Detonation Initiation, Diffraction, and Engine Component Performance

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Research at Caltech is being carried out into initiation of detonation using corona discharge, shock and detonation focusing, detonation diffraction, impulse generation in detonation tubes including the effect of exit nozzles, and pulse detonation engine performance modeling.

Introduction

The Explosion Dynamics Laboratory at Caltech is carrying out investigations on the following aspects of pulse detonation engines (PDEs): detonation initiation, diffraction, thrust generation by detonation tubes, and engine performance modeling. A brief review of activities over the past year is presented here.

Detonation initiation by corona discharge

Experiments are carried out in cooperation with researchers at USC to determine the effectiveness of transient plasma, i.e., corona discharge, to initiate a detonation in a short tube. A high-voltage pulse generator uses a pseudo-spark switch to discharge a capacitor through a transformer connected to electrodes in the combustion initiator section[1]. The resulting voltage pulse (90 kV for 50 ns) produces a plasma discharge consisting of many radial streamers. The transient plasma initiates a deflagration, which can transition to detonation if the mixture is sufficiently sensitive. In some cases, turbulence-generating obstacles are used within the detonation tube to promote the transition from deflagration to detonation.

The experiments are performed in a cylindrical tube that consists of a 200 mm long by 100 mm diameter initiator section and a 1 m long by 76.2 mm diameter test section. The facility is suspended by cables and operated as a ballistic pendulum. The impulse is determined by video recording the swing and measuring the maximum deflection[2]. The test section is equipped with three pressure transducers to measure the pressure histories and detonation velocity. The initiator section has a rod, acting as the anode, which extends along the centerline of the tube axis. The rod can be equipped with various needles to optimize the streamer profile. The two sections are lnked by an insulating flange to protect the instrumentation from the high-voltage discharge. A stoichiometric ethylene-oxygen mixture with varying nitrogen dilution is tested. The current study examines varying the rod geometry and obstacle configuration to find the maximum nitrogen dilution level at which a detonation can be initiated. Impulse measurements are used to compare the relative effectiveness of the plasma initiator to a conventional spark plug with a low-energy (<100 mJ) arc discharge.

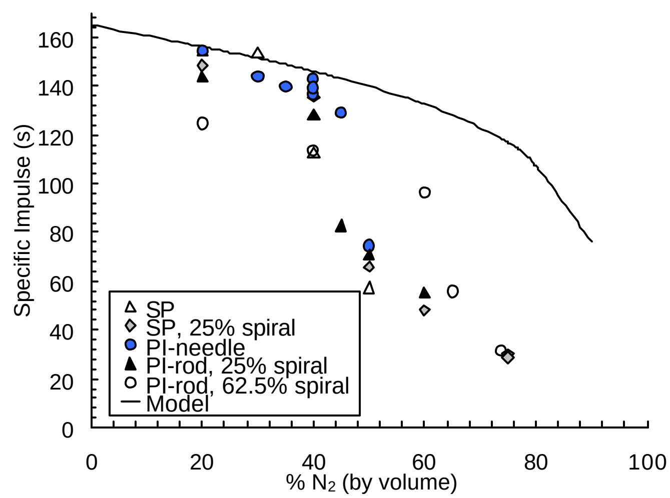

Figure 1: Specific impulse versus % N_2 dilution of stoichiometric ethylene-oxygen mixtures for various initiator-obstacle configurations. SP = spark plug, PI = plasma initiator. Spiral refers to spiral inserts used to promote transition from deflagration to detonation. The model is described in reference 3.

A plot of the experimentally-determined specific impulse (based on the mixture mass) is shown in Figure 1. The specific impulse ranges from 20 s to 160 s depending on the specific mixture composition and initiator-obstacle configuration. It is observed that, at a given nitrogen dilution, the impulse decreases with the increasing use of obstacles due to the additional internal drag generated by the obstacles[2]. The dramatic drop off in impulse as the nitrogen dilution is increased is a result of the failure to generate a detonation for these mixtures. The solid curve is the impulse predicted for an ideal

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Work performed under ONR contract N00014-02-1-0589

detonation[3]. Without the use of obstacles, combustion initiated by the corona discharge can transition to detonation for mixtures with up to 45% nitrogen dilution. A spark plug with no obstacles can initiate combustion that will transition to detonation in mixtures with up to 40% nitrogen dilution.

The corona discharge is slightly more effective than a standard internal combustion engine spark plug initiating combustion that will transition to detonation. In all cases, the use of turbulence-generating obstacles significantly improved the effectiveness of detonation initiation as has been found in many previous studies[2]. The corona discharge is an excellent method to achieve very rapid combustion of the region near the electrodes but additional means appear to be needed to accelerate the resulting flame to a detonation for high nitrogen dilution (greater than 40%) mixtures.

Initiation By Wave Focusing

Toroidal Initiator:

Caltech has developed a device capable of propagating an imploding annular detonation wave into a detonation tube. At the focal point of the collapsing detonation wave, the toroidal initiator generates a region of high pressure and temperature that is able to initiate detonations in stoichiometric propane-air and ethylene-air mixtures at 1 bar initial pressure inside a 1 meter long detonation tube with a 75 mm inner diameter[4].

Figure 2: The second-generation toroidal initiator. The outer sleeve is omitted for clarity. Small initiator channels are on the outside of the cylinder. The inside of the cylinder is the detonation tube.

The initiator (Figure 2) uses a single 30 mJ spark and an array of small diameter channels to generate and merge many detonation waves to create a single imploding toroidal detonation wave. During operation, the detonation tube was filled with either ethylene-air or propane-air. An equimolar acetylene-oxygen driver gas was then rapidly injected into the small initiator channels. The spark was discharged in the initiator immediately after gas injection and the initiator propagated an imploding wave into the detonation tube.

Experiments[4] have shown that the toroidal initiator will initiate detonations in propane-air and ethylene-air mixtures as long as a critical volume of driver gas is injected into the initiator. This critical volume is slightly larger than the total volume of the small initiator channels and was found to decrease with increasingly sensitive detonation tube mixtures and decreasing distance between the implosion focus and the end flange of the tube. Critical volumes are shown in Table 1. Additional details of this experimental study are available in reference 4.

Mixture	Wave focus at end flange	Wave focus 0.4 m from end flange
C_3H_8-air	434 cc	513 cc
C_2H_4-air	367 cc	398 cc

Table 1: Critical driver gas volumes (at 1 bar initial pressure) required to initiate stoichiometric propane-air and ethylene-air mixtures. The volume of the toroidal initiator was 349 cc.

Shock Implosion:

Experiments are now underway to develop criteria and understand the mechanisms responsible for detonation initiation via shock implosion. In a numerical study, Li and Kailasanath[5] were able to initiate detonations in ethylene-air mixtures using imploding shocks generated by an imploding annular jet of air. Caltech has constructed an experimental facility to validate these simulations[5].

The facility consists of a detonation tube that protrudes into the end of a shock tube. The protruding end of the detonation tube has an annular orifice. Before the experiment, the detonation tube is filled with a combustible mixture and the annular orifice is sealed with a diaphragm. A shock wave propagates down the shock tube and passes over the protruding detonation tube. The elevated post-shock pressure ruptures the diaphragm, sending an imploding jet of gas into the detonation tube as was done in the numerical study[5]. This experimental configuration provides an imploding jet of gas for at least 15 milliseconds, which is considerably longer than the 300 µs time required for initiation in the numerical study[5]. The capability of this non-reactive imploding jet to initiate a detonation in the detonation tube will be evaluated by varying the sensitivity of the detonation tube mixture and the strength of the incident shock wave in the shock tube.

Detonation diffraction

The problem of a self-sustaining detonation wave diffracting from confinement into an unconfined space is studied using Planar Laser Induced Fluorescence (PLIF) and Schlieren techniques. The aim of this study is to understand the mechanisms of detonation failure and successful transition for different types of gaseous mixtures. Detonation diffraction applies to PDE research especially for tube initiator geometries. The current setup, Figure 3, consists of a detonation diffraction tube with an inner diameter of 38 mm mated to a square cross section (150 mm x 150 mm) test section, 0.78 m in length. The detonation in the diffraction tube is initiated via a spark plug together with a Shchelkin spiral.

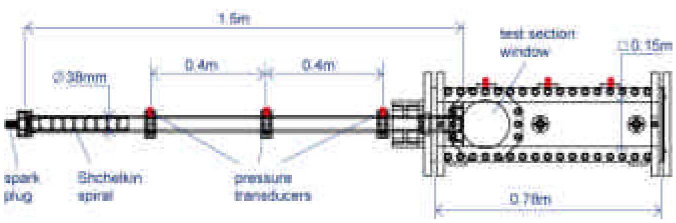

Figure 3: Experimental setup of diffraction experiment.

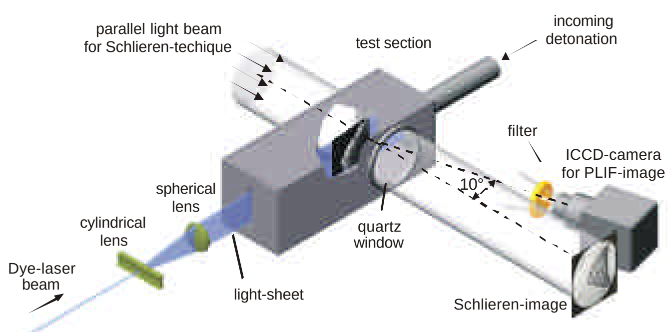

Figure 4: Experimental setup of visualization system.

The optical access for the Schlieren system consists of two 150 mm diameter round windows on opposite sides of the test section, one of them UV-transparent. The light sheet enters the test volume through a narrow slit quartz window in the test section endplate. The fluorescence is imaged with a short-gated ICCD camera perpendicular to the light sheet through the UV transparent window at an angle of 10° to avoid interference with the optical path of the Schlieren system (Figure 4). The laser light source is an Excimer pumped dye laser, with a narrow spectral band energy output of 5 mJ near 284 nm, which allows for PLIF of the OH radical. The setup allows for quasi-simultaneous (max. 80 ns delay) imaging of the reaction front with the PLIF system and shock front with the Schlieren system, and an overlay of the images obtained by both systems.

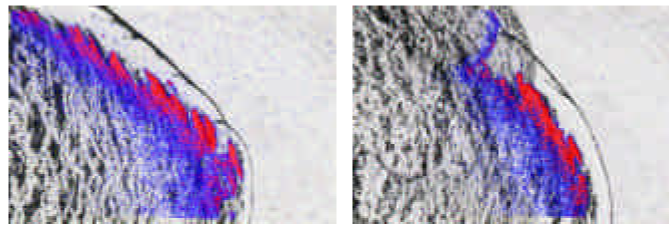

Figure 5: Overlay of Schlieren and false color PLIF image. Critical case, 2H2+O2+5.8Ar, 1bar.

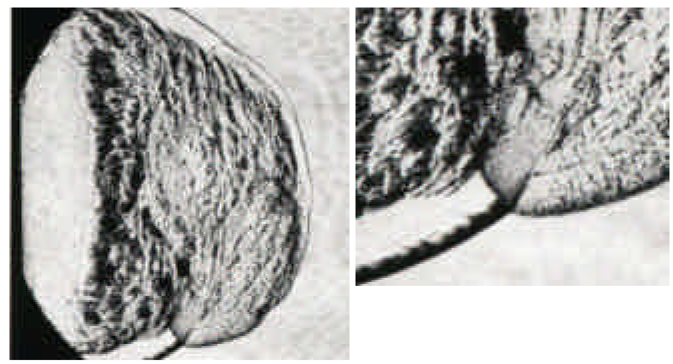

Figure 6: Schlieren image of reaction front traveling into shock region. $2H_2+O_2+0.8N_2$.

So far, H_2-O_2 mixtures with N_2 and Ar dilution have been studied. For critical cases, for which successful transition can occur, the reaction zone is clearly completely decoupled for parts of the diffracted shock (Figure 5 left). The detonation is traveling from left to right in all images. The keystones observed previously for fully-developed detonations are still evident in these regions, but only one family of keystones, pointing away from the axis of symmetry, is present. For successful transition, a reaction front traveling transversely into the shocked gas is observed on PLIF and Schlieren images, (Figure 5 right, Figure 6).

Impulse Generation by Detonation Tubes

An experimental and analytical study has been carried out to investigate impulse generation by detonation tubes. It was motivated by the lack of experimental data and scientific understanding on how operating parameters affect impulse. The main topics that are addressed include quantification of the impulse obtained from partially-filled tubes operating in atmospheric conditions, fully-filled tubes operating in sub-atmospheric conditions, and tubes with exit nozzles.

In the case of partially-filled detonation tubes exhausting into environments at atmospheric pressure, only a fraction of the maximum impulse is obtained if only a fraction of the tube contains the explosive mixture. We determined that a correlation based solely on the volumetric fill fraction[6,7] does not correctly predict the impulse when the densities of the explosive and inert gases are significantly different, such as in the case of a hydrogen-oxygen mixture exhausting into air. Consideration of the principles of energy conservation indicated that the impulse depends primarily on the chemical energy of the explosive and the relative mass ratios. As a result, we proposed a correlation for the impulse with the explosive mass fraction (Figure 7) and, by compiling all the available experimental and numerical data from partially-filled detonation tubes, we showed that the data are predicted by a single unifying relationship.

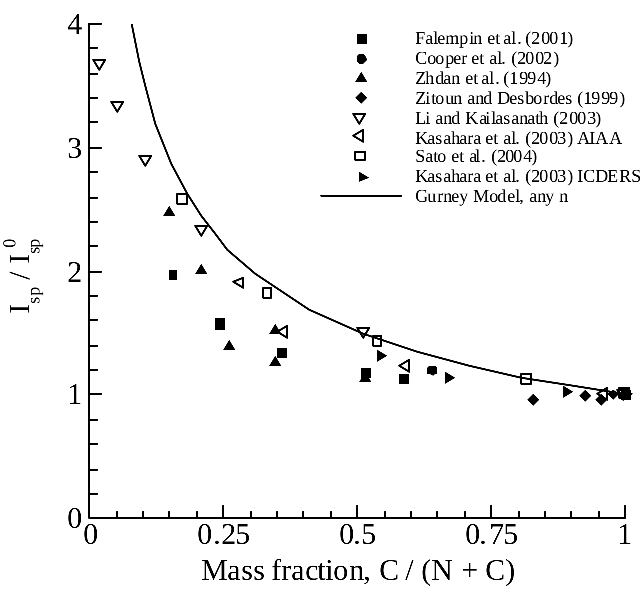

Figure 7: Specific impulse fraction versus mass fraction.

This mass-based relationship clearly fails in the limit when the explosive mass fraction goes to zero because the impulse is dominated by unsteady gas dynamics. An analytical model of an expanding "bubble" of hot, constant-volume combustion products in an infinitely long tube was developed to successfully predict the theoretical maximum specific impulse from an arbitrary explosive-inert gas combination. Our model predicts the thrust surface pressure decay, which is nondimensionalized and integrated over all times. The results of this integration and specific impulse are tabulated in Table 2 for the mixtures analyzed. Also shown are numerical data, if available, for comparison.

Explosive	Inert gas	P_{CV} / P_0	$F(\infty)$	I_{sp} / I_{sp}^o	Published data, I_{sp} / I_{sp}^o
C_2H_4-O_2	Air	16.6	1.53	3.68	3.67[6]
C_2H_2-O_2	Air	17.0	1.49	3.65	-
C_2H_4-Air	Air	9.34	1.36	2.73	-
C_2H_2-Air	Air	9.71	1.37	2.77	-
H_2-O_2	Air	9.56	1.45	4.46	4.33[8]

Table 2. Limiting fraction of specific impulse as the explosive mixture mass goes to zero for partially-filled tubes exhausting into 1 atm air. The explosive initial conditions were pressure 100 kPa, 300 K. The inert gas was air at 1 atm, 300 K. The predictions of Wintenberger et al.[3] were used for the fully-filled impulse value Isp / Isp^o.

In the case of detonation tubes exhausting into sub-atmospheric pressures, we have carried out the first experimental study measuring the impulse under these conditions with the ballistic pendulum installed within the dump tank of Caltech's T5 hypersonic wind tunnel facility. This enabled tests to be carried out in environment pressures from 100 to 1.4 kPa and with initial combustible mixture pressures of 100 to 30 kPa. The results showed that the impulse increases as the environment pressure decreases. For example, at an initial mixture pressure of 80 kPa, decreasing the environment pressure from 100 to 1.4 kPa increases the impulse by 15%. The increase in impulse is attributed to an increase in the pressure differential across the thrust surface and the blow down time.

The effect of varying the environment pressure was also investigated in tubes with exit nozzles. Previous studies have investigated nozzles, but these were all carried out with the tube exhausting into 100-kPa air, and only a few nozzle designs were tested. A total of ten different nozzles including converging, diverging, converging-diverging, and a straight extension were tested.

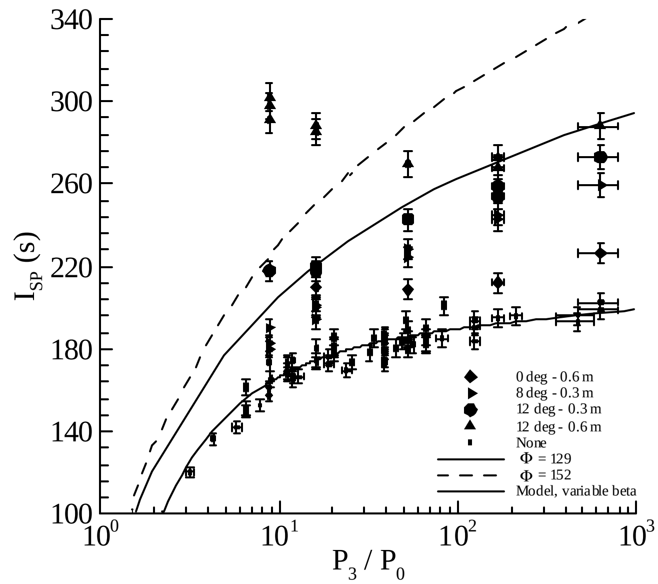

Figure 8: Specific impulse versus nozzle pressure ratio.

The effect of incomplete product gas expansion is observed when all of the impulse data are plotted in terms of the nozzle pressure ratio P_3 / P_0 and compared to the steady flow impulse predictions assuming isentropic expansion. The straight detonation tube with no exit nozzle has the worst performance due to the incomplete product gas expansion. Adding a nozzle successfully increases the impulse over the baseline case, yet how the nozzle affects the impulse depends on the pressure ratio. Figure 8 is the first demonstration that a nozzle on an unsteady device has two operating regimes. At large pressure ratios, a quasi-steady flow regime is established and the nozzle divergence expands the flow. Here the impulse values are ordered in terms of increasing nozzle exit area ratio. At small pressure ratios, the unsteady gas dynamics previously investigated in the partially filled detonation tubes are observed. Here the impulse values are ordered in terms of their mass fractions and are even observed to produce impulse values greater than the steady flow impulse predictions assuming isentropic expansion.

Pulse Detonation Engine Performance Analysis

The issue of PDE performance has been studied using two different approaches - thermodynamics and flow path analysis.

The well-known result that the entropy rise is minimum for a Chapman-Jouguet (CJ) detonation has motivated many efforts to explore detonation applications to propulsion. We developed a new approach to thermodynamic cycle analysis of steady combustion waves by conducting the analysis for a fixed initial stagnation state, which is representative of given flight conditions. Within this framework, we showed that the total entropy rise generated by a steady CJ detonation is larger than that associated with any deflagration[9]. The implications of our analysis are that detonations are less desirable than deflagrations for a steady air-breathing propulsion system since they entail a greater entropy rise at a given flight condition, in agreement with other performance studies[10].

This leads us to consider the situation for unsteady, i.e., intermittent or pulsed, combustion systems which use various modes of operation. For unsteady detonation waves, we consider a notional cyclic process for a closed system (the Fickett-Jacobs, or FJ cycle) in order to circumvent the difficulties associated with analyzing a system with time-dependent and spatially-inhomogeneous states[9]. We use the thermodynamic principles for closed systems to compute the maximum amount of mechanical work produced by a cycle using an unsteady detonation process. This ideal mechanical work is used to compute a thermal efficiency for detonations. Although this efficiency cannot be precisely translated into propulsive efficiency[11], the results are useful in comparing detonations with other combustion modes. We find that the efficiency of cycles based on detonation and constant-volume combustion (Humphrey) are very similar and superior to a constant-pressure combustion (Brayton) cycle[9] when compared on the basis of pressure at the start of the combustion process.

Because of the unsteady nature of the flow field inside an air-breathing PDE, we have to rely on unsteady gas dynamics to model the flow in a PDE. We have developed a performance model for a supersonic air-breathing single-tube PDE, based on control volume methods[12]. Our single-tube PDE model has a large acoustic cavity (or plenum), which acts as a damped reservoir for filling the detonation tube during each cycle. We perform a cycle-averaged control volume analysis in order to determine the average conditions in the plenum. We model the properties at the valve plane as piecewise constant functions of time, based on the results of numerical simulations of the filling process. The different elements of our model (inlet, plenum, detonation, and filling processes) are combined into the first system-level performance analysis of an air-breathing PDE. Our single-cycle PDE generates thrust up to a flight Mach number of about 4 (Figure 9). The specific impulse decreases almost linearly with increasing flight Mach number because of the increasing total pressure losses through the inlet and the increasing value of the filling velocity, which decreases the impulse generated by the detonation process[12]. Our PDE, which has a single straight detonation tube, has a higher specific impulse than the ideal ramjet below Mach 1.4. Potential performance improvements are thought to be possible with the addition of a converging-diverging exit nozzle.

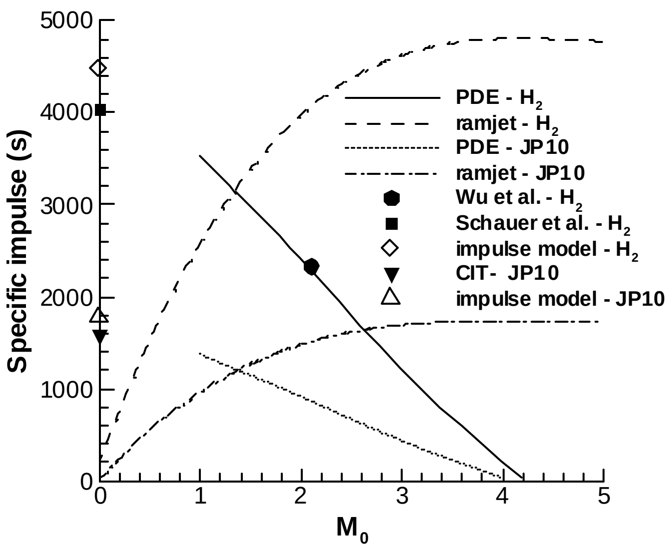

Figure 9: Specific impulse of single-tube PDE compared to the ramjet operating with stoichiometric hydrogen-air and JP10-air at 10,000 m altitude.

References

[1]Wang, F., Kuthi, A., Jiang, C., and Gundersen, M. "Pseudospark Based Pulse Forming Circuit For Transient Plasma Ignition And Combustion Control Systems", 14th International Pulsed Power Conference, Dallas, TX, June 15-18, 2003.

[2]Cooper, M., Jackson, S., Austin, J.M., Wintenberger, E., Shepherd, J.E. "Direct Experimental Impulse Measurements for Detonations and Deflagrations", J. Prop. Power, Vol. 18, No. 5, 2002, pp. 1033-1041.

[3]Wintenberger, E., Austin, J.M., Cooper, M., Jackson, S., Shepherd, J.E. "Analytical Model for the Impulse of Single-Cycle Pulse Detonation Tube", J. Prop. Power, Vol. 19, No. 1, 2003, pp. 22-38.

[4]Jackson, S., Grunthaner, M.P., Shepherd, J.E. "Wave Implosion as an Initiation Mechanism for Pulse Detonation Engines", AIAA 2003-4820.

[5]Li, C., and Kailasanath, K. "Detonation Initiation by Annular-Jet-Induced Imploding Shocks." Tech Note submitted to J. Prop. Power.

[6]Li, C., and Kailasanath, K. "Performance Analysis of Pulse Detonation Engines with Partial Fuel Filling." J. Prop. Power, Vol. 19, No. 5, 2003, pp. 908-916.

[7]Zhdan, S., Mitrofanov, V., and Sychev, A., "Reactive Impulse from the Explosion of a Gas Mixture in a Semi-infinite Space", Combustion, Explosion, and Shock Waves, Vol. 30, No. 5, 1994, pp. 657-663.

[8]Sato, S., Matsuo, A., Kasahara, J., and Endo, T. "Numerical Investigation of the PDRE Performance with Detailed Chemistry", AIAA 2004-0464.

[9]Wintenberger, E., Shepherd J.E. "Thermodynamic Analysis of Combustion Processes for Propulsion Systems", AIAA 2004-1033.

[10]Wintenberger, E., Shepherd, J.E. "The Performance of Steady Detonation Engines", AIAA 2003-0714.

[11]Wintenberger, E., Austin, J.M., Cooper, M., Jackson, S., Shepherd, J.E. "Reply to Comment on 'Analytical Model for Impulse of Single-Cycle Pulse Detonation Tube', by W.H. Heiser and D.T. Pratt", J. Prop. Power, Vol. 20, No. 1, 2004, pp. 189-191.

[12]Wintenberger, E., Shepherd, J.E. "A Model for the Performance of Air-Breathing Pulse Detonation Engines", submitted to J. Prop. Power, also AIAA 2003-4511.

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