DETONATION INITIATION BY A HOT TURBULENT JET FOR USE IN PULSE DETONATION ENGINES

D. H. Lieberman,* K. L. Parkin,† and J.E. Shepherd‡
Graduate Aeronautical Laboratories,
California Institute of Technology, Pasadena, CA 91125

Experiments are carried out to determine the effectiveness of using a hot turbulent jet to initiate a detonation in a short tube. The hot gases are created by combustion in a driver section. The combustion products rupture a Mylar diaphragm and jet into the test section, initiating a turbulent flame. If the appropriate conditions exist, the turbulent flame will form a detonation by a deflagration-to-detonation transition mechanism. This method of detonation initiation may be useful for pulse detonation engines. The present study examined the possibility of using this technique to initiate a detonation in a surrogate fuel-air mixture with a detonation sensitivity similar to that found in mixtures of vaporized liquid fuel and air.

The test section is filled with a stoichiometric propane-oxygen mixture with varying nitrogen dilution. An orifice that can varied between 3 and 19 mm in diameter links the two sections. The current study varies the initial pressure of the driver section, which uses a stoichiometric propane-oxygen mixture, and the orifice diameter to find the maximum nitrogen dilution level for which a detonation can still be initiated. Impulse measurements are obtained using the ballistic pendulum method and the measured maximum deflection of the tube. Driver pressure is found to have a mild effect on increasing the critical N_2 dilution. The 3 mm orifice diameter was used in the pressure variation experiments; a 10% increase in N_2 dilution was obtained when initial driver pressures were increased from 1 to 4 bar. Increasing the orifice diameter from 3 mm to 19 mm increases the critical dilution level from 30% to 40% N_2.

Nomenclature

A_T	cross-sectional area of the orifice, m^2
A_{wet}	surface area of the driver section, m^2
a_T	speed of sound at the orifice, m^2/s
d	inner diameter of detonation tube, m
E_S	energy of fluid in driver section
g	gravitational acceleration, m/s^2
h_c	convective heat transfer coefficient, W/m^2K
h_T	specific enthalpy at the orifice, J/kg
I	single-cycle impulse, kg m/s
I_{sp}	mixture-based specific impulse, s
L_p	length of pendulum arm, m
m	pendulum mass, kg
M_S	mass of fluid in the driver section, kg
P_1	initial pressure in the test section, Pa
P_0	initial pressure in the driver section, Pa
P_{CJ}	Chapman-Jouguet detonation pressure, Pa
S	wetted surface area of inner tube diameter, m^2
T_1	initial temperature of reactants, K
T_S	temperature of the driver section, K
T_{wall}	temperature of the driver wall, K
U_{CJ}	Chapman-Jouguet detonation velocity, m/s
V	inner volume of detonation tube, m^3
β	ratio of N_2 to O_2 moles in initial mixture
Δx	pendulum deflection, m
λ	cell size, m
ρ_1	density of reactants in the test section, kg/m^3
ρ_T	density of venting products at the orifice, kg/m^3

*Graduate student, Aeronautics

†Graduate student, Aeronautics

‡Professor, Aeronautics

Introduction

THE pulse detonation engine (PDE) is an unsteady propulsion system that uses repeated detonation to generate thrust. The basic element is a tube that can be closed at one end by some sort of valve and open at the other. The basic cycle of operation is: a) the tube is filled with reactants, b) a detonation is initiated and propagates through the tube, c) the combustion products flow out of the tube, and d) the tube is purged and refilled with reactants. One important practical requirement of air-breathing PDEs is to use a liquid jet fuel such as JET-A or JP-10. There are a number of issues in handling liquid fuels including the problems of vaporization and mixing. An equally important issue is the ability to initiate a detonation in a fuel-air mixture. One possible initiation method is to use a hot jet of combustion products.

Detonation initiation by a hot turbulent jet is a process which involves the rapid mixing of hot combustion products into a fresh mixture of reactants. If the mixture of combustion products and reactants has the proper conditions, then prompt initiation of a detonation is observed.[1] In some circumstances where a mass of gas is confined to a tube or a channel, the turbulent jet will initiate a flame which can then proceed to transition to a detonation.[2] The ability to initiate a detonation using relatively small amounts of energy has been of interest in many applications and most recently for the successful operation of a PDE.[3,4]

Turbulent jet initiation was observed by Knystautas et al.[1] for sensitive fuel-oxygen mixtures. Moen et al.[5] carried out large-scale tests of acetylene-air mixtures into an unconfined test section. They investigated the effect of obstructing the jet orifice to enhance jet mixing in the test section. Ungut et al.[6] investigated the sensitivity of orifice diameter and initial pressure on hot jet initiation. They studied detonation initiation in stoichiometric propane-oxygen mixtures with nitrogen dilution. More recent work by Dorofeev et al.[7] looked at large-scale tests of hydrogen-air mixtures and the effects of jet orifice diameter. Krok[8] examined the initiation of hydrogen-air mixtures diluted with steam or nitrogen by using jets of hydrogen and steam.

The present study investigates the effectiveness of using a hot turbulent jet to initiate a detonation in a short detonation tube. To avoid the problems associated with vaporization and mixing of liquid fuels, we have used as a fuel gaseous propane, which has a detonation cell width, the most common measure of detonation sensitivity, that is similar[9] to stoichiometric mixtures of JP-10 and air. The study varies the initial driver pressure and the orifice diameter to find the critical test section mixture that will detonate. The test section contains a stoichiometric propane-oxygen mixture diluted with nitrogen. The experiments use a test facility that consists of a driver section to create the hot turbulent jet and a test section to verify whether or not a detonation was realized. The system is mounted on cables in a ballistic pendulum arrangement so that the impulse can be measured.[10]

Experimental setup

The experiments were carried out in the facility shown in Figure 1. There is a 0.14 m long driver section that is used as a combustion chamber to produce the hot products for the jet. The driver section is mounted onto the 1.0 m test section. The orifice linking the sections ranges from 3 to 19 mm in diameter and a Mylar diaphragm (25 μm thick) is placed between the two sections in order to prepare the desired mixtures and to attain higher explosion pressures in the driver section. A second Mylar diaphragm is placed at the end of the test section. The facility is suspended by four cables and balanced so that the impulse can be measured with the ballistic pendulum method. The length of the cables is 1.42 m and the mass of the entire system is 30.0 kg.

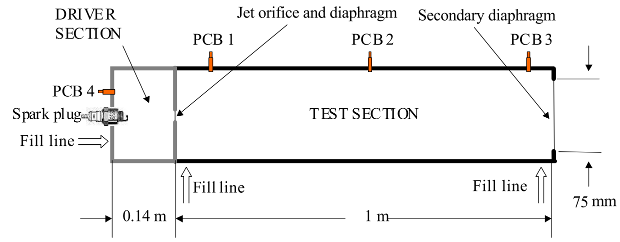

Fig. 1 Experimental facility. PCB1 is located 38.1 mm from the flange containing the jet orifice and diaphragm. PCB2 is located 559 mm from the orifice. PCB3 is located 975 mm from the orifice.

The test section has an internal diameter of 75 mm and is equipped with three piezoelectric pressure transducers as shown in Figure 1. The test section mixture is stoichiometric propane-oxygen with an amount of nitrogen dilution that is adjusted for each test. The mixture is prepared by the method of partial pressures to 1 bar total pressure and then is thoroughly mixed using a recirculation pump.

The driver section shown in Figure 1 has a 100 cm^3 volume and is mounted onto the test section using four quick-release clamps. An automotive spark plug is located opposite the orifice to ignite the mixture with a high voltage discharge; the total stored energy is 30 mJ. Two pressure transducers are mounted next to the spark plug. One is used to measure the static pressure in the driver section during filling and the other is used to measure dynamic pressures during combustion in the driver chamber. The driver uses a stoichiometric propane-oxygen mixture prepared by the method of partial pressure in a separate reservoir.

The ballistic pendulum method has previously been used to measure the specific impulse of detonation tubes.[10] This technique uses the measured maximum horizontal deflection of the tube and elementary mechanics to compute the impulse caused by the detonation and combustion product flowing out of the tube. The impulse is related to deflection by

$$I = m \left[2 g L_P (1 - \sqrt{1 - \left[\frac{\Delta x}{L_P} \right]^2} \right]^{1/2} . \qquad (1)$$

In the present study, the results are given in terms of the specific impulse based on the total mass of mixture

$$I_{SP} = \frac{I}{\rho_1 g V} . \qquad (2)$$

Test Section Mixture

A key parameter in the present experiments is the detonation sensitivity of the test mixture. The width of the detonation cell λ, known as the cell size, is a

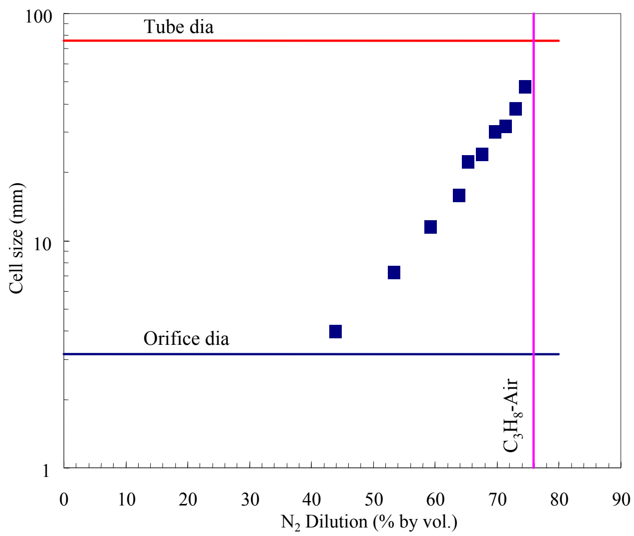

Fig. 2 Cell size vs. N_2 dilution for mixtures C_3H_8 + $5O_2$ +β N_2 (Knystautas et al.[11]).

length scale that is conventionally used to measure the sensitivity of the mixture. The larger the reaction zone, the larger the cell size and the lower the sensitivity of the mixture. Figure 2 shows cell size as a function of N_2 dilution in a stoichiometric propane-air mixture.[11] A line is shown indicating the amount of N_2 dilution corresponding to a propane-air mixture. The diameter of the orifice and the test section are also plotted as horizontal lines for reference.

Previous work[1,5–8] on direct turbulent jet initiation has shown that $d/\lambda \geq 11$ for a detonation to be promptly initiated. In order to meet this criterion in the present tests, the nitrogen dilution would have to be nearly zero. This means that prompt detonation initiation in a propane-air mixture would not be expected in the present facility. However, the confinement of the test section promotes[2,7] the deflagration-to-detonation transition (DDT) process that can aid in generating a detonation after some delay. In the present study, we used nitrogen dilution as a means to vary the main mixture detonation sensitivity. For a given configuration, the effectiveness of the initiation was determined by finding the highest nitrogen concentration at which a detonation could be produced within the tube. The measured impulse, pressure, and ion probe data were used to discriminate between combustion modes within the tube.

Experimental results

Characterization of Driver Explosion Pressure

The pressure time history is measured in the driver section using a PCB pressure transducer. Figure 3 is a plot of a pressure history for an initial driver pressure of 1 bar. The trace shows the experimental pressure history of the driver section along with the analytical model described subsequently. The pressure trace shows a steep rise to roughly 1.25 MPa and then a decay to 1 bar.

The processes in the driver can be idealized as two sequential events. First, the mixture combusts, and second, the combustion products vent through the orifice into the main tube. In fact, combustion and venting may occur simultaneously and play a role, along with heat transfer, in determining the peak pressure within the driver chamber. Neglecting these effects, a preliminary estimate of the driver peak pressure can be made by assuming adiabatic, constant-volume, complete combustion. A chemical equilibrium computation[12] is used to estimate the peak pressure under these conditions. For 1 bar initial pressure, the predicted adiabatic explosion pressure is 1.84 MPa.

The venting of the driver section was modeled using a simple control volume analysis assuming that the flow through the orifice could be modeled as choked, which is true for sufficiently large pressure ratios between the chamber and main mixture. The conservation of energy (3) and (4) for the control volume can be integrated to determine the variation of pressure with time inside the driver chamber. The analysis also incorporated a simple convective heat transfer model to account for energy loss from the products to the cold chamber walls. It is well known[13] that radiative heat transfer is a very important loss mechanism but we did not attempt to simulate this with any fidelity. The convection heat transfer model was used only to get an idea of the relative importance of heat transfer during the venting process.

$$\frac{dE_S}{dt} = h_c A_{wet}(T_{wall} - T(t)) - \dot{m}_T(h_T + \frac{u_T^2}{2}) \quad (3)$$

$$\frac{dM_S}{dt} = -\dot{m}_{out} = -\rho_T u_T A_T \quad (4)$$

In order to match analysis and the experiment, it is necessary to choose a starting pressure that is lower than that predicted by the adiabatic computation. As shown in Figure 3, the peak pressure obtained in the driver section is approximately two-thirds of the computed adiabatic, constant-volume explosion pressure. Using the observed peak pressure as a starting value, the analytic model was used to compute the subsequent pressure decay. The heat transfer coefficient is unknown so computations were carried out for a range of values of h_c between 0–150 W/m^{2}K, typical for forced convection. Comparing the analysis to the experiments in Figure 3, some discrepancy is evident for all values of h_c examined. The rate of pressure decrease in the driver section is overpredicted by the model. Increasing the magnitude of the heat transfer coefficient improves the agreement between model and experiment.

Figure 4 shows a pressure trace for a 1 bar initial driver pressure with a 19.05 mm diameter orifice. The maximum pressure rise is 1.2 MPa, similar to the 3.175 mm orifice diameter. However, the venting time is

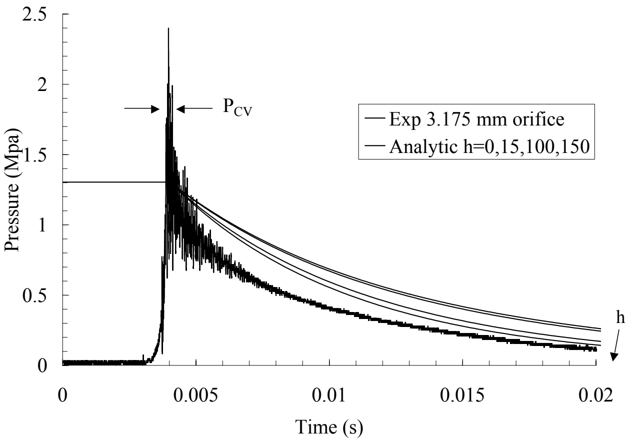

Fig. 3 Driver section experimental pressure history and analytical solution for a 3.175 mm orifice diameter.

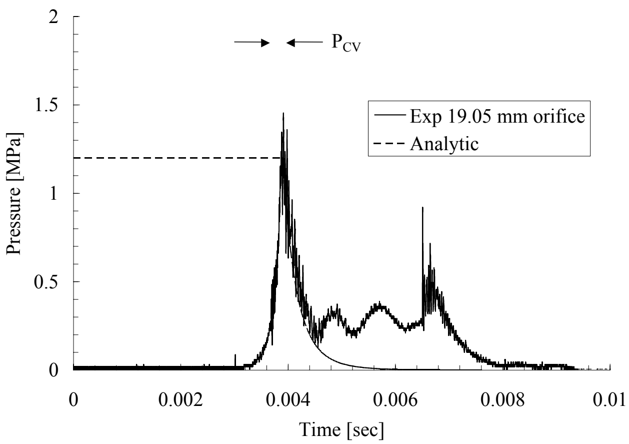

Fig. 4 Driver section experimental pressure history and analytical solution for a 19 mm orifice diameter ($h_c = 0$).

about 15 times shorter which reduces the effects of heat transfer. The analytic venting model with $h_c = 0$ matches very well with the experimental pressure trace. Note that around 5 ms, compression waves due to combustion in the test section enter the driver section, and a shock wave is seen at 6.8 ms. The shock could be due to the DDT process or reflection of pressure waves from the diaphragm at the end of the main tube.

Prompt detonation event

Detonations and shock waves are quite distinct in the pressure histories. Measurements of pressure histories at several locations enabled the determination of detonation and shock velocities. Typically, waves that propagated within 10% of the Chapman-Jouguet (CJ) velocity and had an associated pressure rise greater than or close to the CJ pressure were classified as detonations.

Figure 5 shows a case in which detonation occurs between gauges PCB1 and PCB2. A low-amplitude compression wave is observed on PCB1 before 2.9 ms, when a shock followed by a sharp compression at 3 ms are observed. The low-amplitude compression wave on PCB1 is characteristic of a flame and the subsequent shock and compression up to 40 bar is due to transition to detonation. The sharp pressure wave at 2.75 ms on PCB2 is detonation wave. The two indications that this is a detonation are the peak pressure of about 80 bar, higher than $P_{CJ} = 30.5$ bar, and speed of travel (2289 m/s) between PCB2 and PCB3 compared to $U_{CJ} = 2249.8$.

The peak pressure far exceeds the predicted CJ pressure at PCB2 because the transition to detonation took place in a mixture that had been compressed by the initial flame motion. Detonation waves created by DDT processes also tend to be overdriven and initially travel faster than the CJ velocity due to the transient nature of DDT. It should be noted that even in propagating detonations, measured pressures can vary considerably from the predicted CJ values due to the oscillation of the main front and the associated transverse waves that propagate along the front, however average front velocities are typically within 10% of the CJ value. Following the initial appearance of detonation at PCB2, we observe numerous waves behind the main wave. Some of these waves may be compressions propagating to the left toward PCB1 and then reflecting from the flange holding the diaphragm. Other waves may be generated when the detonation wave reflects from the open end of the test section, producing expansion waves propagating to the left. Eventually, the waves die down as the pressure is reduced to atmospheric by the venting of the combustion products from the open end of the main test section.

Deflagration Event

Figure 6 shows data from a test in which detonation does not occur. The most obvious indication that detonation does not occur is that the pressures are at most 5 bar, while the predicted CJ pressure is 20.32 bar. Evidence of combustion is first seen as compression waves on PCB1 in the first 1 ms. Some of these waves coalesce into a shock wave, seen first at 1.2 ms on PCB2. A distinct leading pressure wave is observed on PCB3 at 2.1 ms.

The propagation velocity of this shock is measured between PCB2 and PCB3. Assuming that it is traveling through unburned reactants, this corresponds to Mach 1.46. We can verify that this is a nonreactive shock by checking the consistency of the observed pressure rise and wave shock speed determined from the arrival times at the two gauges. Using a measured average wave speed of 492 m/s, the shock jump conditions predict a pressure $\Delta P = 1.6$ if we suppose the shock is traveling in reactants with a specific heat ratio of $\gamma = 1.4$. The observed pressure rise is about 1.4 bar. The 0.2 bar discrepancy can be explained by the uncertainty of the parameters, especially the ini-

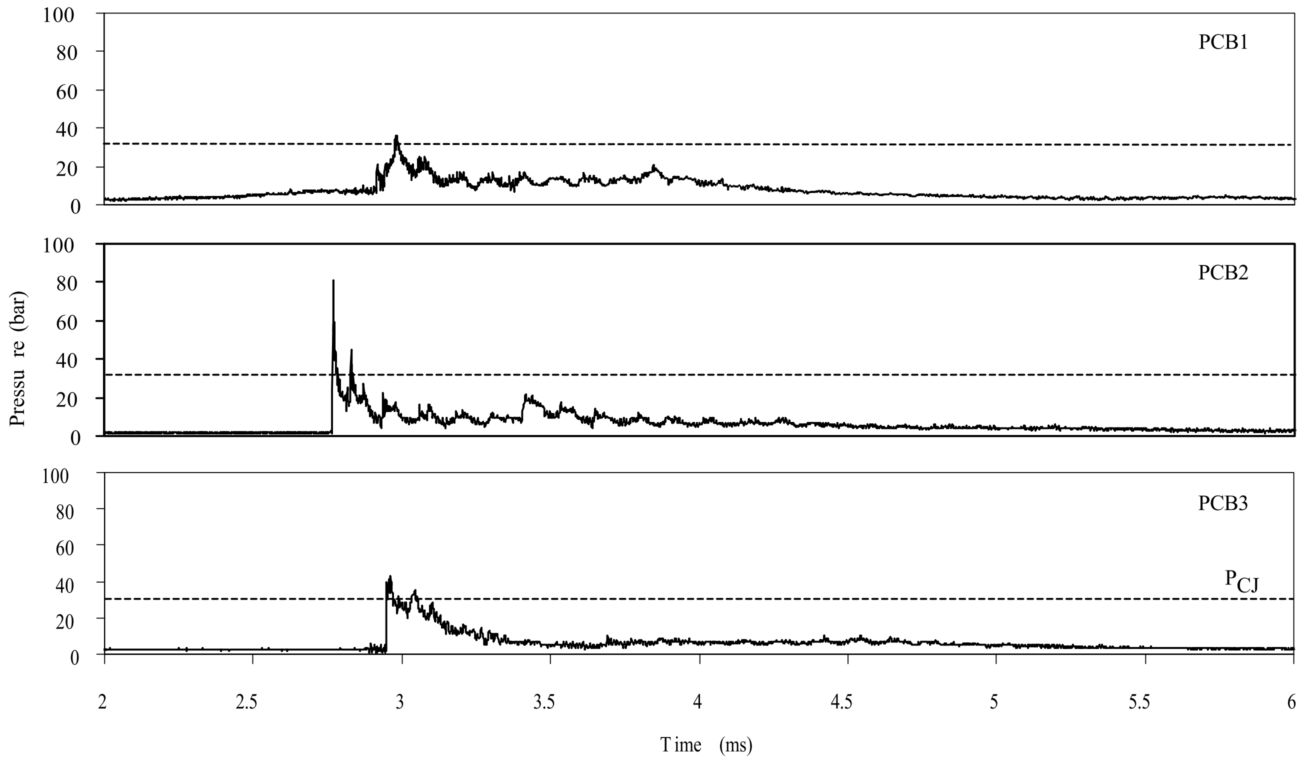

Fig. 5 Pressure histories for a case where detonation is initiated between gauges PCB1 and PCB2 . P_0 = 1.02 bar with 20% N_2 dilution. The detonation velocity between gauges PCB1 and PCB2 is computed from the transit time of 0.177 ms to be 2289 m/s.

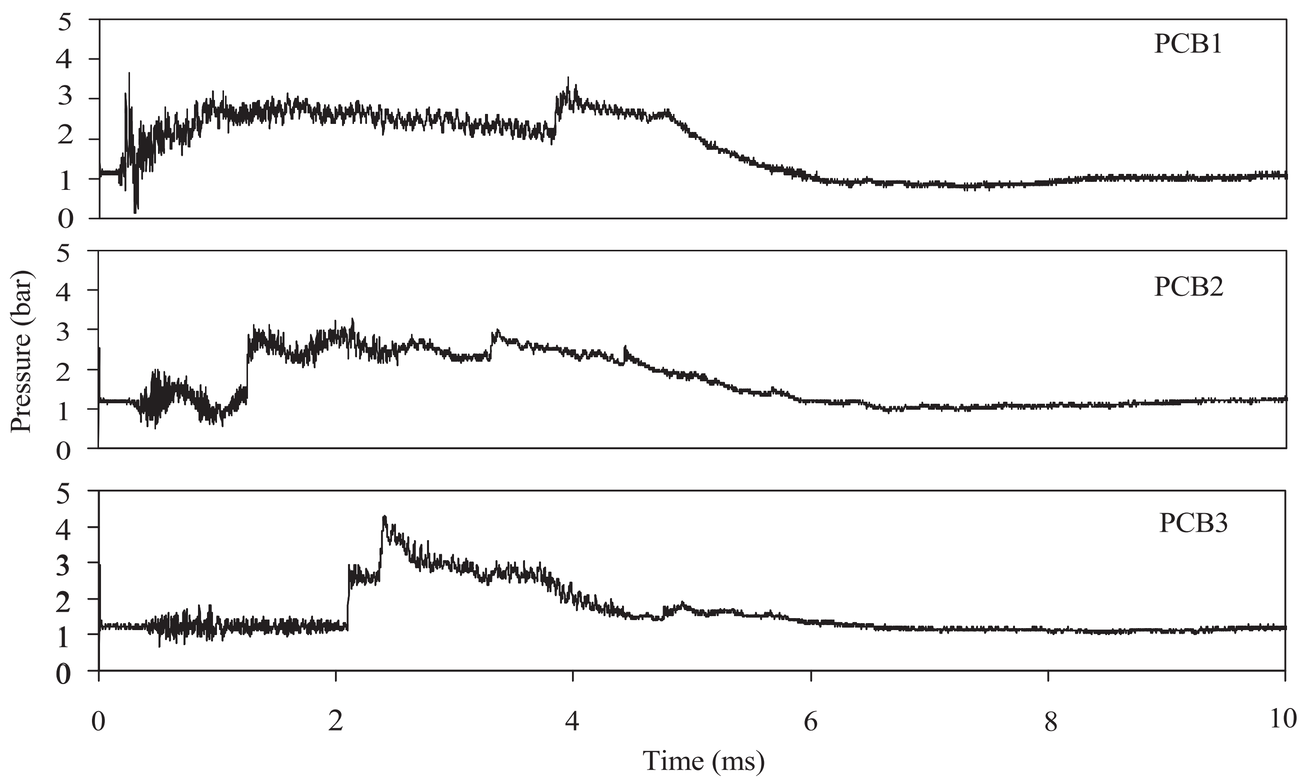

Fig. 6 Pressure histories for a case with only deflagration initiation. P_O = 4.02 bar with 70% N_2 dilution, the CJ velocity is U_{CJ} = 1878.3 m/s and the CJ pressure is P_{CJ} = 20.32 bar.

tial pressure P_1, whose value is small and consequently subject to measurement error. We conclude that the first pressure wave observed on PCB3 is a shock wave in the reactants that originated as a compression wave in the first portion of the tube.

The shock reflects from the diaphragm and causes a subsequent pressure rise of roughly 1.6 bar. In this particular case, the shock wave is not sufficiently strong to rupture the diaphragm. Following the reflected shock back into the tube, we find that it propagates at 492 $m \cdot s^{-1}$ from PCB3 to PCB2, consistent with a Mach number 1.46 shock wave in the reactants. The contact surface between combustion reactants and products apparently is between PCB1 and PCB2 for the time that the reflected shock travels from PCB3 to PCB2. Between PCB2 and PCB1, the shock velocity increases significantly, consistent with the higher sound speed of 1030 $m \cdot s^{-1}$ for products.

Effect of driver pressure on detonation initiation

The motivation of this study is to examine hot jet initiation for air-breathing PDEs. A figure-of-merit for the effectiveness of the initiator is the critical N_2 dilution: the highest N_2 dilution for which a detonation can be initiated in the test section. Experiments were performed with both driver and test section at an initial pressure of 1 bar, and the critical N_2 dilution was found to be between 30–40%. In an effort to increase the effectiveness of the initiator, the initial pressure of the driver was increased up to 4 bar. Critical N_2 dilution versus initial driver pressure is shown in Figure 7. Triangles denote the highest dilution at which a detonation could be initiated at a particular driver pressure. Circles denote the next highest dilution attempted. It can be seen that increasing the driver pressure by a factor of four only increases the critical N_2 dilution from 30 to 40%.

Specific impulse measurements are shown in Figure 8. In cases where a detonation is initiated in the test section, the measured impulse agrees well with the analytical model developed by Wintenberger et al.[14] The decrease in impulse with increasing N_2 dilution is due to the reduction in the mixture energy content. As discussed previously, no detonation could be initiated in mixtures with more than 40% dilution. As shown by Cooper et al.,[10] the impulse obtained in the case of a deflagration is significantly reduced as compression waves may rupture the diaphragm before the arrival of the flame allowing a substantial fraction of the mixture to be ejected from the tube before being burned.

Specific impulse versus initial driver pressure is shown in Figure 9. Over the range of pressures studied, increasing the driver pressure had a negligible effect on the specific impulse.

Effect of Orifice diameter on detonation initiation

The influence of the orifice diameter on the effectiveness of hot jet initiation was investigated, again using

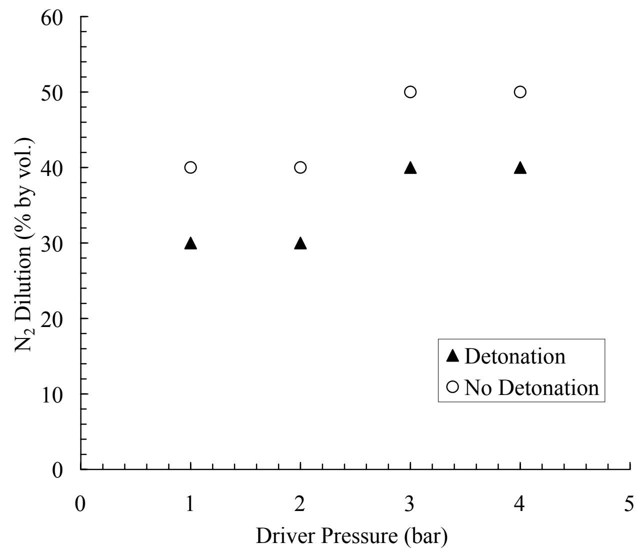

Fig. 7 Variation of critical detonation dilution with driver chamber initial pressure for a 3.2 mm orifice diameter.

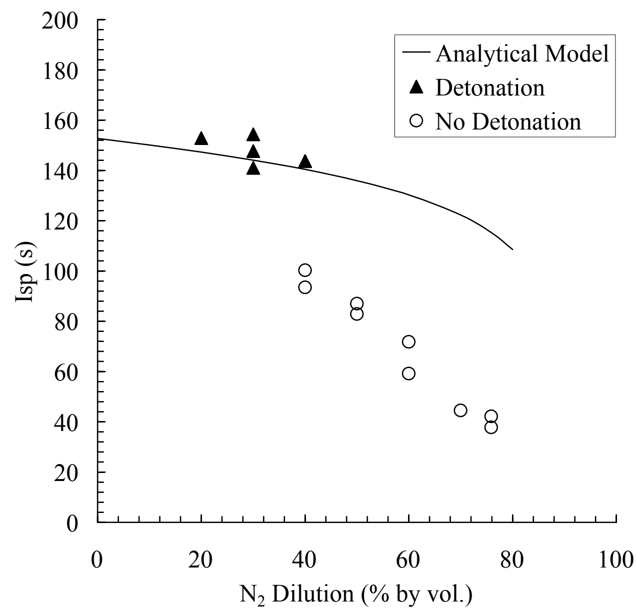

Fig. 8 Comparison of experimentally determined specific impulse with impulse model[14] as a functionof N_2 dilution for all initial driver pressures with a 3.2 mm orifice diameter.

the critical N_2 dilution ratio as a figure-of-merit. Four orifice diameters were studied: 3.2, 6.35, 12.7, and 19.0 mm. All the orifice diameter experiments were conducted with an initial driver pressure of $P_0 = 1$ bar. Figure 10 shows the $\%N_2$ dilution of the test section gas versus orifice diameter. The critical N_2 dilution increases slightly with increasing orifice diameter. For the largest orifice diameter attempted, the critical N_2 dilution was 40%.

To promote transition to detonation, obstacles were mounted in the test section. The obstacles were orifice plates with a blockage ratio of 0.43. The plates

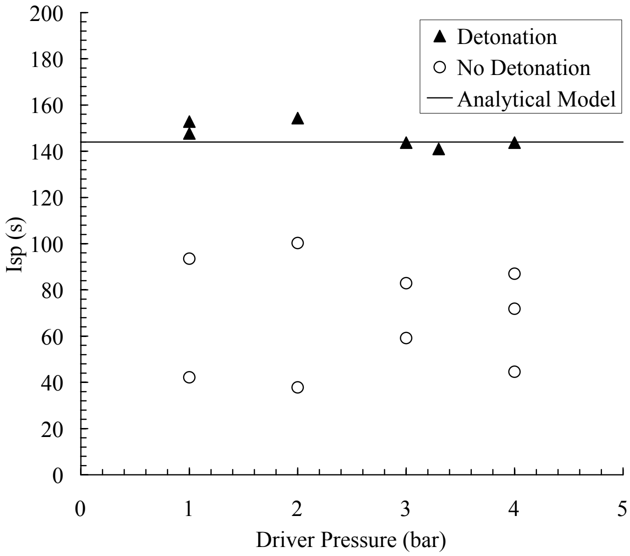

Fig. 9 Comparison of specific impulse for detonation and non-detonation cases as a function of driver chamber initial pressure. For 20 to 50% N_2 dilution with a 3.2 mm orifice diameter.

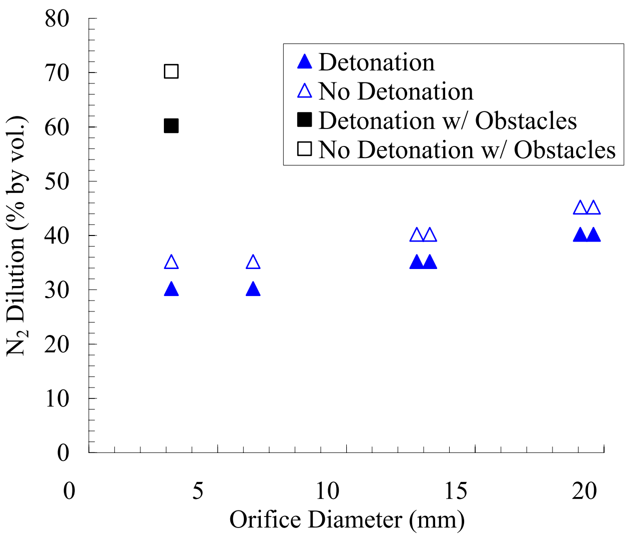

Fig. 10 Variation of critical detonation dilution with orifice diameter. Driver chamber initial pressure of 1 bar.

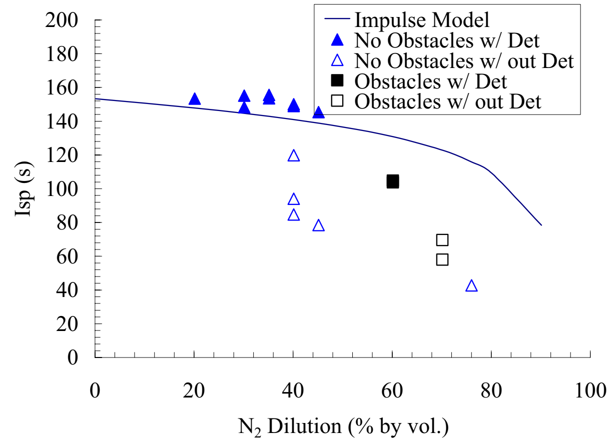

Fig. 11 Comparison of experimentally-determined specific impulse with impulse model[14] as a function of N_2 dilution for all orifice diameters. Driver chamber initial pressure of 1 bar.

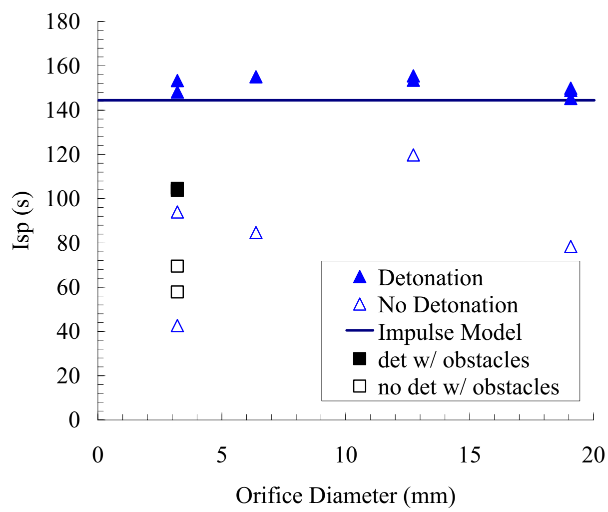

Fig. 12 Comparison of specific impulse for detonation and non-detonation cases as a function of orifice diameter. Driver chamber initial pressure of 1 bar, various N_2 dilutions.

were spaced one tube diameter apart. The critical N_2 dilution increased from 30% to 60% with the addition of the obstacles, as shown in Figure 10. Specific impulse measurements for these experiments are shown in Figure 11 as a function of N_2 dilution. In the case in which obstacles are used and a detonation is initiated, the specific impulse is 40% lower than the value predicted by the model. This is due to the momentum or drag loss over the obstacles.[10] Additional heat transfer due to increased surface area may also play a role.

Figure 12 shows the specific impulse versus the driver orifice diameter. The data show that the variation in the orifice size does not affect the impulse over the range of orifice diameters studied.

The experiments show that the effectiveness of a hot turbulent jet in initiating detonation is only weakly dependent on both the initial reservoir pressure and the orifice diameter. Figure 13 presents a compilation of shots that either detonate or do not detonate. It can be seen that mixtures in which detonation could be initiated had a $d/\lambda \geq 1$ or higher. Our critical d/λ ratio is lower than the value reported by Carnasciali et al.[15] The difference is most probably due to differences in the experimental facilities. Carnasciali et al. examined a turbulent jet emerging into a large vessel so that the boundaries had very little influence on the transition process. They obtain a d/λ ratio of 11-15, indicating that roughly 11-15 cells must fit across the orifice diameter for detonation initiation to occur. In

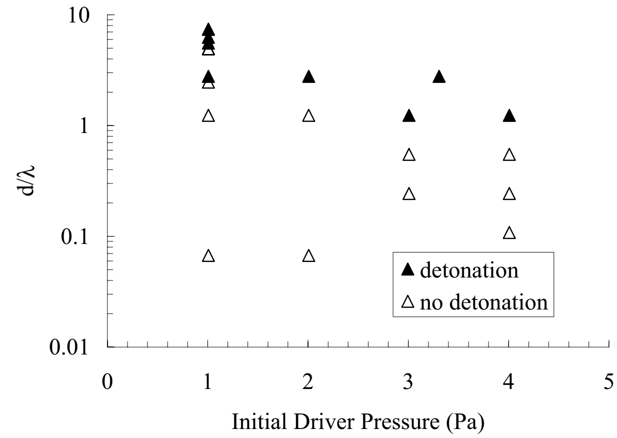

Fig. 13 Turbulent jet initiation threshold d/λ as a function of driver chamber initial pressure. For 20 to 70% N_2 dilution with 3.2 to 19 mm orifice diameters.

the present study, the jet emerged into a tube which provided a confining effect which greatly enhanced the transition process. Detonation was possible with mixtures that had $d/\lambda \geq$ 1–2. This enhancement is apparently due to the higher flow and flame velocities due to confinement, and also the reflection of pressure waves from the test section walls.

Conclusions

Detonation initiation by a hot turbulent jet was examined experimentally. Using propane as a surrogate hydrocarbon fuel and combustion of propane-oxygen mixtures for the jet, we were unable to initiate detonations in mixtures with greater than 40% nitrogen dilution. In particular, we were not able to initiate propane-air mixtures within our 75 mm diameter, 1 m long detonation tube. The limits for jet initiation of detonation were relatively insensitive to variations in the driver chamber initial pressure between 1–4 bar and orifice diameters between 3-19 mm. Adding obstacles to the main tube section did enable detonation of mixtures with up to 60% nitrogen dilution but the impulse was significantly reduced over the ideal value due to the drag of the obstacles. The impulse measurements clearly confirm the benefits of detonation initiation for impulse generation; the I_{sp} values for detonations are roughly double that of deflagrations.

Acknowledgment

This work was supported by the Office of Naval Research Multidisciplinary University Research Initiative *Multidisciplinary Study of Pulse Detonation Engine* (grant 00014-99-1-0744, sub-contract 1686-ONR-0744), and General Electric contract GE-PO A02 81655 under DABT-63-0-0001.

References

[1]Knystautas, R., Lee, J., Moen, I., and Wagner, H., "Direct Initiation of Spherical Detonation by a Hot Turbulent Gas Jet," In:Proc. of 17th Symp.(International) on Combustion, The Combustion Institute, Pittsburgh, pp.1235.

[2]Breitung, W., Chan, C. K., Dorofeev, S. B., Eder, A., Gelfand, B. E., Heitsch, M., Klein, R., Malliakos, A., Shepherd, J. E., Studier, E., and Thibault, P., "Flame Acceleration and Deflagration-to-Detonation Transition in Nuclear Safety," Tech. Rep. NEA/CSNI/R(2000)/7, OECD Nuclear Energy Agency, August 2000, A State-of-the-Art Report by a Group of Experts.

[3]Brophy, C. M. and Netzer, D. W., "Effects of Ignition Characteristics and Geometry on the Performance of a JP-10/O_2 Fueled Pulse Detonation Engine," 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, June 20–24, 1999, Los Angeles, CA, AIAA 99-2635.

[4]Brophy, C., Sinibaldi, J., and Damphousse, P., "Initiator Performance for Liquid–Fueled Pulse Detonation Engines," 40th AIAA Aerospace Sciences Meeting and Exhibit, January 14–17, 2002, Reno, NV, AIAA 02-0472.

[5]Moen, I., Bjerketvedt, D., Engebretsen, T., and Jenssen, A., "Transition to Detonation in a Flame Jet," *Combustion and Flame*, Vol. 75, 1989, pp. 297–308.

[6]Ungut, A., Philip, J., and Shuff, J., "Deflagration to Detonation Transition from a Venting Pipe," *Combust. Sci. and Tech.*, Vol. 63, 1989, pp. 75–87.

[7]Dorofeev, S., Bezmelnitsin, A., Sidorov, V., Yankin, J., and Matsukov, I., "Turbulent Jet Initiation of Detonation in Hydrogen-Air Mixtures," *Shock Waves*, Vol. 6, 1996, pp. 73–78.

[8]Krok, J. C., *Jet Initiation of Deflagration and Detonation*, Ph.D. thesis, California Institute of Technology, Pasadena, California, May 1997.

[9]Austin, J. M. and Shepherd, J. E., "Detonations in Hydrocarbon Fuel Blends," *Combustion and Flame*, 2002, accepted for publication.

[10]Cooper, M., Jackson, S., Austin, J., Wintenberger, E., and Shepherd, J., "Direct experimental impulse measurements for deflagrations and detonations," 37st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, July 8–11, 2001, Salt Lake City, UT, AIAA 01–3812.

[11]Knystautas, R., Lee, J., and Guirao, C., "The Critical Tube Diameter for Detonation Failure in Hydrocarbon-Air Mixtures," *Combustion and Flame*, Vol. 48, No. 1, 1982, pp. 63–83.

[12]Reynolds, W., "The element potential for chemical equilibrium analysis: implementation in the interactive program STANJAN," Tech. Rep. A-3991, Dept. of Mechanical Engineering, Stanford University, Stanford, CA, January 1986.

[13]Ratzel, A. C. and Shepherd, J. E., "Heat Transfer Resulting from Premixed Combustion," *Heat Transfer in Fire and Combustion Systems*, edited by C. K. Law, Y. Jaluria, W. W. Yuen, and K. Miyasaka, No. HTD-45, ASME, New York, NY, 1985, pp. 191–201.

[14]Wintenberger, E., Austin, J., Cooper, M., Jackson, S., and Shepherd, J., "An analytical model for the impulse of a single-cycle pulse detonation engine," 36st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, July 10–12, 2000, Salt Lake City, UT, AIAA 01–3811.

[15]Carnasciali, F., Lee, J., and Knystautas, R., "Turbulent Jet Initiation of Detonation," *Combustion and Flame*, Vol. 84, 1991, pp. 170–180.