JOURNAL OF PROPULSION AND POWER
Vol. 23, No. 4, July–August 2007

Effect of Supercritical Fuel Injection on Cycle Performance of Pulsed Detonation Engine

Timothy M. Helfrich* and Paul I. King†
Air Force Institute of Technology, Wright–Patterson AFB, Ohio 45433
John L. Hoke‡
Innovative Scientific Solutions, Inc., Dayton, Ohio 45440
and
Frederick R. Schauer§
U.S. Air Force Research Laboratory, Wright–Patterson AFB, Ohio 45433

DOI: 10.2514/1.26551

Pulsed detonation engines produce impulsive thrust through rapid ignition and formation of detonation waves. An operational goal is a reduction in time for the formation of detonation waves in conjunction with low-vapor-pressure liquid hydrocarbons. This study focuses on pulsed detonation engine operation enhancements using dual-detonation-tube, concentric-counterflow heat exchangers to elevate liquid hydrocarbon fuel temperatures up to supercritical levels. Variation of operating parameters includes fuel type (JP-8, JP-7, JP-10, RP-1, JP-900, and S-8) and firing frequency. Of interest is the effect on ignition time, deflagration to detonation transition time, detonation distance, and the percent of ignitions resulting in a detonation (detonation percentage). Except for JP-10, results for all fuels with increasing fuel injection temperatures indicate decreases in deflagration to detonation transition time by up to 15%, decreases in detonation distance by up to 30%, increases in the detonation percentage by up to 180%, and minimal impact on ignition time. JP-10 is difficult to detonate and results are inconsistent. An increase in firing frequency results in a 5% decrease in deflagration to detonation transition time at high fuel injection temperatures, but has little effect on ignition time and detonation distance.

Nomenclature

A = Arrhenius constant
E_a = activation energy
E_{crit} = critical initiation energy
[fuel] = concentration of fuel
[oxidizer] = concentration of oxidizer
P = detonation tube—closed-end pressure
RR = reaction rate
R_u = universal gas constant
T_{mix} = fuel/air mixture temperature
λ = cell size

I. Introduction

ALTHOUGH the pulsed detonation engine (PDE) has the potential to provide significant advantages over current aircraft propulsion systems, it is still in the early stages of development [1]. Several technological barriers need to be overcome before the PDE can be considered a practical means of providing propulsion to operational aircraft [2–4]. One is the efficient use of low-vapor-pressure hydrocarbon fuels, such as JP-8, JP-7, JP-10, JP-900,¶ RP-1, and S-8.** The majority of research with pulsed detonation engines has employed gaseous fuels, such as hydrogen and simple hydrocarbons [6,7], resulting in a dearth of liquid hydrocarbon data and a large gap between research and the operational use of pulsed detonation engines. Also, nearly all U. S. Air Force aircraft and air-breathing missiles use liquid hydrocarbon fuels, primarily JP-8 and JP-10 [5]; therefore it is pertinent to develop a method to efficiently use these fuels.

Four key cycle parameters are adversely affected by using liquid hydrocarbon fuels in lieu of gaseous fuels. The parameters are 1) ignition time, the time from spark deposition to the creation of a deflagration wave within the fuel/air mixture, 2) deflagration to detonation transition (DDT) time, the time to transition the deflagration wave into a detonation wave, 3) detonation distance, the length of the detonation tube required for the mixture to transition to a detonation, and 4) detonation percentage [7], the percentage of ignitions that result in a detonation wave. Both the ignition time and the DDT time are nearly an order of magnitude larger for complex liquid hydrocarbon fuels than for hydrogen. For example, ignition time of a hydrogen/air mixture is on the order of 1 ms, whereas that of a JP-8/air mixture is approximately 7 ms. A reduction in DDT or ignition time would shorten the PDE cycle time, allowing for higher frequency operation and higher average thrust. Reduction in detonation distance allows for a decrease in detonation tube length, resulting in a decreased engine weight. An increase in detonation percentage directly improves the efficiency of the PDE, leading to an increase in specific impulse.

Until this work, the performance of a liquid-hydrocarbon-fueled PDE with fuel injection temperatures above the flash vaporization point was unknown. Previous research [8] demonstrated that flash vaporization of liquid hydrocarbon fuels significantly decreased the ignition and DDT times, but no work has been reported on the effect

---

Presented as Paper 5133 at the 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Sacramento, California, 9–12 July 2006; received 30 August 2006; revision received 5 February 2007; accepted for publication 6 February 2007.

*Capt., USAF, AFIT, Department of Aeronautics and Astronautics, 2950 Hobson Way. Member AIAA.

†Professor, AFIT, Department of Aeronautics and Astronautics, 2950 Hobson Way. Senior Member AIAA.

‡Research Engineer, 2766 Indian Ripple Road. Senior Member AIAA.

§Senior Engineer, Head PDRF, AFRL/PRTC, 1950 5th Street. Senior Member AIAA.

¶The fuel referred to as JP-900 in this paper is a coal-derived liquid hydrocarbon fuel developed at Penn State University. It is denoted as JP-900 due to its thermal stability up to 900°F.

**S-8 is a synthetic fuel derived from natural gas via the Fischer-Tropsch process [5]. S-8 is also referred to as Fischer-Tropsch JP-8 or simply Fischer-Tropsch.

of operation with fuel injection temperatures beyond the point of flash vaporization. Additionally, Cheatham and Kailasanath [9] have shown, using numerical simulations, that the vaporization of liquid JP-10 droplets is necessary for optimum performance. Card et al. [10] studied the effect of elevating initial mixture temperature (up to 573 K) on the DDT distance (called flame run-up distance in [10]) for gaseous hydrocarbon/air mixtures in a 10-cm diam tube. They found that there was no strong dependency of DDT distance on the initial mixture temperature in the range tested. The objective of this work was to examine the effect of heated fuel produced by a dual-concentric counterflow heat-exchanger system on the ignition time, DDT time, detonation distance, and detonation percentage. The variables included fuel type (JP-8, JP-7, JP-10, JP-900, RP-1, and S-8) and firing frequency.

II. Background and Theory

A. Ignition Time for a Hydrocarbon Fuel/Oxidizer Mixture

For single species chemical reactions, reaction rate is given by the Arrhenius expression (global reaction theory):

$$\text{Ignition Time} \propto \frac{1}{RR} = \frac{1}{A} P^{-n}[\text{fuel}]^{-m}[\text{oxydizer}]^{-j} e^{\left(\frac{E_a}{R_u T_{\text{mix}}}\right)} \quad (1)$$

where n, m, and j are experimentally determined constants [11]. Low-vapor-pressure hydrocarbon fuel/air mixtures are not single species, but, as shown later, the trend of the ignition time can be inferred. The reaction rate of a fuel/oxidizer mixture will increase with increasing mixture temperature and pressure, thus decreasing the ignition time. For the moderate elevation of fuel temperatures in this work, only a small rise in the fuel/air mixture temperature occurred, and, as shown later, ignition time remained relatively constant.

B. Detonability of a Hydrocarbon Fuel/Oxidizer Mixture

The ability to initiate a detonation in a hydrocarbon fuel is related to its critical initiation energy, which for a low-vapor-pressure hydrocarbon/air mixture is around 10^5 J (a typical spark plug generates about 0.1 J). The critical initiation energy is related to the detonation cell size of a propagating detonation wave, shown in Fig. 1 for several stoichiometric fuel/oxidizer mixtures [12]. A curve fit shows a cubic relationship between the two (inset of Fig. 1). Knystautas et al. [13] also found the relationship between detonation cell size and critical initiation energy to be cubic.

Cell size, and thus critical initiation energy, is affected by the initial temperature and pressure. As shown in Figs. 2a and 2b for three light hydrocarbons and one H_2/O_2 mixture, cell size decreases with increased mixture temperature and pressure [14–17]. To improve detonability, therefore, pressure and temperature should be increased. Such data do not exist for heavy hydrocarbons, but the suggestion is that increasing initial mixture temperature and/or detonation tube closed-end pressure will decrease the cell size and improve detonability for those fuels also. As will be shown later, such increases in temperature did result in decreased DDT time and detonation distance, as well as increased detonation percentage.

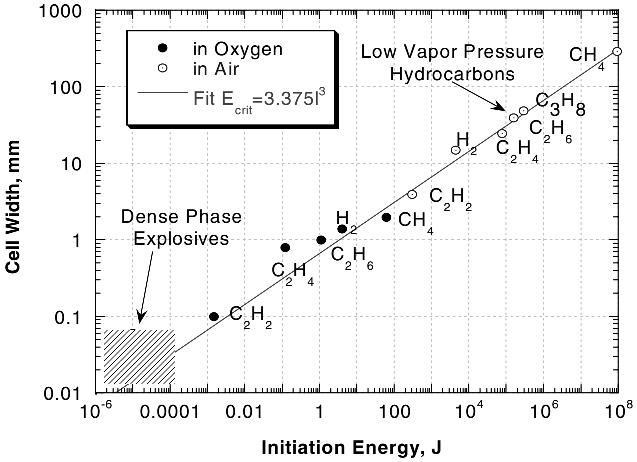
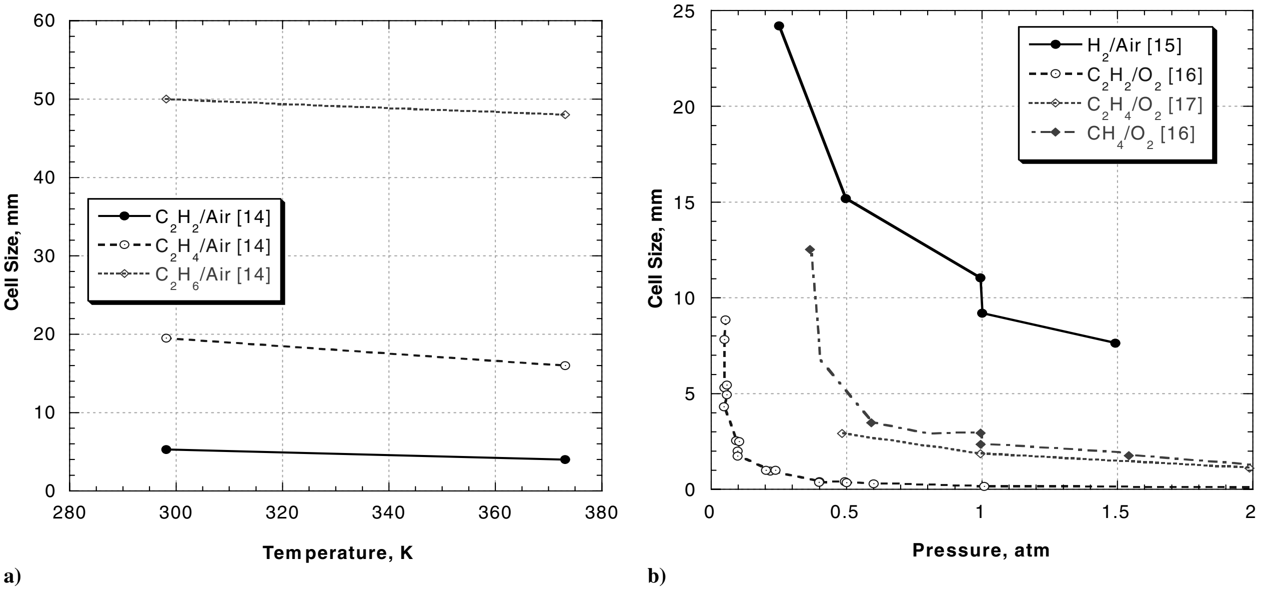


Fig. 1 Critical initiation energy for various stoichiometric fuel/oxidizer mixtures (data taken from [12]).

III. Experimental Setup and Instrumentation

A. Facilities and PDE Specifics

This research was conducted at the detonation research facility located in Building 71A, D Bay, Wright–Patterson AFB, Ohio. This facility was described in detail in other literature [18], and only the details relevant to this effort are provided. The PDE for this research consisted of the valve train from a General Motors (GM) automobile quad four head with two schedule-40 stainless-steel detonation tubes. Each tube was 52.5 mm in diameter, 1.83 m in length, and equipped with a Schelkin-like spiral, 0.91 m in length, adjacent to the closed end of the detonation tube to promote DDT [19]. Each tube was outfitted with a stainless-steel heat exchanger (described later). Each spiral was constructed of 3/16 in. stainless-steel rod with a



a) b)

Fig. 2 Effect of a) initial temperature and b) initial pressure on detonation cell size (data taken from [12]).

spiral pitch of 38.1 mm. A schematic of one head cavity with valving and spark plug is shown in Fig. 3.

Because an automotive cam was used to drive the valve system, the three phases of the PDE cycle (fill, fire, and purge) were necessarily equal. The allotted time for each phase varied based on firing frequency: 33.33 ms for 10 Hz and 16.67 ms for 20 Hz. Firing frequency was a test parameter, which varied between 10 and 20 Hz. Depending on the firing frequency, the time required to complete any one phase could be less than the time allotted for the phase, where the time required for a phase is defined as the time necessary to complete all functions of that phase, for example, the necessary function of the fill phase is to introduce the fuel/air mixture to the detonation tubes. During the fill phase the intake valves introduce premixed fuel and air equal to the volume of the detonation tube (fill fraction of one at ambient pressure and fuel/air mixture temperature). For all tests the fill air was initially heated to 394 K before mixing with the fuel. For the fire phase an automotive ignition system provided 115 mJ spark pulses through modified spark plugs. The fire phase consists of spark delay, ignition, DDT, and blow down; the latter three totaling approximately 11 ms for the configuration tested. Figure 4 is a schematic of a typical fire phase, broken down into the critical segments. Detonation occurrence was confirmed using ion probes to measure wave speed, similar to the methods used by Card et al. [10] and Ciccarelli et al. [20]. Any combustion waves propagating at speeds within 10% of the upper Chapman–Jouguet point (assumed to be 1800 m/s) [21] were considered detonation waves. During the purge phase the exhaust valves introduced unheated air equal to half the volume of the detonation tube (purge fraction of 0.5 at ambient pressure and fuel/air mixture temperature). The purge air cooled the detonation tube and removed a portion of the exhaust gases from the detonation tube to prevent autoignition during the following fill phase.

B. Supercritical Fuel Heating System

The flow path and instrumentation are shown in schematic form in Fig. 5. The liquid fuel required for this testing was contained in two hydraulic bladder accumulators, pressurized by nitrogen bottles. The fuel pressure was maintained above critical pressure for the duration of the test to prevent phase change. The supercritical fuel heating system (SFHS) consisted of a nitrogen purge system (described later), two stainless-steel heat exchangers, fuel filter assembly (not shown in Fig. 5), fuel injection nozzles, instrumentation, and associated tubing and fittings necessary to connect the critical components ([22] contains details on fuel injection nozzles). The fuel entered the test stand through a pneumatically operated ball valve and split into two fuel lines, one for each heat exchanger. At the exit of the heat exchangers, the lines were teed together and run through a fuel filter. After the filter, fuel was fed to the fill air manifold and injected into the airstream via the fuel injection nozzles. The fuel filter removed small amounts of coking formed due to endothermic cracking of the fuel [23]. Lines carrying heated fuel were insulated with fiberglass to prevent heat loss. A nitrogen purge system cleared supercritical fuel from the heat exchangers at the end of a test [7] (Fig. 5) via a remotely activated pneumatic valve.

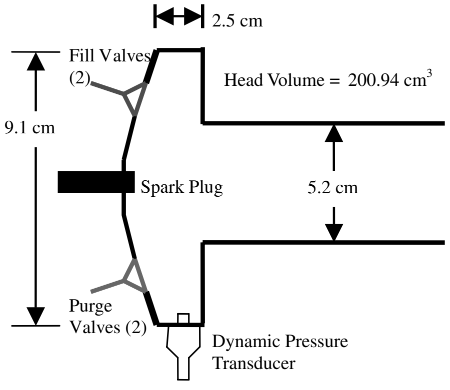


Fig. 3 Schematic of one head cavity with valving, spark plug, and dynamic pressure transducer.

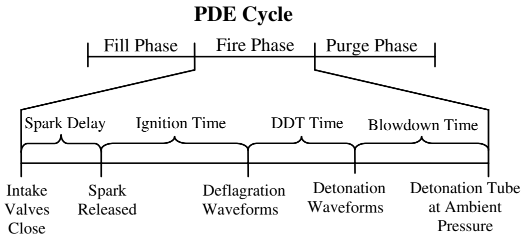


Fig. 4 Typical pulse detonation engine fire cycle divided into critical segments.

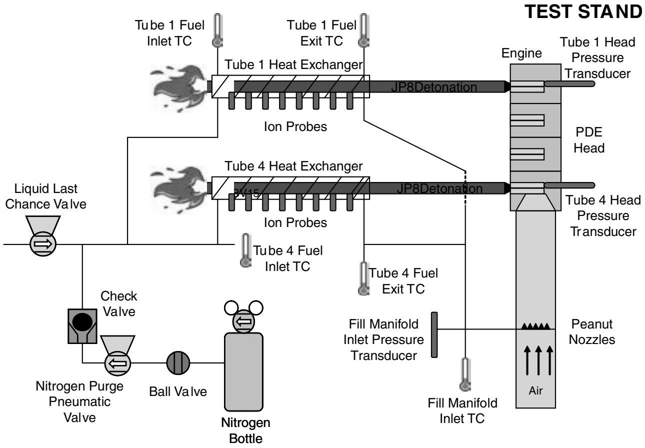


Fig. 5 Diagram of the PDE with the supercritical fuel heating system.

To compensate for the decrease in fuel density during heating in the supercritical regime [24,25], the charge pressure of the accumulators was increased to maintain a constant fuel mass flow rate. To allow for variations in accumulator charge pressure during testing, a pneumatic dome loader was installed for nitrogen pressure regulation (for details, see [5]). Pressures at the exit of the heat exchangers varied from 37 to 68 atm, with lower pressures at lower fuel injection temperatures and higher pressures at higher fuel injection temperatures to compensate for the density variation.

To minimize carbon deposition in the SFHS, the JP-8 was deoxygenated through a nitrogen sparging process. The sparging process involved bubbling a volume of nitrogen through the JP-8 to displace oxygen from the fuel. The volume of nitrogen necessary to reduce the oxygen concentration to acceptable levels was determined experimentally in previous work [22].

C. Spark Delay

Pressure fluctuations are created as fill and purge valves open and close. With compression and expansion waves in the head end of the tube, a spark delay can cause spark deposition during a beneficial pressure peak. Figure 6 shows the pressure-time history during an unsparked fire phase (no combustion) at 15 Hz with a mixture temperature of 394 K and spark delays from 2 to 10 ms. It can be seen that 6, 8, or 10 ms spark delays would initiate combustion during a compression wave, while a zero ms spark delay would do so during an expansion wave. However, because ignition time is also affected by the pressure history during the formation of a deflagration wave, selection of a 10 ms spark delay is not necessarily optimal. A 4 ms spark delay was chosen to minimize the overall time to detonation. Other spark delays (6, 8, and 10) showed inconsequential improvement in DDT time and ignition time; additionally, the 0 and 2 ms spark delays failed to produce detonations [26].

It was also beneficial to compare global reaction theory estimates with the ignition times for a series of spark delays (2, 4, 6, 8, and 10 ms) with fuel injected at 422 K. The global reaction theory approximation, shown in Eq. (1), for normalized ignition time as a function of average head pressure is shown in Fig. 7. Also,

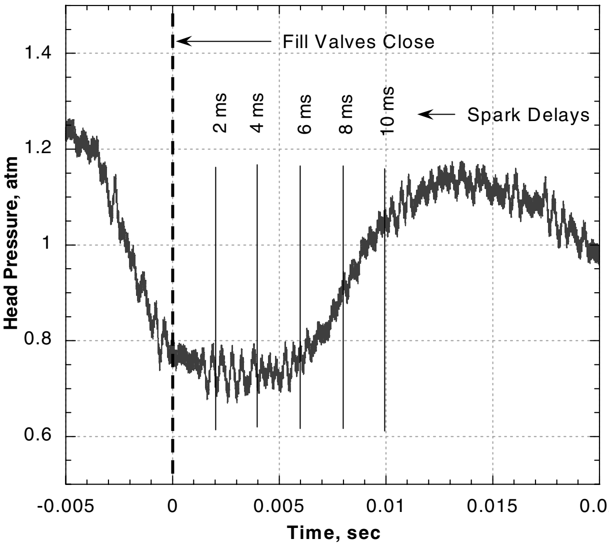


Fig. 6 Pressure in the closed end of the detonation tube during fire phase without combustion (vertical lines denote spark delays).

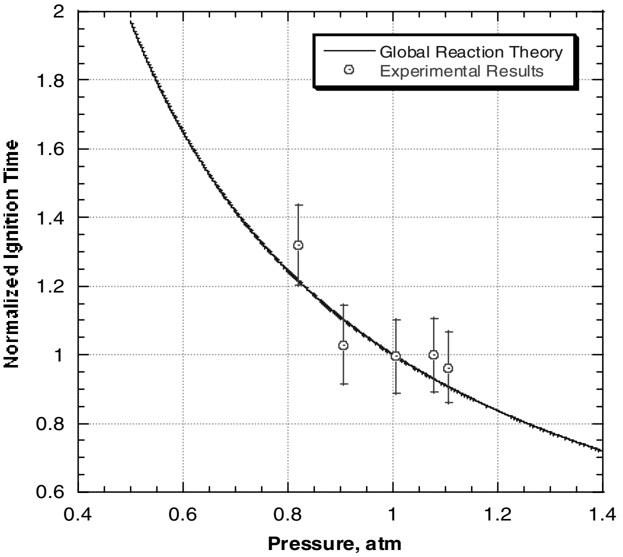


Fig. 7 Normalized ignition time as a function of initial head pressure.

experimentally determined normalized ignition times as a function head pressure for a JP-8/air mixture are displayed in Fig. 7. The ignition times for the global reaction theory were normalized by the ignition time corresponding to ambient pressure of the fuel/air mixture. Ignition times for the experiment were normalized by the 6 ms case for which the average pressure was nearly ambient (within 0.5%). The low temperature experimental results compare well with global reaction theory, falling within the experimental uncertainty.

D. Heat Exchangers

Two identical concentric-tube heat exchangers were fabricated from 316-stainless-steel schedule-40 tubes, with a length of 0.91 m, tube inner diameters of 52.5 and 63.5 mm, respectively, allowing for a 1.22-mm annular space. A photograph of one heat exchanger with the associated instrumentation ports is shown in Fig. 8.

E. Instrumentation

To gather temperature data, J-type thermocouples were placed in the center of the flowpath at the inlet and outlet of each heat exchanger, and a T-type thermocouple was placed at the inlet to the fill air manifold. Heat-exchanger external wall temperatures were measured with J-type thermocouples mounted externally with compression clamps. A pressure transducer situated at the closed end of the detonation tubes measured the pressure used to determine the ignition time.

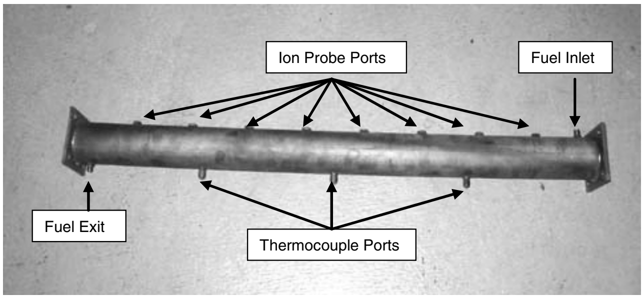


Fig. 8 Photograph of one heat exchanger.

F. Data Reduction

All combustion data were gathered on a dedicated computer employing a *LabVIEW* program, and analyzed using a C++ program. The program segmented the data into separate firing cycles using the spark trace. Each spark trace denoted a new firing cycle. Each firing cycle was then analyzed for ignition time information. The head-pressure trace data were passed through a fourth-order, 401-point, Savitzky–Golay, digital, finite-impulse, response filter to reduce the high-frequency noise. The head-pressure trace is shown before and after the filter was applied, Fig. 9. Linear regression was then used to determine the slope of the pressure curve. The ignition time was taken as the time where an average pressure rise of 5000 psi/s was detected.

After the ignition time was determined, the probe times were calculated. The probe times were the time that the combustion wave crosses each of the ion probes. Wavespeeds were calculated by dividing the difference in distance between two ion probes by the difference in the corresponding probe times. Once a wavespeed above the Chapman–Jouguet (CJ) limit was found, linear interpolation between the wavespeed above the CJ wavespeed and the wavespeed at the location before it (below the CJ wavespeed) was performed to determine the time and location where a wavespeed matched that of the CJ wavespeed. The time and location found were the DDT time and the detonation distance, respectively.

G. Experimental Uncertainties

The total experimental uncertainty was determined by combining the bias and precision uncertainties using the root sum square method

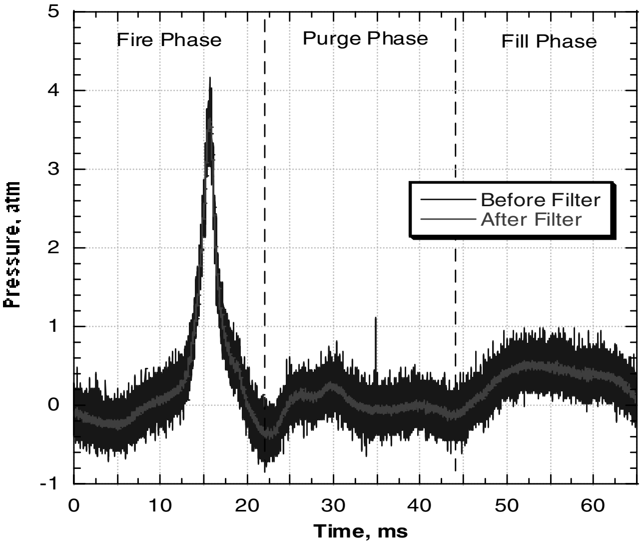


Fig. 9 Head-end pressure history during a single PDE cycle at a firing frequency of 15 Hz.

Table 1 Summary of bias uncertainties for experimental results

Experimental result	Bias uncertainty
Wavespeed	±55.12 m/s
Ignition time	±0.292 ms
DDT time	±0.0568 ms
Detonation distance	±0.0568 m
Fuel injection temperature	±3.6 K
Fuel/air mixture temperature	±2.5 K
Equivalence ratio	±0.0247

[27,28]. The bias uncertainties were constant for all data points of the same variable, while the precision uncertainties varied by data point. Therefore, the total experimental uncertainty varies by data point and is included with the data. Total bias uncertainties are displayed in Table 1 [7].

IV. Results and Discussion

For varying fuel injection temperatures, ignition time, deflagration to detonation transition time, detonation distance, and detonation percentage were measured. Each data point represents the mean value of 40 to 60 ignitions, using data averaged from two tubes. The effect of fuel injection temperature on the performance of the PDE is shown with variation of fuel type and firing frequency. All testing was performed with an equivalence ratio of 1.1, which has been shown by Tucker [22] to produce the minimum ignition and DDT times for JP-8.

A. Fuel Study

Figure 10 shows ignition time for all six fuels. Little variation occurred among the fuels, though JP-8 has a slightly higher ignition time in the range of 586 to 755 K. The probable cause of this higher time was adverse effects of thermal degradation (oxidative coking). S-8 produced the smallest ignition times for almost the entire temperature range. JP-7, JP-900, and RP-1 times displayed little difference in slope or magnitude, which was expected due the similarity of the fuels. With the exception of JP-8, ignition times for all fuels were independent of fuel injection temperature in the temperature range examined, as mentioned in the earlier discussion of global reaction theory.

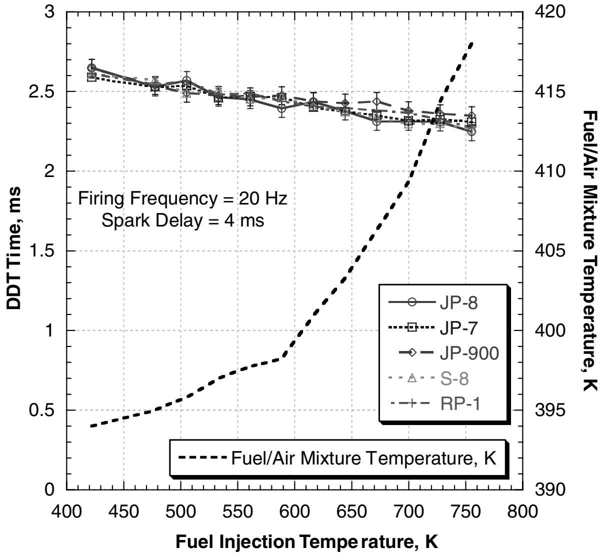


Fig. 11 DDT times for several fuels.

Attempts at detonation of a JP-10/air mixture were erratic and data were inconsistent, rendering the results unusable; therefore, the DDT time and detonation distance results for JP-10 have been omitted. The DDT times for the other five fuels are displayed in Fig. 11. In Fig. 11, little variation in DDT time is seen among the fuels. The small differences between any two fuels are within the experimental uncertainty for the entire temperature range. DDT times for all five fuels decrease with increasing fuel injection temperature. The fuels display a nearly linear decrease in DDT time of approximately 15% over the temperature range. The DDT time decreases despite the two competing effects of increasing fuel/air mixture temperature and decreasing density that causes a decrease in pressure. The first effect tends to increase reaction rate and lower DDT time [cf., Eq. (1)], whereas the second reduces detonability (refer to Sec. II.B) and tends to increase DDT time. The net effect is a decrease in DDT time, but probably not as much as would occur without the reduced detonability effect.

The variation of detonation distance with fuel injection temperature for all fuels except JP-10 is shown in Fig. 12. As expected, the detonation distance of all five fuels decreases with increasing fuel injection temperature. The detonation distance decrease is probably less than would occur absent the competing effects of density decrease and reaction rate increase discussed above. In Fig. 12, only below approximately 650 K does the detonation distance of the five fuels differ in magnitude and slope. Below 650 K, JP-8 has the smallest detonation distances, followed closely by JP-900, while JP-7 is highest at 1.14 m. RP-1 and S-8 perform similarly, both with detonation distance between JP-7 and

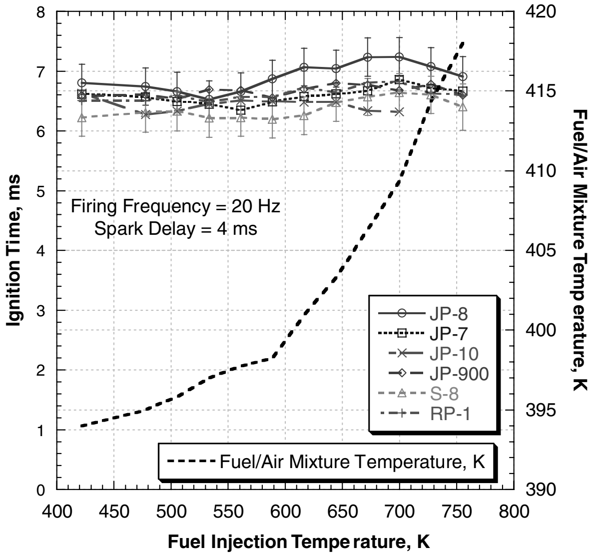


Fig. 10 Ignition times for several fuels.

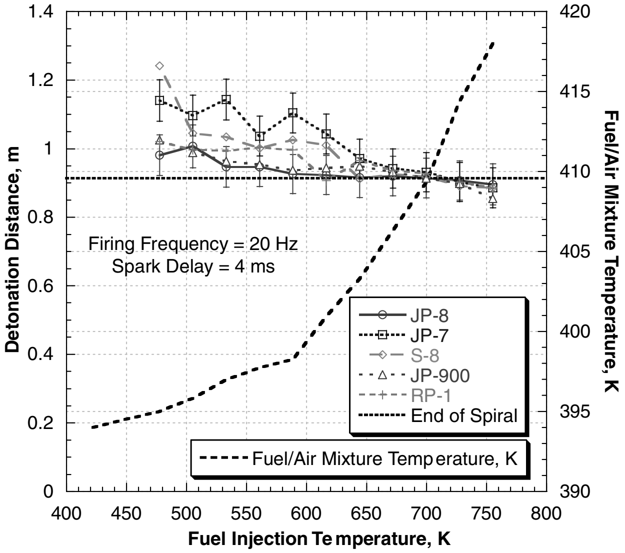


Fig. 12 Comparison of the detonation distance for five fuels.

JP-900. It was also noted that above roughly 675 K, detonations occur near the downstream end of the spiral for all five fuels shown. It was assumed that the difference in detonation distance of the five fuels would be negligible, similar to the DDT time trend. This stratification of detonation distances is possibly due to variation in laminar flame speeds between the fuels, although laminar flame speeds were not measured and data for all five fuels at these conditions are not available in literature. Card et al. [10] found that fuel/air mixtures with higher laminar flame speeds resulted in shorter detonation distances.

Detonation percentage is defined as the percentage of ignitions that result in a combustion wavespeed of 1800 m/s or greater. In Fig. 13, all fuels demonstrate a strong trend of increasing detonation percentage with increasing fuel injection temperature. The percentages displayed in Fig. 13 are dependent on the PDE configuration, but the trends demonstrate an increase in detonability with increasing fuel injection temperature. This increase is a result of a more homogenous mixture at higher fuel/air mixture temperatures but moderated by the same competing effects mentioned earlier (density decrease vs reaction rate increase). The effect of fuel injection temperature is more apparent in the detonation percentage as compared to the DDT time and detonation distance, most likely because detonation percentage is more dependent on the fuel/air mixing. Doungthip et al. [29] found that the injection of supercritical JP-8 resulted in greatly enhanced mixing compared to that of subcritical JP-8. The fuels can be divided into three categories based on Fig. 13. The first group, JP-7 and S-8, demonstrate the largest increases in detonations as fuel injection temperature increases, achieving nearly 100% detonations at 755 K. JP-8, JP-900, and RP-1 make up the second category, achieving detonation percentages between 65 and 75% at a fuel injection temperature of 755 K. The final category includes only JP-10. Although JP-10 slightly increases detonation percentage with increased fuel injection temperature, the magnitude of the detonation percentage remains low, 14–38%, leading to a large uncertainty in DDT time and detonation distance. The small detonability increase with increased JP-10/air mixture temperature is consistent with the findings of Ciccarelli and Card [20], which showed that the JP-10 detonation cell size was very insensitive to initial temperature.

B. Firing Frequency

The motivation to decrease ignition time and DDT time is to decrease the fire phase time, thus allowing a higher cycle frequency and higher average thrust. The relationship between firing frequency and thrust has been shown by Fan et al. [30]. To examine the effect of the firing frequency on PDE performance parameters, two frequencies, 15 and 20 Hz, were examined. Frequencies much above 20 Hz, for example, 25 Hz, would allow only 13 ms for the fire phase, too short for 15 ms required for the detonation of a JP-8/air mixture. Also, at frequencies much below 15 Hz, for example, 10 Hz, insufficient waste heat was generated for the heat transfer system to elevate fuel injection temperatures above 644 K.

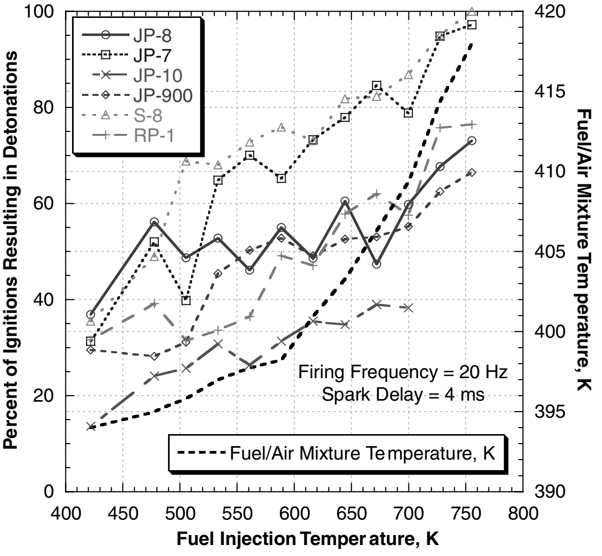


Fig. 13 Comparison of the detonation percentage for six fuels.

Figure 14 shows ignition and DDT times for a PDE operating at 15 and 20 Hz. Within experimental uncertainty, the ignition times are nearly equal for the entire temperature range. DDT time for the 20 Hz case is slightly less than the 15 Hz case for the entire temperature range. This 20 Hz decrease in DDT time is a result of higher pressures within the detonation tube that occur at higher frequencies, as shown by Tucker [22]. The total time to detonation, sum of spark delay (same for both), ignition time, and DDT time, is thus slightly less for the 20 Hz case.

Figure 15 shows detonation distance for two firing frequencies. The differences between the detonation distances are within the measurement uncertainty for the entire temperature range. From ion probe data (not shown) detonations occur at the downstream end of the internal spiral for both frequencies. DDT often occurs at the end of a tripping device, such as a spiral, due to the abrupt absence of such

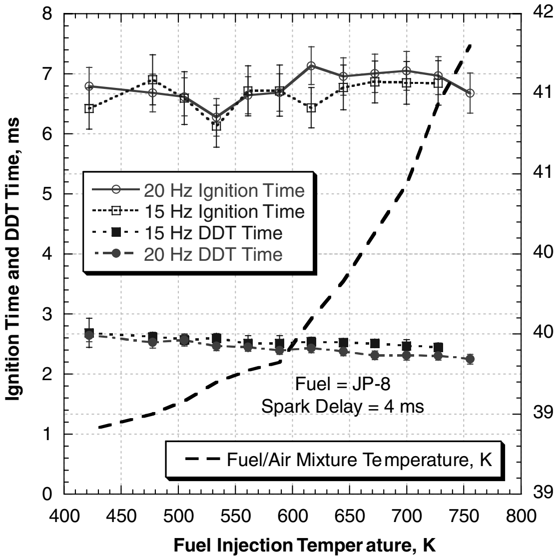


Fig. 14 Comparison of ignition time and DDT time for two frequencies for a JP-8/air mixture.

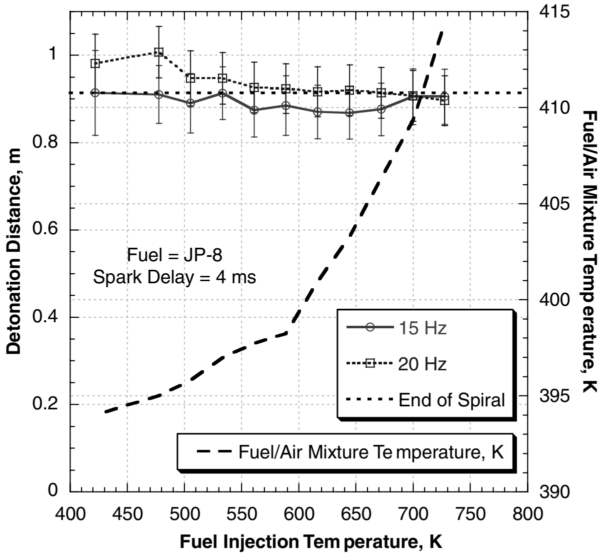


Fig. 15 Comparison of detonation distance for two frequencies for a JP-8/air mixture.

obstacle, as shown by Lee et al. [31]. In summary, increasing the firing frequency was found to have little effect on cycle performance.

C. Fuel Heating Value

Using the waste heat from PDE detonation tubes to preheat fuel to supercritical temperatures is important not only for detonation initiation. By regeneratively heating the fuel, the effective fuel heating value is increased, which corresponds directly to an improvement in specific fuel consumption (SFC). The significance of this effect is evaluated in Fig. 16, which is a plot of the percent of improvement in fuel heating value (over that of fuel at ambient temperatures) as a function of fuel injection temperature. Preheating the fuel to the supercritical temperatures results in a 2–3% improvement in fuel heating value, which directly corresponds to an SFC improvement of 2–3%. The percent of improvement in heating value was calculated using the heat of vaporization and heat capacity from the CRC Handbook of Aviation Fuel Properties [32]. The highly linear property data were extrapolated to the temperature limits shown in Fig. 15. This effective improvement in fuel heating value and thus fuel efficiency can be applied to conventional gas turbine engines using regenerative fuel cooling as well.

V. Conclusions

This research marked the first analysis of the effect of increasing fuel injection temperature, up to 755 K, on key pulsed-detonation-engine performance parameters, including ignition time, DDT time, detonation distance, and detonation percentage. Six fuels were examined, JP-8, JP-7, JP-10, JP-900, RP-1, and S-8. Ignition time was found to be virtually independent of fuel injection temperature for all fuels, except JP-8. JP-10 was found to detonate inconsistently, compared to the other fuels. The DDT time of the other five fuels demonstrated a nearly identical linear decrease of 15% over the temperature range tested. The detonation distance for all fuels, other than JP-10, linearly decreased down to a limit of spiral length with increasing fuel injection temperature. The detonation percentage for all fuels increased considerably with increasing fuel injection temperature, with JP-7 and S-8 producing the most consistent detonations. Based on this performance criterion, JP-8, JP-7, JP-900, RP-1, and S-8 can all be used to fuel a PDE with this configuration at elevated fuel injection temperatures; however, the configuration could be varied to aid in JP-10 detonation transition.

Increasing firing frequency from 15 to 20 Hz was found to slightly reduce the total time to detonation for a PDE. DDT time decreases with higher firing frequency, due to the higher pressure in the detonation tube, while ignition time and detonation distance are relatively independent of firing frequency.

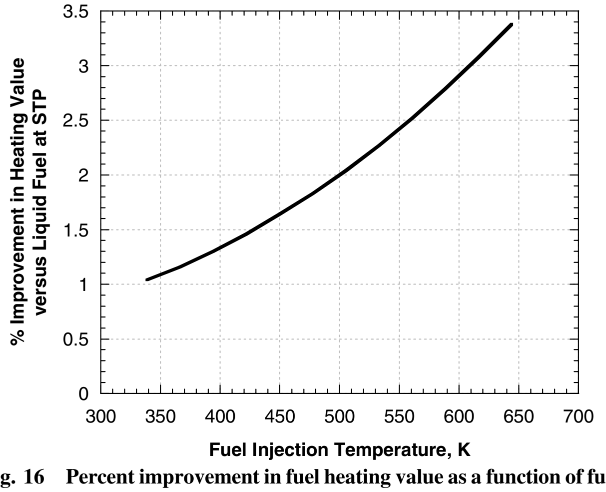


Fig. 16 Percent improvement in fuel heating value as a function of fuel injection temperature.

Acknowledgments

Funding was provided by the U.S. Air Force Research Laboratory Propulsion Directorate (AFRL/PR), and the U.S. Air Force Office of Scientific Research (AFOSR). This work would not have been possible without the technicians who worked on this project. Our thanks go to Curtis Rice, Dave Baker, and Dwight Fox of Innovative Scientific Solutions (ISSI). Tim Edwards (AFRL/PR) was extremely helpful in developing the fuel systems for this work. The authors would also like to thank Jeff Stutrud (AFRL/PR) for his controls and data acquisition expertise and Captain Wesley Knick (AFRL/PR) for his help. The technical leadership of Robert Hancock (AFRL/PR) was invaluable.

References

[1] Desbordes, D., Dauiau, E., and Zitoun, R., "Pulsed Detonation Propulsion: Key Issues," *High Speed Deflagration and Detonation: Fundamentals and Control*, edited by G. D. Roy, S. M. Frolov, D. W. Netzer, and A. A. Borisov, ELEX-KM Publishers, Moscow, 2001, pp. 177–192.

[2] Kailasanath, K., Patnaik, G., and Li, C., "On Factors Controlling the Performance of Pulsed Detonation Engines," *High-Speed Deflagration and Detonation: Fundamentals and Control*, edited by G. D. Roy, S. M. Frolov, D. W. Netzer, and A. A. Borisov, ELEX-KM Publishers, Moscow, 2001, pp. 193–206.

[3] Chuanjun, Y., Jun, L., Wei, F., Liming, H., and Hengren, L., "Principle and Cycle Analysis of Pulsed Detonation Engine," *Journal of Propulsion Technology*, Vol. 17, No. 3, June 1996, pp. 56–63.

[4] Kailasanath, K., "Review of Propulsion Applications of Detonation Waves," *AIAA Journal*, Vol. 38, No. 9, 2000, pp. 1704–1706.

[5] Edwards, T., "Liquid Fuels and Propellants for Aerospace Propulsion: 1903–2003," *Journal of Propulsion and Power*," Vol. 19, No. 6, 2003, pp. 1089–1107.

[6] Eidelman, S., Grossman, W., and Lottati, I., "Review of Propulsion Applications and Numerical Simulations of the Pulse Detonation Engine Concept," *Journal of Propulsion and Power*, Vol. 7, No. 6, 1991, pp. 857–865.

[7] Helfrich, T. M., "Cycle Performance of a Pulse Detonation Engine with Supercritical Fuel Injection," M.S. Thesis, Department of Aeronautics and Astronautics, Air Force Institute of Technology, Wright–Patterson AFB, OH, 2006.

[8] Tucker, K. C., King, P. I., Bradley, R. P., and Schauer, F. R., "The Use of a Flash Vaporization System with Liquid Hydrocarbon Fuels in a Pulse Detonation Engine," AIAA Paper 2004-0868, 5–8 Jan. 2004.

[9] Cheatham, S., and Kailasanath,. K., "Single-Cycle Performance of Idealized Liquid-Fueled Detonation Engines," *AIAA Journal*, Vol. 43, No. 6, 2005, pp. 1276–1283.

[10] Card, J., Rival, D., and Ciccarelli, G., "DDT in Fuel-Air Mixtures at Elevated Temperatures and Pressures," *Shock Waves*, Vol. 13, No. 3, 2005, pp. 167–173.

[11] Lefebvre, A., Freeman, W., and Cowell, L., "Spontaneous Ignition Delay Characteristics of Hydrocarbon Fuel/Air Mixtures," NASA CR-175064, Feb. 1986.

[12] Kaneshige, M., and Shepherd, J. E., *Detonation Database*, GALCIT Rept. FM97-8, GALCIT, Graduate Aeronautical Laboratories, California Institute of Technology, Pasadena, CA, July 1997.

[13] Knystautas, R., Guirao, C., Lee, J. H., and Sulmistras, A., "Measurement of Cell Size in Hydrocarbon-Air Mixtures and Predictions of Critical Tube Diameter, Critical Initiation Energy, and Detonability Limits," *Progress in Aeronautics and Astronautics*, Vol. 94, AIAA, New York, 1984, pp. 23–37.

[14] Tieszen, S. R., Stamps, D. W., Westbrook, C. K., and Pitz, W. J., "Gaseous Hydrocarbon-Air Detonations," *Combustion and Flame*, Vol. 84, No. 3, 1991, pp. 376–390.

[15] Stamps, D. W., and Tieszen, S. R., "The Influence of Initial Pressure and Temperature on Hydrogen-Air-Diluent Detonations," *Combustion and Flame*, Vol. 83, No. 3, 1991, pp. 353–364.

[16] Manzhalei, V. I., Mitrofanov, V. V., and Subbotin, V. A., "Measurement of Inhomogeneities of a Detonation Front in Gas Mixtures at Elevated Pressures," *Combustion, Explosion, and Shock Waves*, USSR, Vol. 10, No. 1, 1974, pp. 89–95.

[17] Bauer, P., Presles, H. N., Heuze, O., and Brochet, C., "Measurement of Cell Lengths in the Detonation Front of Hydrocarbon Oxygen and Nitrogen Mixtures at Elevated Initial Pressures," *Combustion and Flame*, Vol. 64, No. 1, 1986, pp. 113–123.

[18] Schauer, F., Stutrud, J., Bradley, R., Katta, V., and Hoke, J., "Detonation Studies and Performance for a Research PDE," *Confined*

Detonations and Pulse Detonation Engines, edited by G. D. Roy, S. M. Frolov, R. J. Santoro, and S. A. Tsyganov, Torus Press, Moscow, 2003.

[19] Schelkin, K. L., *Soviet Journal of Technical Physics*, Vol. 10, 1940, pp. 823–827.

[20] Ciccarelli, C., and Card, J., "Detonation in Mixtures of JP-10 Vapor and Air," *AIAA Journal*, Vol. 44, No. 2, 2006, pp. 362–367.

[21] Austin, J. M., and Shepherd, J. E., "Detonation in Hydrocarbon Fuel Blends," *Combustion and Flame*, Vol. 132, Nos. 1–2, 2002, pp. 73–90.

[22] Tucker, K. C., "A Flash Vaporization System for Detonation of Hydrocarbon Fuels in a Pulse Detonation Engine," Ph.D. Dissertation, Department of Aeronautics and Astronautics, Air Force Institute of Technology, Wright Patterson AFB, OH, 2005.

[23] Altin, O., and Eser, S., "Analysis of Solid Deposits from Thermal Stressing JP-8 Fuel on Different Tube Surfaces in a Flow Reactor," *Industrial and Engineering Chemistry Research*, Vol. 40, No. 2, 2001, pp. 596–603.

[24] Bartok, W., and Sarofim, A. F., *Fossil Fuel Combustion—A Source Book*, Wiley, New York, 1991.

[25] Miser, C. L., Helfrich, T. M., Schauer, F. R., and Phelps, D. K., "Supercritical Fuel Density from Experimental Pulse Detonation Engine," AIAA Paper 2006-1025, 9–12 Jan. 2006.

[26] Helfrich, T. M., King, P. I., Hoke, J. L., and Schauer, F. R., "Effect of Supercritical Fuel Injection on the Cycle Performance of a Pulsed Detonation Engine," AIAA Paper 2006-5133, 9–12 July 2006.

[27] Coleman, H. W., and Steele, W. G., Jr., *Experimentation and Uncertainty Analysis for Engineers*, Wiley, New York, 1989.

[28] Dieck, R. H., *Measurement Uncertainty: Methods and Applications*, 3rd ed., Instrumentation, Systems, and Automation Society, Research Triangle Park, NC, 2002.

[29] Doungthip, T., Ervin, J. S., Williams, T. F., and Bento, J., "Studies of Injections of Jet Fuels at Supercritical Conditions," *Industrial and Engineering Chemistry Research*, Vol. 41, No. 23, 2002, pp. 5856–5866.

[30] Fan, W., Yan, C., Huang, X., Zhang, Q., and Zheng, L., "Experimental Investigation of Two-Phase Pulse Detonation Engine," *Combustion and Flame*, Vol. 133, No. 2, 2004, pp. 441–450.

[31] Lee, S., Watts, J., Saretto, S., Pal, S., Conrad, C., Woodward, R., and Santoro, R., "Deflagration to Detonation Transition Processes by Turbulence-Generating Obstacles in Pulse Detonation Engines," *Journal of Propulsion and Power*, Vol. 20, No. 6, 2004, pp. 1027–1036.

[32] *Handbook of Aviation Fuel Properties*, 3rd ed., CRC Rept. No. 635, Coordinating Research Council Inc., Alpharetta, GA, 2004.

J. Powers
Associate Editor