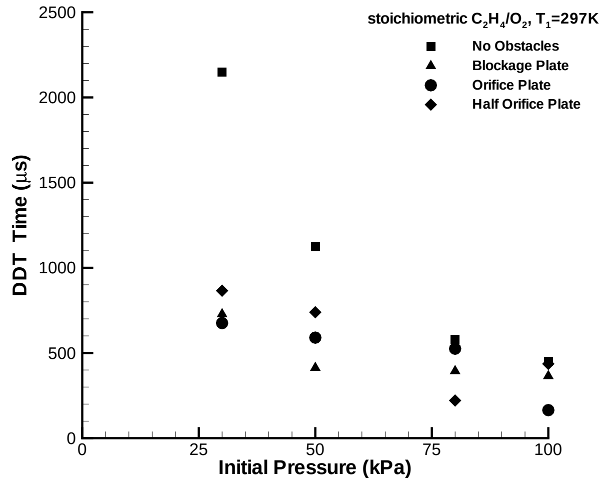

Fig. 7 Measured DDT time for stoichiometric C_2H_4-O_2 mixtures with varying initial pressure for three obstacle configurations in the 76-mm diameter tube, $L/d = 13$.

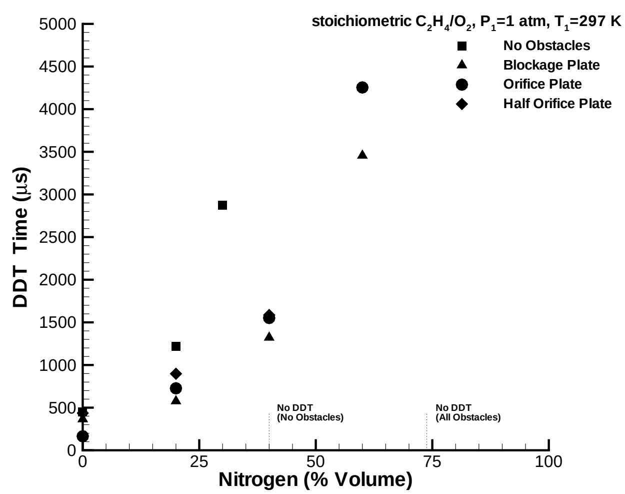

Fig. 8 Measured DDT time for stoichiometric C_2H_4-O_2 mixtures with varying nitrogen dilution for three obstacle configurations in the 76-mm diameter tube, $L/d = 13$.

The relative ability of the mixture to transition to detonation can be related to[3,4] the detonation cell size and other properties of the mixture, such as the expansion ratio. Critical conditions for DDT require that the cell width be smaller than a specified fraction of the tube or obstacle dimensions, the expansion ratio (ratio of burned to unburned gas volume) must be larger than a minimum value, and that the deflagration speed exceed a minimum threshold. For simple situations, transition to detonation is possible only if the detonation cell width is smaller than the tube diameter (unobstructed tube) or smaller than the obstacles' aperture (obstructed tube).

Detonations in stoichiometric ethylene-oxygen mixtures could be initiated by DDT in an unobstructed tube for all the pressures studied between 30 and 100 kPa. Since cell size increases with decreasing initial pressure, the largest cell size observed was about 0.5 mm corresponding to ethylene-oxygen at 30 kPa. Similarly, for nitrogen-diluted mixtures, DDT was obtained in the unobstructed tube configuration up to 30% dilution. Since cell size increases with increasing dilution, the largest cell size observed was about 0.6 mm corresponding to ethylene-oxygen at 30% dilution. These cell size values are significantly less than the tube diameter of 76 mm. This indicates the difficulty of obtaining a detonation in a such a short tube with no obstacles and a weak spark as the ignition source.

When internal obstacles were included, DDT was observed up to 60% dilution (corresponding to a cell size of the order of 10 mm) but could not be obtained for ethylene-air mixtures (corresponding to a cell size of 29 mm). The cell size increases with nitrogen dilution, as the mixtures become less sensitive. The presence of obstacles enabled less sensitive mixtures to transition to detonation, but there are limits to obstacle effectiveness. Wintenberger et al.[1] have used the ideas of Dorofeev et al.[3] to estimate limits for DDT in obstructed tubes.

Impulse determination

The impulse was calculated by measuring the deflection of the ballistic pendulum and utilizing conservation of momentum and energy to convert the deflection to impulse

$$I = m\sqrt{2gL_p\left(1-\sqrt{1-\left(\frac{\Delta x}{L_p}\right)^2}\right)}\ , \qquad (1)$$

where m is the pendulum mass, Δx is the measured displacement, g is the gravitational acceleration, and L_p is the pendulum arm. We refer to I measured in this fashion as the *ballistic* impulse. The ballistic impulse is specific to a given facility and tube size. Two measures of the impulse that are independent of tube size are the impulse per unit volume

$$I_V = I/V \qquad (2)$$

and the specific impulse based on the total explosive mixture mass

$$I_{sp} = \frac{I}{g\rho_1 V}\ . \qquad (3)$$

The impulse can also be calculated by placing a control volume around the detonation tube and considering the conservation of momentum. The conventional control volume used in rocket motor analysis is not suitable since the exit flow is unsteady, and the required quantities (pressure and velocity) are unknown. More useful is to place the control volume on the surface of the detonation tube as shown in Figure 9.

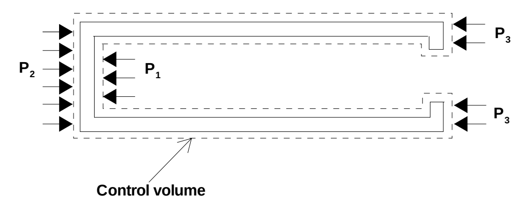

Fig. 9 Pulse detonation engine control volume.

The force balance in the x-direction (along the axis of the tube) can be written as

$$F = (P_2 - P_1)A_1 + \sum_{obstacles}\int P\mathbf{n}\cdot\mathbf{x}\,dA + \int \tau\,dS + (P_2 - P_3)A_3\ , \qquad (4)$$

where τ is the wall shear stress, S is the wetted surface area of the tube's inner diameter, A_1, A_2, and A_3 are the areas that correspond to the pressures as displayed in Figure 9. The first term on the right side of the equation is the force on the thrust surface, the second term is the drag (due to pressure differentials) associated with the separated flow over the obstacles, the third term is the viscous drag, and the last term represents the force over the tube wall thickness. The impulse is obtained by integrating the force over a cycle

$$I = \int F\,dt\ . \qquad (5)$$

Obviously, if all of the terms making up F can be correctly computed or measured, the ballistic impulse and the impulse computed from this control volume integration should be identical. Previous studies[5] have used Equation 4 for analyzing data from unobstructed tubes and neglected all but the first contribution to the force. For a tube without obstructions and prompt transition to detonation, this is a reasonable approximation which we have verified by direct experimental measurement of P_2 and simultaneous measurement of the ballistic impulse. However, in the case of obstacles, the net contribution of the two drag terms may be substantial and using the first term alone can result[6] in overestimating the force and impulse by up to 50%. Since it would be very difficult, if not impossible, to estimate or measure accurately all of the terms in

Equation 4, direct measurement of the impulse is the only practical method for tubes with obstructions or other unusual features like nozzles at the exit.

Impulse measurements

Direct impulse measurements for propane-oxygen-nitrogen mixtures at different initial pressures are shown in Figure 10 for two different spiral configurations in two tubes, $L/d = 8$ and 40. Similar results for the nitrogen dilution case are displayed in Figure 11. The measured impulse values appear along with the analytical model predictions.[1] The impulse normalized by the tube volume, I_V, as well as the mixture-based specific impulse, I_{sp}, are given in order to facilitate comparison between the different tube sizes. The impulse per unit volume increases linearly with increasing initial pressure while the specific impulse reaches a constant value, as predicted by the model.[1] The impulse per unit volume and specific impulse both decrease with increasing nitrogen dilution. The amount of fuel present in a given volume of mixture decreases with increasing amounts of dilution, reducing the total energy released during detonation. This is consistent with the model predictions.

Failure to transition to detonation causes the substantial deviation of the measurements from the model predictions for the cases of higher dilution, even though a Shchelkin spiral extends over the entire tube length. As the pressure is decreased or amount of diluent is increased, the detonation cell width becomes larger and it becomes progressively more difficult to initiate a detonation within the tube. For large amounts of diluent, only deflagrations are observed within the tube, see Figures 5 and 6. The impulse for these cases is much smaller than the predicted value for detonations, even in the cases of fast flames, since a substantial fraction of the fuel is burned outside of the tube. This indicates the importance of using more sophisticated initiation methods for fuels with detonation cell widths similar to propane, this includes all of the storable liquid hydrocarbons such as Jet A, JP-8, JP-5 or JP-10. Experiments with more sensitive ethylene-oxygen-diluent mixtures, described subsequently, show that using obstacles to induce DDT within the tube can be effective.

The results for ethylene-oxygen mixtures, $L/d = 13$ are presented in Figure 12 for initial pressure variation and in Figure 13 for varying nitrogen dilution. The measured impulse values appear along with the analytical model predictions.[1] The measured values are at most 10 to 20% lower than the predicted values over the range of pressure studied. The experimental and model results are also comparable in the nitrogen-diluted cases as long as the concentration of nitrogen is less than 50%. Note that without obstacles, detonation cannot be achieved in this tube for nitrogen concentrations of 40% or greater. This is indicated by

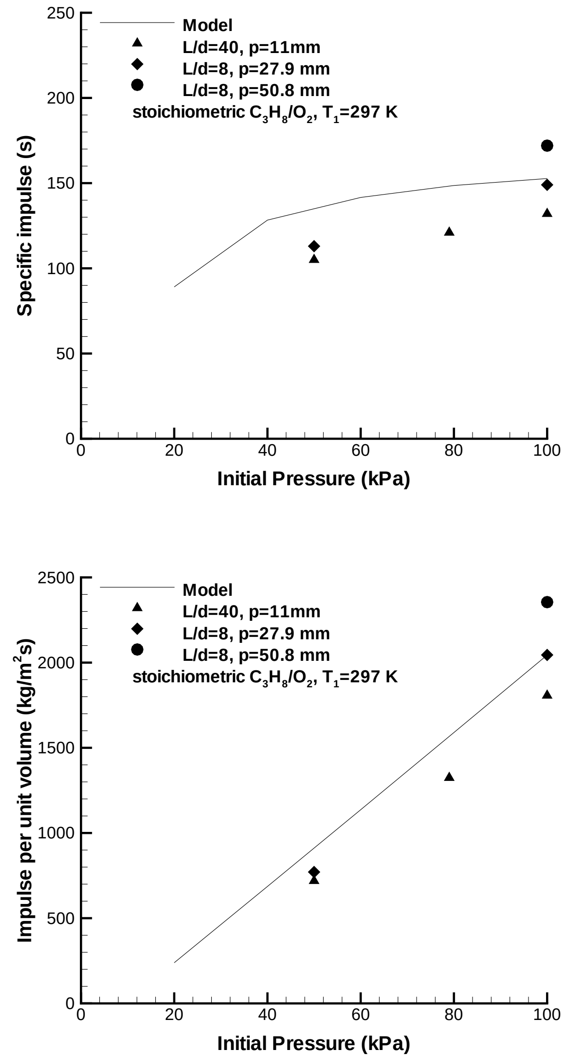

Fig. 10 Impulse measurements for stoichiometric C_3H_8-O_2 mixtures with varying initial pressure. Results are shown for two Shchelkin spiral pitches.

the dramatic drop in measured impulse for the "No obstacles" case shown in Figure 13. Using obstacles within the tube is effective at inducing transition to detonation until the nitrogen concentration is greater than about 60%. Beyond this point, the cell width is sufficiently large that transition to detonation occurs only in the later portion of the tube and not all of the mixture burns within the tube.

When obstacles are present in the tube, they promote the onset of DDT, which can significantly increase the impulse over the values for an unobstructed tube. The loss in impulse that occurs when there is only a flame or DDT occurs very late in the process can be easily understood. When a deflagration wave is initiated at the closed end and propagates slowly for an extended period of time, it can compress the unburned gas ahead of it enough to rupture the diaphragm. The

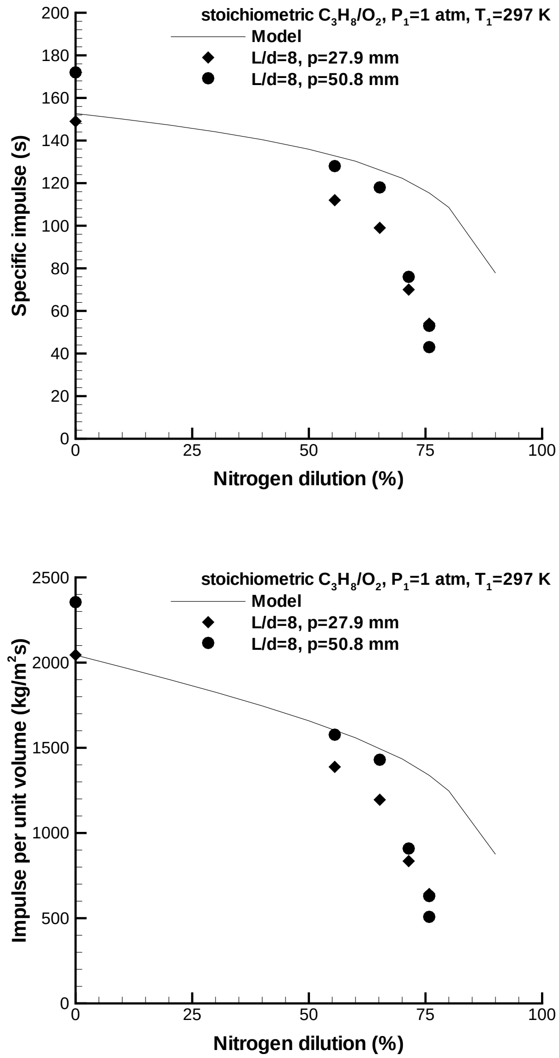

Fig. 11 Impulse measurements for stoichiometric C_3H_8-O_2 mixtures with varying nitrogen dilution.

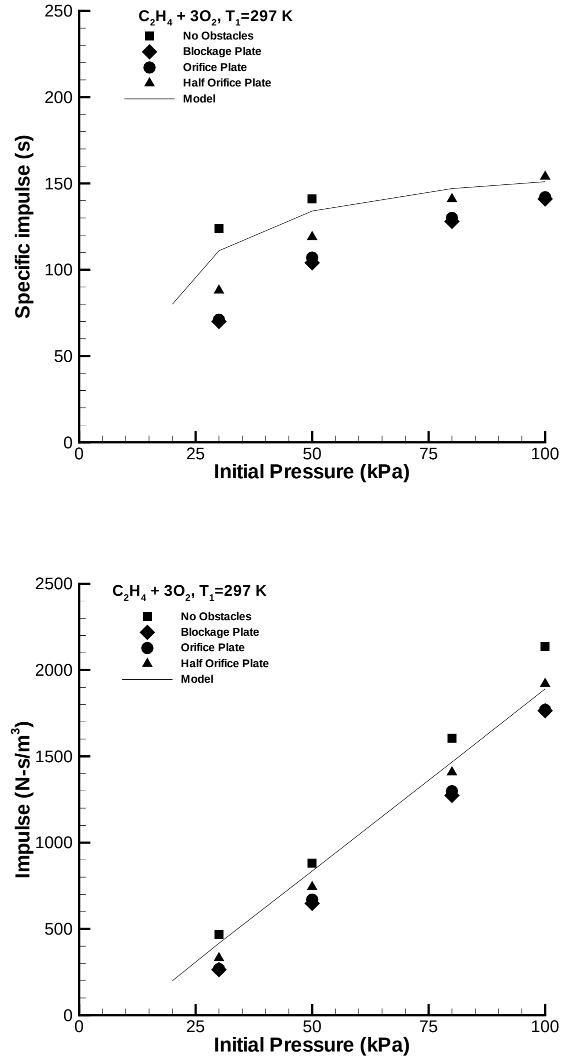

Fig. 12 Impulse measurements for stoichiometric C_2H_4-O_2 mixtures with varying initial pressure in the $L/d = 13$ tube.

rupture of the diaphragm results in a considerable part of the mixture being ejected outside the tube, where its combustion will not contribute materially to the impulse. The onset of a detonation wave can mitigate this effect due to the higher propagation speed of the detonation. If DDT occurs early enough in the process, the detonation can overtake the compression waves created by the deflagration before they reach the diaphragm. The loss associated with this phenomenon is expected to become pronounced when DDT occurs in the last quarter of the tube, so that the detonation does not have time to catch up with the deflagration compression waves. The disadvantage of obstacles is that in cases where DDT occurs promptly, the drag of the obstacles can decrease the impulse by up to 25% from the value measured without obstacles.

Experimental error analysis

An error analysis was performed to quantify experimental uncertainties. We used the standard method[7] for estimating the propagation of errors to determine the uncertainty in the ballistic impulse given the uncertainties in the initial conditions. Generally, the variance ΔI_V, associated with the measured quantity $I_V(x_1, ...x_n)$ can be estimated as

$$\Delta I_V = \sqrt{\left(\frac{\partial I_V}{\partial x_1}\right)^2 (\Delta x_1)^2 + ... \left(\frac{\partial I_V}{\partial x_n}\right)^2 (\Delta x_n)^2} \, .$$

Using the expression for ballistic impulse in Equation 1, the uncertainty in the direct experimental measurements of the impulse per unit volume, I_V, can be quantified. The estimated uncertainties in the pendulum mass, the tube volume, the pendulum arm length,

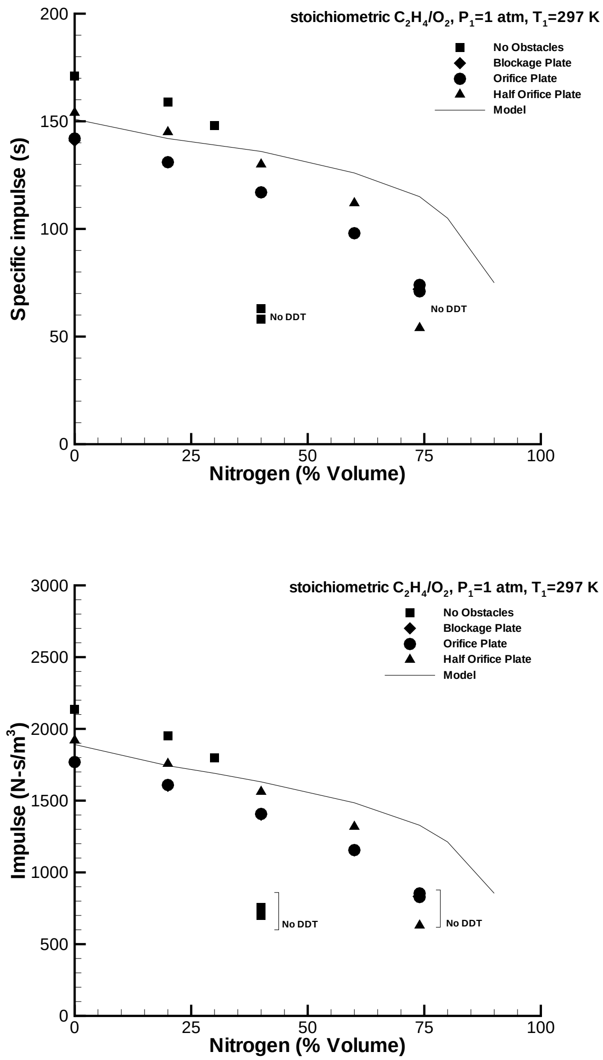

Fig. 13 Impulse measurements for stoichiometric C_2H_4-O_2 mixtures with varying nitrogen dilution in the $L/d = 13$ tube.

Table 1 Uncertainties used in determining the error for experimentally measured impulse.

Quantity	Range of values	Uncertainty
L_p	1.4-1.55 m	$\pm$0.0016 m
Δx	2-292 mm	$\pm$0.5 mm
m	12.808-55.483 kg	$\pm$0.001 kg
V	1.14-4.58$\times10^{-3}$ m^3	$\pm$4.5$\times10^{-8}$ m^3

and the measured pendulum deflection are given in Table 1. From this analysis, we estimate the total experimental uncertainty in the direct impulse measurements to be at most $\pm$4%.

Uncertainties in the initial conditions can also be quantified. The measured leak rate was 0.5 mbar/min from an initial vacuum of 100 mTorr. The maximum time required to complete the experiment was 15 minutes which results in a worst-case dilution of 8 mbar. A study to identify the mixture most affected by this leak rate found stoichiometric C_2H_4-O_2 at an initial pressure of 0.3 bar to be the most sensitive case. An error analysis was then performed for this mixture to find the maximum uncertainty in initial conditions for all experiments. The analytical model[1,8]) can be used to express I_V as a function of U_{CJ}, P_3, and c_3. The quantity ΔU_{CJ} is the difference in the Chapman-Jouguet velocity for a mixture containing an additional 8 mbar of air as a result of the leak and the ideal case. STANJAN[9] was used to calculate U_{CJ} for the two cases. ΔP_3 and Δc_3 can then be found from differences in P_3 and c_3 for the two mixtures, where P_3 and c_3 are given by the relationships below, which are derived by using the method of characteristics through the Taylor wave,[1]

$$\frac{P_3}{P_2} = \left(\frac{c_3}{c_2}\right)^{\frac{2\gamma}{\gamma-1}} \tag{6}$$

$$= \left(\frac{\gamma+1}{2} - \frac{\gamma-1}{2}\frac{U_{CJ}}{c_2}\right)^{\frac{2\gamma}{\gamma-1}} . \tag{7}$$

Table 2 Variations in flow parameters resulting from uncertainty in initial conditions due to error in dilution (leak rate), initial pressure, and initial temperature as described in the text. The mixture chosen is stoichiometric C_2H_4-O_2 at an initial pressure of 0.3 bar, which corresponds to the worst case of all the mixtures considered in experiments. The percentage error in I_V is based on the model predicted impulse.[1]

	Ideal	Dilution	Pressure	Temperature
P_1 (bar)	0.3	0.3	0.301	0.3
T_1 (K)	295	295	295	298
U_{CJ} (m/s)	2317.9	2301.3	2307.5	2317.3
P_2 (kPa)	970.2	955.2	965.4	960.0
c_2 (m/s)	1249.	1240.	1243.	1249.
γ_2	1.23	1.23	1.23	1.23
P_3 (kPa)	318.5	314.8	317.2	315.3
c_3 (m/s)	1123.	1117.	1119.	1123.
ΔU_{CJ}(m/s)	-	16.6	10.4	0.6
ΔP_3 (Pa)	-	3620	1242	3185
Δc_3 (m/s)	-	6.2	4.6	0.040
ΔI_V	-	1.7%	0.6%	1.5%

Table 2 lists the calculated maximum changes in the flow parameters due to the leak rate. Also shown are the largest possible error contributions due to uncertainty in the initial pressure because of gauge precision ($\pm$1 mbar) and due to uncertainty in the initial temperature (295-298 K). All uncertainties shown are calculated for comparison with the same ideal case, stoichiometric C_2H_4-O_2 at an initial pressure of 0.3 bar, and initial temperature 295 K.

Combining the results in Table 2, the error in the initial conditions is found to contribute at most ±2.3%, resulting in an overall maximum uncertainty of ± 6.3% in ballistic measurements of the impulse.

Experimental repeatability was also considered. Experiments in which a detonation was initiated directly were repeatable to within ±0.7%. In cases where late DDT or fast flame was observed, the impulse in repeat experiments varied by as much as ±17% due to the turbulent nature of the initiation process.

In addition, experiments were carried out to eliminate some systematic errors. There is no detectable out-of-plane motion during the initial pendulum swing. The ballistic impulse was correlated against the impulse calculated by integrating the thrust surface pressure for C_2H_2-O_2 at 100 kPa (a sensitive mixture expected to minimize the losses due to detonation initiation) and found to be within 3%.

The mass of the diaphragm is 0.27 g. For comparison, the mass of the C_2H_4-air mixture at 50 kPa (one of the lighter mixtures) is 3.3 g. Since the mass of the diaphragm is 8% of the total mass of the explosive mixture, we expect that in the worst case this would have a tamping effect equivalent to adding an inert gas-filled extension that is 8% of the original tube length. This would have the effect of slightly (1-2%) increasing the impulse over the ideal (zero mass diaphragm) case. However, since the diaphragm is located at the end of the tube, the acceleration of the diaphragm away from the tube exit is expected to rapidly diminish the tamping effect.

Effect of extensions on the specific impulse

Proposed concepts for pulse detonation engines have often included the addition of different kinds of extensions, including nozzles, to the basic straight detonation tube. In part, this is motivated by the effectiveness of converging-diverging nozzles in conventional rocket motors. The effectiveness of a converging-diverging nozzle is based on the steady flow conversion of the thermal to kinetic energy in the supersonic flow downstream of the throat. However, the pulse detonation engine is a completely unsteady device and the conversion of thermal to kinetic energy is accomplished through waves. It is not obvious how a nozzle would affect performance since the diffraction of the detonation wave through a nozzle is a complex process.

We have approached this problem experimentally by examining the effect of various exit treatments on the measured impulse. Previous experiments by Zhdan et al.[10] with straight cylindrical extensions indicate that the mixture-based specific impulse will increase as the ratio of the overall tube length, L_t, to the tube length filled with combustible gases, L, increases. Note that the mass of air in the extension volume is not included in the mixture mass used to compute the specific impulse. In these tests, a thin diaphragm separated the tube length filled with the combustible mixture from the extension, which was filled with air at atmospheric conditions. This simulates the condition of having a single tube only partially filled with explosive mixture.

Extensions tested

Three different extensions were tested on the detonation tube with an L/d ratio of 13 in a ballistic pendulum arrangement to determine their effect on the mixture-based specific impulse. Each extension modified the total tube length, L_t, while the charge length, L, remained constant.

The first extension was a flat plate ($L_t/L = 1$) or flange with an outer diameter of 0.381 m that extended radially in the direction perpendicular to the tube's exhaust flow. A hole located in the center of the plate matched the tube's inner diameter, thus increasing the apparent wall thickness at the exhaust end from 0.0127 m to 0.1524 m. The purpose of this flange was to see if the pressure behind the diffracting shock wave would contribute significantly to the specific impulse. In effect, we are studying the role of the last term (wall thickness) in the momentum control volume analysis, Equation 4. The second extension was a straight cylinder ($L_t/L = 1.6$) with a length of 0.618 m. This extension simulated a partial fill case. The third extension was a diverging conical nozzle ($L_t/L = 1.3$) with a half angle of eight degrees and a length of 0.3 m.

Impulse measurements

Each extension was tested with ethylene-oxygen-nitrogen mixtures where the nitrogen percentage varied from 0% to 40%. The flat plate and straight extension were tested without internal obstacles and the specific impulse values appear in Figure 14.

The flat plate extension yielded a maximum specific impulse increase of 5% at 0% nitrogen dilution which is within experimental error. At 40% nitrogen dilution, DDT did not occur and the flat plate extension decreased the impulse by 7%. This percentage decrease is within the experimental error for cases with late or no DDT, preventing any conclusion about the plate's performance for this test case. The straight extension increased the measured specific impulse by 18% at 0% nitrogen dilution, whereas a 230% increase in the specific impulse occured at 40% nitrogen dilution. This large increase in the specific impulse occurred since the additional tube length enabled DDT to occur in the extension's confined volume.

To better isolate the effect of the extensions over the range of diluent percentages tested, cases of late or no DDT were eliminated by the addition of internal obstacles in the combustion chamber. The results appear in Figure 15. The obstacles consisted of orifice plates spaced one tube diameter apart over half of the detonation tube starting at the closed end of the the tube. The straight extension was retested along with the di-

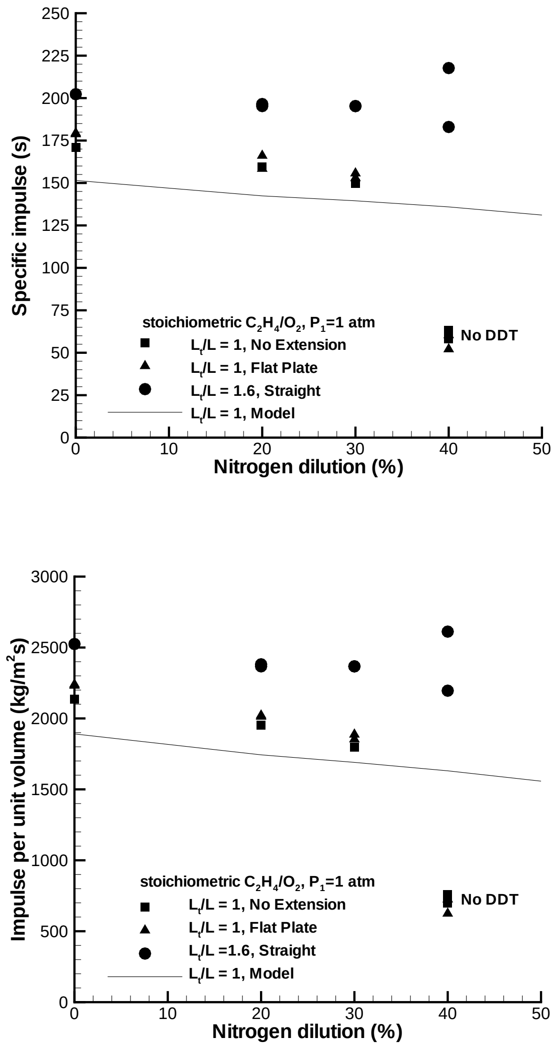

Fig. 14 Specific impulse for varying diluent with no internal obstacles.

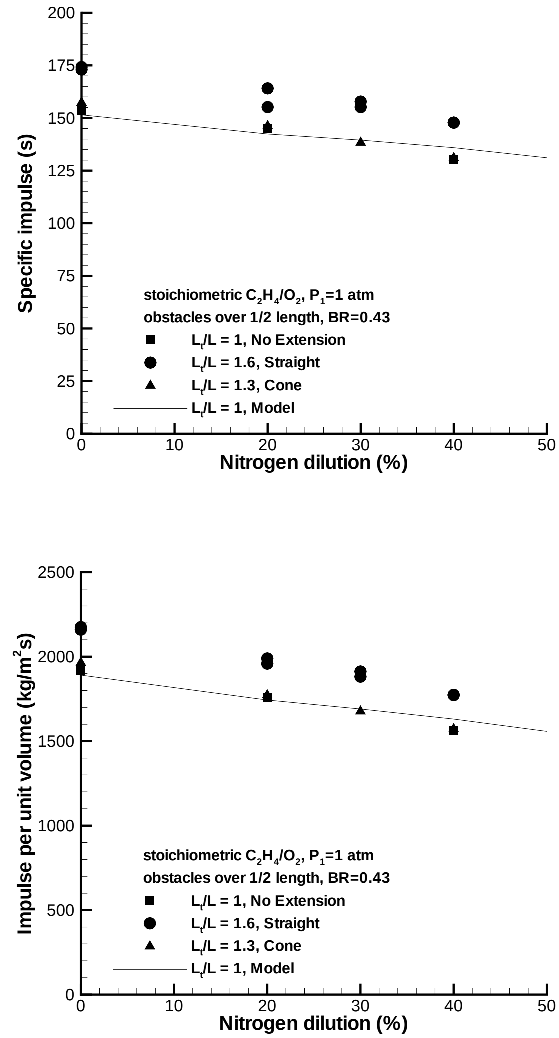

Fig. 15 Specific impulse for varying diluent with half orifice plate internal obstacles.

verging nozzle at varying percent diluent. The flat plate extension was not retested due to its small effect on the measured impulse as shown above. The addition of the internal obstacles resulted in the straight extension increasing the specific impulse by an average of 13%. The reduction in impulse from the unobstructed tube case is due to pressure and viscous drag losses induced by the obstacles. The diverging nozzle had a minor effect, increasing the specific impulse by an average of 1%, which is within the experimental error.

The straight extension was much more effective than the diverging nozzle at increasing impulse; this is due to the additional length of the extension delaying the arrival of the expansion wave from the tube exit, effectively increasing the pressure relaxation time. Standard gas dynamics considerations, supported by numerical studies of partial filling by Li et al.,[11] indicate that two expansion fans will be created when an extension filled with inert gas is added to a detonation tube. The first expansion fan is due to the reflection of the detonation at the mixture-air interface and is much weaker than the expansion fan created by the shock or detonation diffraction at the tube exit.[11] Another way to interpret this effect is that the added inert gas provides additional tamping[12] of the explosion which will increase the momentum transfer from the detonation products to the tube.

The straight extension is much more effective than the diverging nozzle at delaying the arrival time of the expansion fan. The diverging nozzle is shorter than the straight extension, but more significantly, the continuous area change of the diverging nozzle creates expansion waves that propagate back to the thrust surface resulting in a gradual but continuous decrease in pressure that starts as soon as the detonation reaches the entrance to the diverging nozzle. The flat plate or flange extension has a minimal effect on the impulse since the shock Mach number decays very quickly as the shock diffracts out from the open end. The amount of impulse contributed by the pressure of the decaying shock is relatively small compared to that obtained from the pressure of the detonation products on the thrust surface at the closed end of the tube. In addition, the rate of pressure decrease at the exit is relatively unaffected by the flange so that the rate of pressure decay at the thrust surface is very similar with and without the flat plate.

Summary and Conclusion

Direct impulse measurements were made in three separate detonation tubes with diameters of 38 ($L/d = 40$) and 76 mm ($L/d = 8, 13$). A flame was initiated with a low-energy spark and transition to detonation occurred after some period of flame acceleration. A ballistic pendulum arrangement was used to measure impulse and these values were compared to those obtained from a simple analytical model.[1] Tests were conducted in plain tubes without any internal obstructions and in tubes with internal obstacles having a blockage ratio of 0.43. In plain tubes, DDT occurred only for very sensitive mixtures where the cell size was two orders of magnitude smaller than the tube diameter. The addition of obstacles enabled DDT to occur in less sensitive mixtures where the cell size was only one order of magnitude smaller than the tube diameter. However, the impulse was 25% less with obstacles than without at the same initial conditions. A late DDT event was also found to decrease the measured impulse. An error analysis of the impulse yielded an overall uncertainty of $\pm 6.3\%$ in cases were DDT occured sufficiently early within the tube.

The effect of different exit arrangements was studied by using three different types of extensions. A relationship between the overall length-to-charge length (L_t/L) ratio and impulse was observed. The straight extension with a L_t/L ratio of 1.6 resulted in the greatest increase in impulse. A direct comparison with other research on extensions and partial filling is difficult due to the significant differences in detonation tube and extension dimensions between the various facilities. Research by Zitoun et al.[5] studied L_t/L ratios between 1.03 and 1.2; however, the L/d values varied from 1 to 8.5. The L/d ratio of the tube tested with the extensions was 13, preventing a direct comparison in impulse values. A numerical study[11] in partial filling observed a decrease in the mixture-based specific impulse as L_t/L increased. However, this study involved a tube of constant overall length and a variable length of tube filled with the explosive mixture. Alternatively, the results presented above suggest an increase in the mixture-based specific impulse if the tube length filled with the charge remains constant and the overall tube length varies because of the extensions. The effective of diverging nozzles and flanges on the impulse was slight.

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