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A HYDROCARBON FUEL FLASH VAPORIZATION SYSTEM FOR A PULSED DETONATION ENGINE (PREPRINT)

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14. ABSTRACT

Practical operation of pulsed detonation propulsion requires operation on kerosene-based jet fuels. These low vapor pressure fuels remain in liquid form at typical pulsed detonation inlet conditions and residence times, and the subsequent presence of fuel droplets significantly hinders performance. A fuel flash vaporization system (FVS) was designed and built to reduce evaporation time and provide gaseous fuel to the PDE. Four fuels that vary in volatility and octane number were tested: n-heptane, isooctane, aviation gasoline, and JP-8. Results showed the FVS quickly provides a detonable mixture for all of the fuels tested without coking the fuel lines. A significant result was the detonation of flash vaporized JP-8 in air without a pre-detonator.

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A Hydrocarbon Fuel Flash Vaporization System for a Pulsed Detonation Engine

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Abstract

Practical operation of pulsed detonation propulsion requires operation on kerosene-based jet fuels. These low vapor pressure fuels remain in liquid form at typical pulsed detonation inlet conditions and residence times, and the subsequent presence of fuel droplets significantly hinders performance. A fuel flash vaporization system (FVS) was designed and built to reduce evaporation time and provide gaseous fuel to the PDE. Four fuels that vary in volatility and octane number were tested: n-heptane, isooctane, aviation gasoline, and JP-8. Results showed the FVS quickly provides a detonable mixture for all of the fuels tested without coking the fuel lines. A significant result was the detonation of flash vaporized JP-8 in air without a pre-detonator.

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Introduction

The PDE is an attractive propulsion system for military use because of its simplicity, low cost and potential for large flight Mach numbers (0-5).[1,2] Some difficulties in the development of the PDE have been in creating a vaporized liquid fuel and air mixture quickly enough and initiating or transitioning detonations at a high enough frequency to create practical thrust levels.[3] In a typical high pressure fuel liquid injection system (without flash vaporization), high performance nozzles can atomize fuel droplets to within 25 to 70 microns.[4] When mixed with moderately heated air, the droplets will evaporate prior to combustion. If the fuel remains partly liquid, however, some ignition energy is consumed in evaporating liquid droplets, thus slowing completion of ignition and limiting the combustion temperature rise. Such has been the case in PDEs with conventional injection of liquid hydrocarbon fuels. Tucker[5] shows that to avoid inhibiting combustion, a mixture of air and fuel (JP-8) must be above about 400 K for the mixing process to completely evaporate the fuel in a typical length of mixing tube. A solution discussed in this paper is the use of a pre-combustion flash vaporization system to raise the enthalpy of the fuel prior to air mixing such that no energy is required from the air to evaporate the droplets.

Heating hydrocarbon fuels to high temperatures is not without certain problems, however. At flash vaporization temperatures, oxygen dissolved in the fuel can react to induce deposition of carbon and cause other problems within the fuel system. In the earliest documented flash vaporization system,[6] Whittle heated fuel above the boiling point in a gas turbine combustor, but poor fuel flow control and clogged fuel lines hindered efficient combustion. The clogged fuel lines were due to thermal oxidation and endothermic reactions - reactions that have since delayed the implementation of flash vaporization systems.

Thermal oxidation reactions can begin at fuel temperatures between 393 K and 533 K. The products from these reactions cause carbon particulates[7] and carbonaceous deposits on metal surfaces in fuel systems[8] that clog spray nozzles and cake on tubing walls. Depositions increase with increased dissolved oxygen in the fuel[9] and with increased fuel temperature.[18] Reactions can be negated up to a 755 K fuel temperature, however, by reducing the oxygen content to less than 1 part per million (ppm).[7, 8]

Endothermic reactions (due to cracking) also produce particulates and clog fuel lines. Cracking percentage, though, is highly dependent on soak time at high temperatures. Yoon et al[10] showed that N_2-deoxygenated n-dodecane (n-$C_{12}H_{26}$) decomposed by 20% in about four hours at 400 °C, but decomposed a like amount in only 17 minutes at 450 °C. For the flash vaporization system described in this work, the fuel was statically heated prior to use to temperatures below 350 °C. If higher temperatures were required, soak time was minimized (on the order of seconds). In flowing systems, low residence, and thus low soak times, allow for higher fuel temperatures. Ward et al.[11] was able to sustain no measurable cracking of flowing n-dodecane (n-$C_{12}H_{26}$) with a wall temperature of 500 °C. Ervin[7] heated flowing deoxygenated Jet A near 480 °C before significant cracking occurred.

To prevent thermal-oxidative reactions in this work, dissolved oxygen was removed by sparging the fuel with nitrogen prior to pressurization and heating. Sparging consists of bubbling gaseous nitrogen through ambient temperature liquid fuel to agitate and displace dissolved oxygen. Figure 1 shows a drilled spiral tube at the bottom of the sparging tank to bubble nitrogen through the fuel. Tests were performed with a gas chromatograph on air-saturated fuel to determine the amount of nitrogen to fully deoxygenate the fuels to the O_2 detection limit of the chromatograph. To further prevent the reaction between the fuel and heated metal structure, silicon based coatings were applied to all hot section components including the fuel nozzles.

Fig. 1. Top view of sparge spiral in the bottom of the fuel preparation tank.

Of the four fuels tested, kerosene based JP-8, used by the military, was of primary interest, since the fuel has high energy density and the handling and infrastructure are readily available. JP-8 has a low vapor pressure, good for preventing accidental spills from forming a combustible mixture, but unfavorable for ease of creating a purely gaseous mixture capable of transitioning and sustaining a detonation wave. Table 1 shows a comparison of JP-8 vapor pressure with other fuels tested.

Table 1. Fuel vapor pressures (kPa) at various temperatures: from Refs. 12 and 13.

Temperature (°C)	isooctane	n-heptane	aviation gasoline	JP-8
20	5.2	4.7	23	0.05
50	19.5	18.9	70	1.3
60	28.6	28	94	2
80	56.9	56.9	190	5
100	103.6	105.6	250 (est)	8.4

Prior to this work, JP-8/air detonations have been difficult to sustain because of a necessarily narrow equivalence ratio range and unsatisfactory fuel injection schemes. An incentive for this work was that of Brophy et al.[14,15] in tests with JP-10 and air in which small fuel droplets were evaporated with a vitiated air supply (with O_2 makeup). [Single species JP-10 has similar low vapor pressure behavior to that of the multiple component JP-8.] Detonations were generated using a JP-10/O2/air pre-detonator that channeled a developed detonation into the JP-10 and air mixture in the thrust chamber.

Flash Vaporization System

Flash vaporization, as defined here, occurs when a fuel is heated to a high enough temperature that upon injection into air for pre-combustion mixing, vaporization occurs in the absence of heat transfer from the air, i.e., the air temperature prior to and after mixing remains unchanged or is increased. The required flash vaporization temperature depends on the final pressure and temperature of the fuel/air mixture after the injection process and is not necessarily as high as the critical temperature for the fuel. In this work, fuel was pressurized above the critical pressure to prevent phase change within the system prior to injection, but was heated to temperatures sufficient to ensure flash vaporization, but below critical. Fuel nozzles were standard turbine engine pressure atomization nozzles, unmodified except for the application of a silicon coating. From photographs of superheated steam injected through the nozzles, it was clear that the fuel spray would not impinge on the mixing duct walls.

Flash vaporization temperature envelope

Pressures in the PDE intake manifold determine whether a fuel vapor/air mixture will condense out at equilibrium conditions. One can model the amount of condensate expected in the fuel/air mixture at an equilibrium pressure and temperature with the National Institutes of Standards and Technology (NIST) program SUPERTRAPP. The program uses the database for thermo physical properties of hydrocarbon mixtures and computes vapor-liquid equilibrium using the Peng-Robinson model.[16] The model assumes unlimited time to reach equilibrium adiabatically. Inputs included the initial stoichiometric fuel and air enthalpies and final equilibrium pressure, in this case 2.0 bar, slightly above the maximum pressure in the actual manifold during testing. N-heptane, n-C_7H_{16}, and isooctane, i-C_8H_{18}, are single component fuels, and were input as such, but JP-8 was modeled as a multi-component fuel. Table 2 shows the 10-component surrogate mixture[5] used. With the desired end point 100% fuel vapor after mixing, the JP-8 surrogate model performed well and missed the actual JP-8 bubble point line by 12.5 °C (1.84% of $T_{critical}$) and dew point line by 22 °C (3.24% of $T_{critical}$). (The multi-component aviation gasoline was not modeled.)

Table 2. JP-8 Surrogate for modeling vaporized mixture.

Name	SUPERTRAPP Symbol	Formula	MW	Mass of fuel	Moles
isooctane	224TMP	C_8H_{18}	114.229	5.00%	0.0683
methyl cyclohexane	MCC6	C_7H_{14}	98.186	5.00%	0.07945
meta-xylene	MXYL	C_8H_{10}	106.165	5.00%	0.07348
n-decane	C10	$C_{10}H_{22}$	142.282	15.00%	0.16449
butyl benzene	C4BNZ	$C_{10}H_{14}$	134.218	5.00%	0.05812
n-dodecane	C12	$C_{12}H_{26}$	170.335	22.00%	0.20152
1-methylnaphthalene	1MNAPH	$C_{11}H_{10}$	142.197	10.00%	0.10972
n-tetradecane	C14	$C_{14}H_{30}$	198.388	18.00%	0.14156
n-hexadecane	C16	$C_{16}H_{34}$	226.441	15.00%	0.10335
surrogate		$C_{11.9}H_{21.6}$	156.024	100.00%	1

The results of the model were used to determine a fuel/air test envelope for negligible fuel droplets. Table 3 shows results for a 100% vapor mixture in the manifold at a maximum pressure of 2 bar for three fuels. For resultant fuel/air mixture temperatures at or above those in

Table 3, the fuel vapor should not condense. For higher manifold pressures, such as required to run the PDE at higher frequencies, temperatures above those in Table 3 would be required.

Table 3. Minimum fuel/air mixture temperature required for 100% vapor in the intake manifold at 2 bar.

Fuel	Mixture Temperature (K)
n-C_7H_{16}	282
i-C_8H_{18}	287
JP-8	400

Figures 2, 3 and 4 show modeled fuel injection envelopes for a stoichiometric fuel/air mixture. The figures can be used to determine fuel and air conditions necessary for the mixture to fully evaporate or sustain a vaporized fuel. The axes are incoming fuel temperature and final mixture temperature. The horizontal line below the hatched box denotes the mixture temperature liquid-vapor equilibrium point from Table 3, and the temperature lines represent the initial air temperature prior to mixing. The minimum flash vaporization temperature line is the locus of the intersections of equal air and mixture temperatures. Those minimums are shown in Table 4. Fuel temperatures to the left of the minimums will result in heat removed from the air to evaporate the fuel. At the flash vaporization temperatures given in Table 4, the time to change the phase of the fuel is effectively zero since no evaporation time is required. The minimum flash vaporization temperature is an important parameter in designing the length of an intake manifold for a PDE since some distance (time) will be required to mix the fuel and air sufficiently.

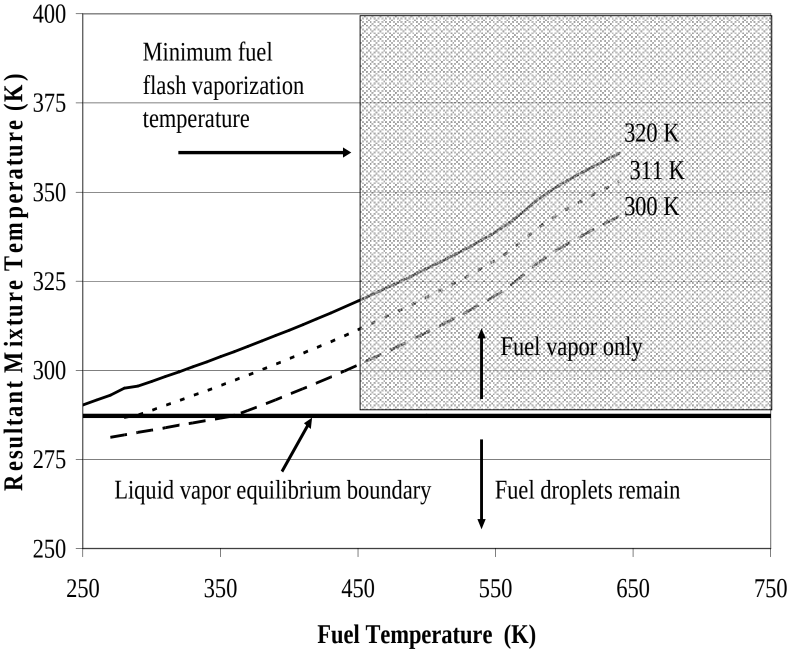

Fig. 2. Stoichiometric n-heptane and air mixture, liquid vapor equilibrium in the intake manifold for 3 air temperatures at 2 bar. The hatched region is where the fuel is flash vaporized.

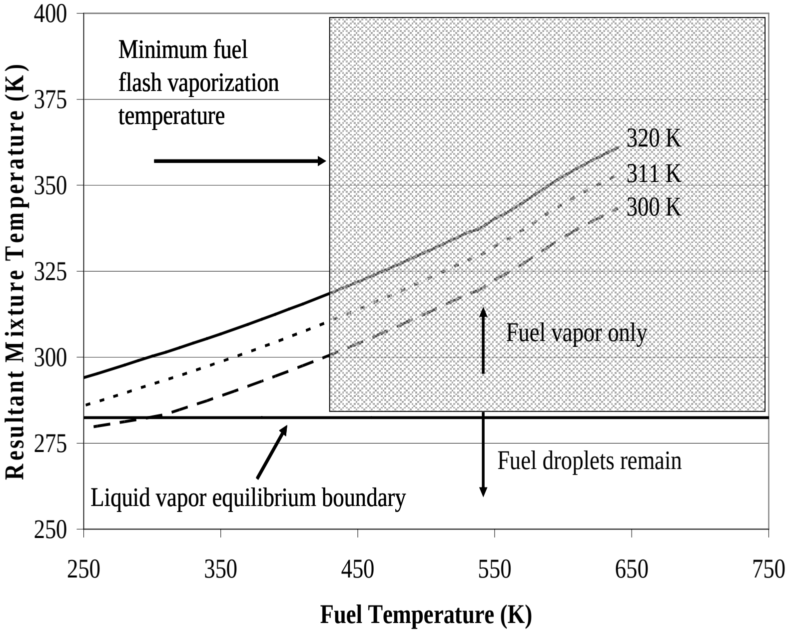

Fig. 3. Stoichiometric isooctane and air mixture liquid vapor equilibrium in the intake manifold for 3 air temperatures at 2 bar. The hatched region is where the fuel is flash vaporized.

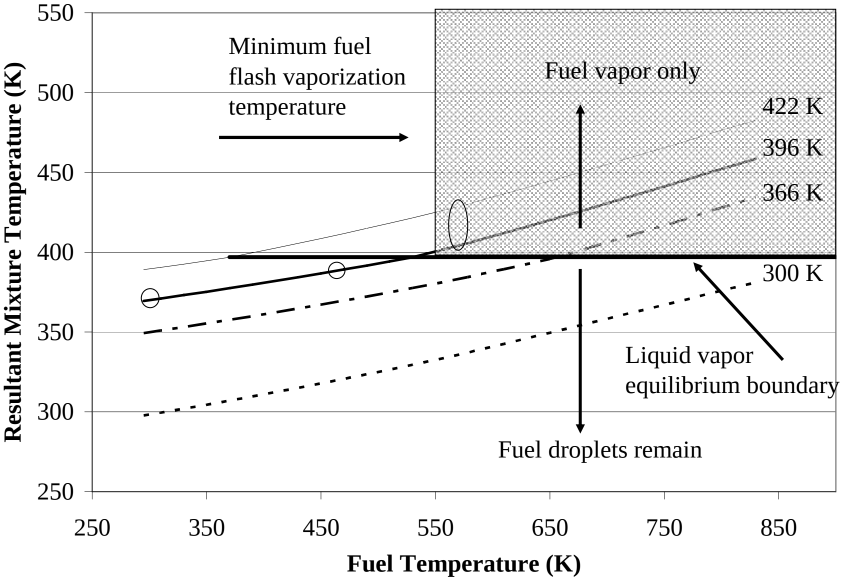

Fig. 4. Stoichiometric JP-8 surrogate and air mixture liquid vapor equilibrium in the intake manifold for 4 air temperatures at 2 bar. The hatched region is where the fuel is flash vaporized and the circles and ellipse denote test points.

Table 4. Minimum fuel temperature to flash vaporize for a given air temperature at 2 bar.

Fuel	Air Temperature (K)	Fuel Temperature (K)
n-C_7H_{16}	311	450
i-C_8H_{18}	311	430
JP-8	422	530

Figures 2 and 3 show that high vapor pressure fuels will vaporize in air at relatively low fuel and air temperatures (300-320 K) without flash vaporizing. The low vapor pressure JP-8 surrogate (Fig. 4), however, will not completely vaporize in air at 300 K without going to fuel temperatures well above 800 K, though at temperatures above 725 K, the model is not reliable due to the expected endothermic reactions and the creation of smaller molecular weight species.

The models indicate the benefit of heating the fuel to temperatures higher than the flash vaporization minimum for increased margin over the liquid vapor equilibrium line.

Experimental Setup

Experiments were performed in the Air Force Research Laboratory (AFRL) Pulsed Detonation Research Facility at Wright Patterson AFB, Ohio. The PDE engine is comprised of a General Motors Quad 4 head with two electrically driven camshafts. The rotating cams provide a three-part cycle with equal time (120 degrees) to fill, fire, and purge the thrust tubes. Four thrust tubes are attached where pistons and block would normally be, but generally only two of the four tubes were run. The steel tubes are 5.2 cm in diameter and 152 cm in length. Firing frequency for each tube was 15 Hz for an aggregate 30 Hz. Manifold pressure upstream of the valves was set provide a full tube fill (fill fraction of one). The required fill mass was based on the tube volume with the fuel air mixture at atmospheric pressure (due to the open end) and at the temperature of the mixture in the manifold upstream of the values. A more detailed explanation of the setup can be found in elsewhere.[1, 5]

Two fuel injection locations were used. For the high vapor pressure fuels (n-heptane, isooctane, and aviation gasoline), a tube of length 6.5 m with an axial mixer provided ample time for the fuel and air to mix (Fig. 5). For such long tubes flow quality is also improved due to farther distance from pressure and velocity fluctuations caused by intake valves. For the JP-8/air mixture, a shorter tube of length 1.3 meters with no axial mixer was used (Fig. 6). This shorter length prevented cooling and condensation at the higher air temperatures (422 K versus 311 K for the first three fuels). With fuel closer to the intake valves and an increase in the air velocity fluctuations were seen in the mixing tube.

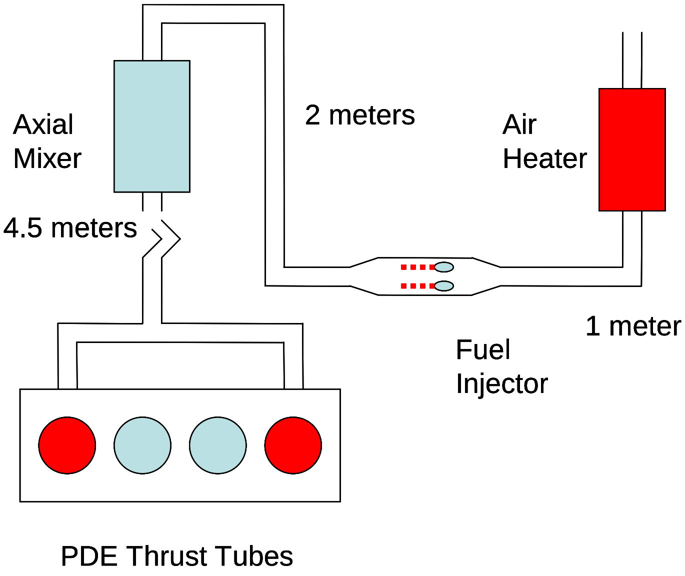

Fig. 5. High vapor pressure fuel/air schematic. Filled circles represent tubes used.

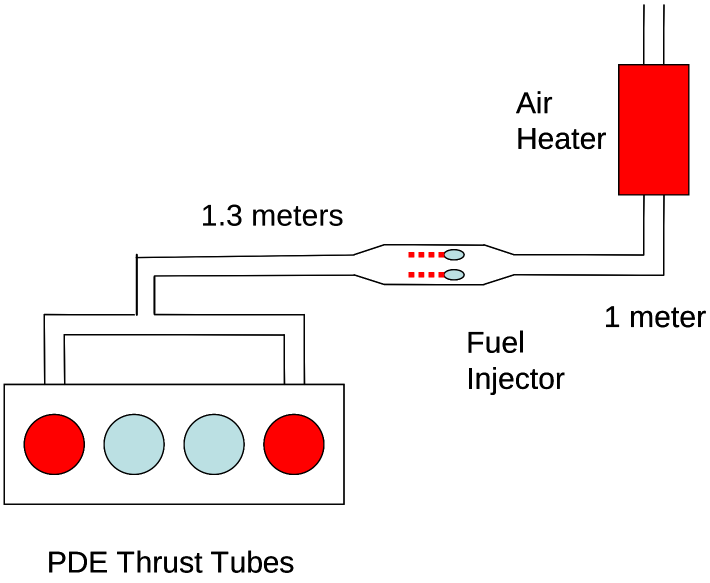

Fig. 6. JP-8/air flow schematic. Filled circles represent tubes used.

High pressure fuel system

Figure 7 shows the fuel system schematic. Not shown is a fuel pretreatment system that removed dissolved oxygen in the fuel. After de-oxygenation, fuel filled a hydraulic accumulator pressurized with gaseous nitrogen. Sufficiently high pressure near or above critical was applied to prevent phase change of the fuel during heating. After fuel heating and with fuel and air properties at desired levels, a high temperature rated pneumatic ball valve was opened to allow the pre-heated fuel to feed the fuel injection nozzles (fuel injectors). Fuel flow rates were controlled by nitrogen bottle pressure and by varying the number and size of the atomization nozzles. Downstream, the fuel/air mixture traveled to the intake manifold and was intermittently fed at the cycle frequency into the two thrust tubes for combustion. Run times of up to two minutes were possible before exhausting stored heated fuel. This process was repeated until the deoxygenated fuel stored in the accumulator was emptied.

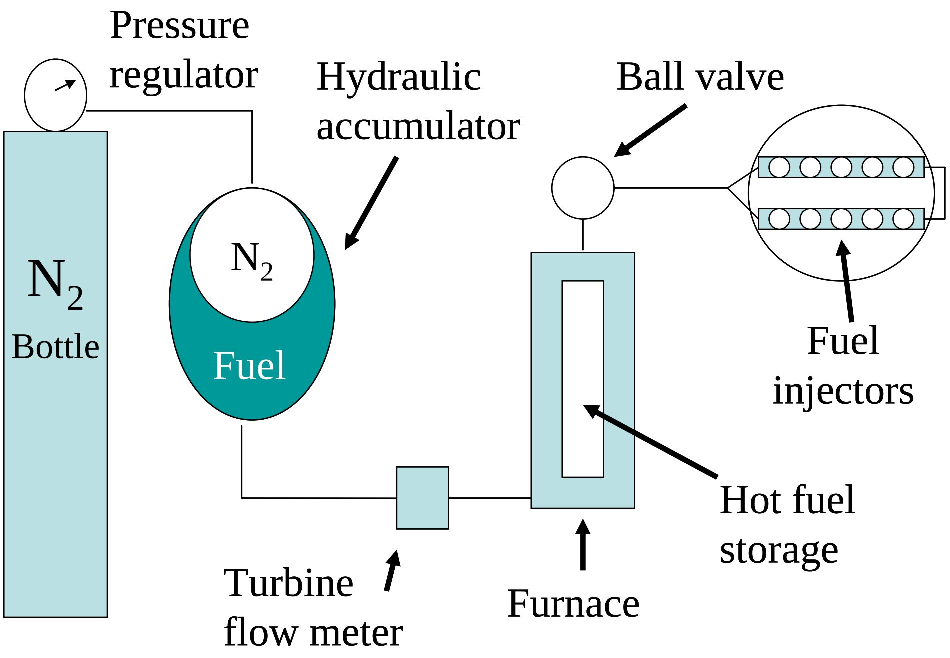

Fig. 7. High pressure fuel system schematic.

A dual spray bar depicted in Fig. 7 allowed nozzle sizing for a variety of fuel temperatures and fuel flow rates. Ten fuel pressure atomization nozzles could be used in combinations of nozzle flow numbers (FN) to match the desired flow rate using the relationship,[17]

$$FN = \frac{\dot{m}}{\sqrt{\Delta P}} \tag{1}$$

where $\dot{m}$ is mass flow in (lbm/hr) and ΔP is the pressure drop across the nozzle (psi). The flow numbers are additive and allow the use of several nozzles to match the desired flow rate. For increased fuel temperatures the density decreases (Figs. 8 and 9) and Eq. 1 must be corrected:

$$FN = \frac{\dot{m}}{\sqrt{\Delta P}}\sqrt{\frac{\rho_{CAL}}{\rho_{ACTUAL}}} \tag{52}$$

where ρ_{CAL} is the nozzle calibration density[4] (768.9 kg/m^3) and ρ_{ACTUAL} is the density as given by Figs. 8 and 9. As seen in the figures, above the critical temperature, density depends on both temperature and pressure.

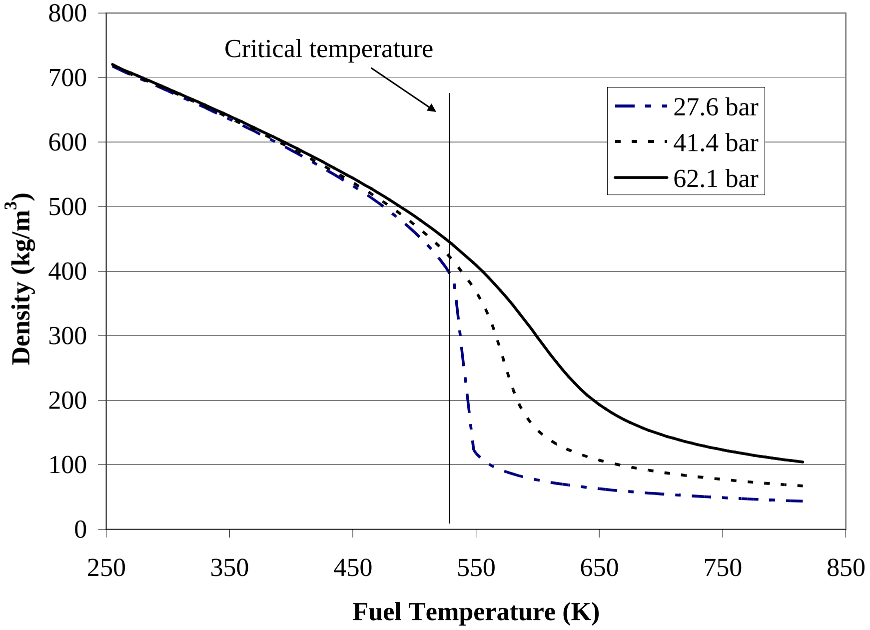

Fig. 8. Heptane density for three pressures. The vertical line denotes the critical temperature.

The fuel nozzles were made by Delevan and are widely used in gas turbine engines. The injector pressure and both the fuel (T1) and wall (T2) temperatures were recorded during testing (see Fig. 10). The area between the spray bars and the manifold walls (A1, A2, and A3) are equal and thus allow roughly equal air flow around the injectors. The fuel is injected tangentially with the air.

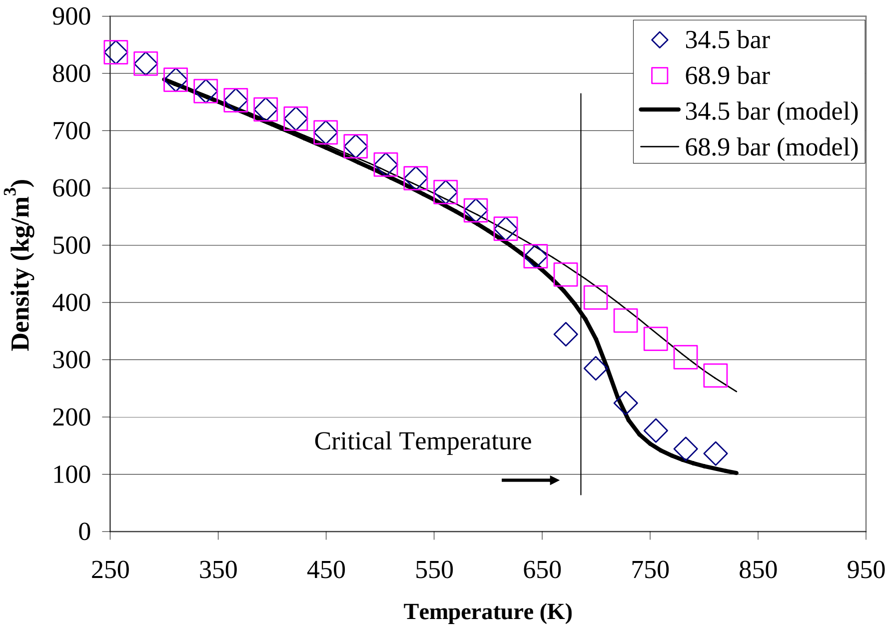

Fig. 9. Comparison of modeled JP-8 surrogate with experimental data from Ref. 18.

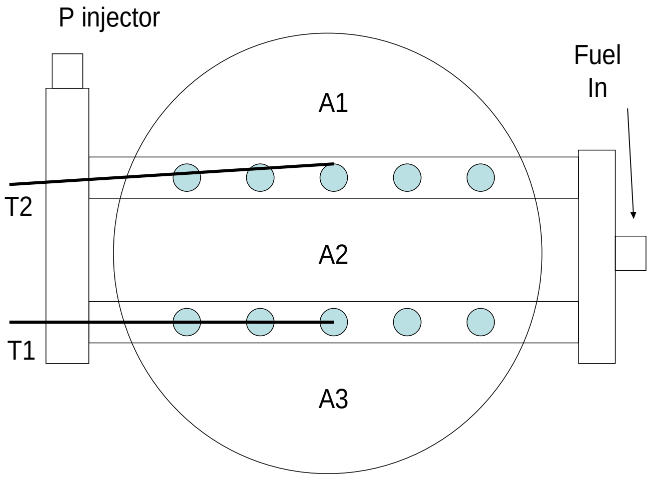

Fig. 10. Fuel Injector Spray Bars (front view). Filled circles denote pressure atomizing fuel nozzles. Areas between the spray bars are equal (A1=A2=A3) and the pipe diameter is 10 cm. The T1 thermocouple measures fuel temperature and the T2 thermocouple measures the wall temperature inside the fuel injector. Fuel flows out of the page.

Figure 11 is a schematic of thrust tube instrumentation for measuring head pressure, wave speeds and spiral transit time. The pressure rise in the head (closed end) of the PDE was used to determine ignition initiation. The pressure was measured by a dynamic PCB Piezotronics ICP pressure transducer. Combustion wave speeds were captured by ion probes used as time of flight sensors. The ion probes were located near the end of the tube, forward and aft of the end of the spiral. The wave speeds shown later are the average between probes 2 and 3. The spiral length was kept constant for all four fuels tested.

A 12 Volt DC MSD® Digital DIS-4 Ignition System powered the spark plug used to initiate combustion. The system provided three 105 – 115 milli-Joule sparks[19] into the fuel and air mixture via a capacitive discharge.

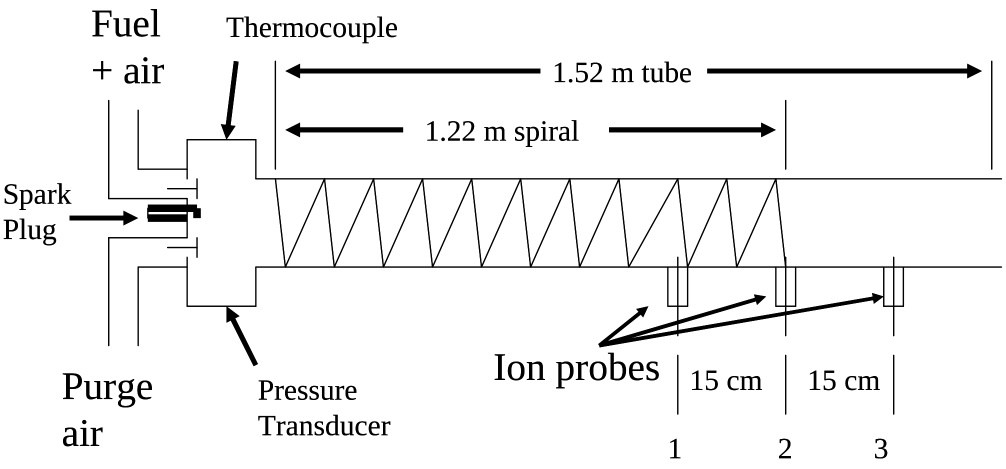

Fig. 11. Instrumentation on a single PDE thrust tube.

Results

The performance of the FVS was evaluated by comparing the combustion performance of fuels at ambient temperature to those heated to temperatures up to and above the flash vaporization temperatures shown in Table 4. Three combustion parameters were examined. First was the time for a combustion wave to exit the spiral at probe 2 after spark deposition in the closed end of the tube. This time is important in determining the maximum operating frequency of a PDE tube. Second was the combustion wave speed between probes 2 and 3, which determines whether a detonation was achieved. For wave speeds within ± 10% of the theoretical Chapman-Jouguet (CJ) wave speed, a detonation was considered to have occurred. The third variable was the time after ignition required for the combustion wave to exit the spiral. This represents the time required to transition the deflagration into a detonation.

Results are presented in two sections. The first section contains the three high vapor pressure fuels (n-heptane, isooctane, and aviation gasoline) and represents cases with the highest likelihood of gaseous injection and combustion, due in part to the long mixing length (6.5 m). As shown in Figs. 3 and 4, fuels at ambient temperature will completely evaporate in 311 K air. The aviation gasoline was not modeled but has a vapor pressure three to four times that of isooctane (Table 1) and should evaporate even more easily. The second section deals with vaporization of low vapor pressure JP-8. This was the more difficult case due to the shorter mixing length (1.3 m) and higher air and fuel temperatures needed to elevate the mixture temperature above the liquid vapor equilibrium line (Fig. 4).

The maximum times recorded were limited by the mechanical setup and the firing frequency. At 15 Hz firing frequency, total cycle time is 66.6 ms, with equal time (22.2 ms) allowed to fill, fire and purge the PDE tube. The 22.2 ms fire portion of the cycle consists of spark deposition, ignition, transitioning of the deflagration into a detonation and exhausting the high pressure gases (blow down) prior to purge. Given an 8 ms spark delay to prevent ignition during the expansion portion of the pressure fluctuation caused by intake valve closure, and since the tube required roughly 4 ms to blow down, only about 10 ms remained to ignite and detonate the mixture. Many runs had measured ignition times over 10 ms, resulting in hot gases remaining in the thrust tube and causing the temperature in the purge manifold to increase. In extreme cases, insufficient purge occurred and the incoming fuel and air mixture was ignited by the hot waste products from the previous fire portion of the cycle instead of the spark plug. Such ill-timed combustion waves can travel into the intake manifold during the fill process and potentially damage the PDE. In all cases that follow, data points are averages of eight combustion events and error bars are ± 1 standard deviation.

High vapor pressure fuel/air

Figure 12 shows the time from spark deposition in the closed end of the PDE tube to a combustion wave occurrence at ion probe 2 for the high vapor pressure fuels. Fuel temperatures ranged from ambient to 500 K. Solid and dashed lines are curve fits. The figure contains unheated and heated flash vaporized fuels, and as can be seen, no fuel temperature dependence is evident. It appears that a richer mixture favors lower detonation time, but as shown later, wave speeds can fall off at higher φ. For $\varphi = 1$, the isooctane takes roughly 12 ms to transit the spiral, 1 ms more than the aviation gasoline and 2 ms more than the n-heptane.

The combustion wave speed measured between probes 2 and 3 determines whether a detonation wave was achieved. Figure 13 shows combustion wave speeds for the high vapor pressure fuels compared with the predicted Chapman-Jouguet wave speeds from Gordon and McBride’s CEA program.[20] Again, no fuel temperature dependence was observed. Larger standard deviations are observed at lean and rich limits (i.e., the detonation limits), especially for the isooctane, due to the difficulty in obtaining detonations at those locations. The isooctane also has narrowest equivalence ratio range of detonation occurrence ($0.95 < \varphi < 1.2$). The n-heptane and aviation gasoline both achieved detonations for the entire range φ (0.9 to 1.3).

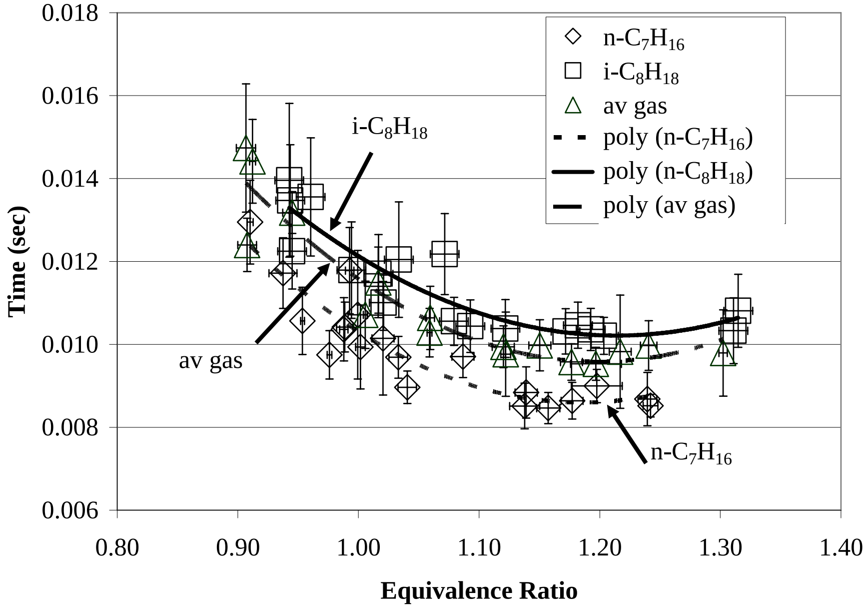

Fig. 12. Total time from spark deposit to combustion wave arrival at probe 2 for three high vapor pressure fuels.

In Fig. 13, n-heptane agrees best with the predicted CJ velocities. This is most likely due to an earlier transition from a deflagration to a detonation. Panzenhagen et al.[21] found in a similar setup that the detonation transitioned at roughly 1 m of spiral. The aviation gasoline and isooctane most likely transitioned later and had not yet reached the steady state velocity at one meter.

The detonability limits of the mixtures fall within equivalence ratio bounds for gaseous normal alkane fuels with a high explosive (HE) initiator[22] (see Table 5). The range of equivalence ratios that can sustain a detonation is narrow compared with the combustion limits, and although the detonation initiation method in Fig. 12 differs, the combustion results fall near the 1 MJ HE initiation energy values in Table 5.

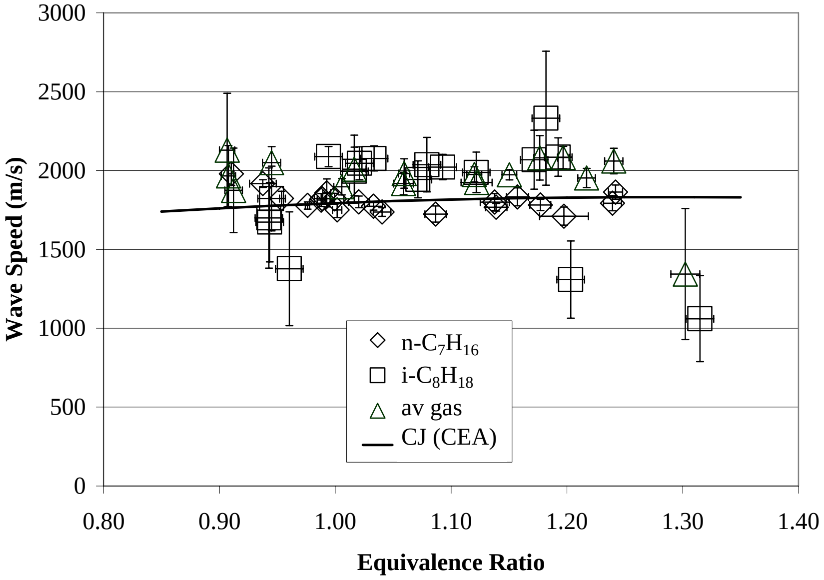

Fig. 13. Average wave speeds between probes 2 and 3 for three high vapor pressure fuels.

Table 5. Detonation limits for gaseous hydrocarbon fuels in air at 293 K and 1 atm with 1 MJ initiation energy and max available energy (estimated from Ref. 22).

Fuel	Formula	1 MJ Lean Limit φ_L	1MJ Rich Limit φ_R	Max Lean Limit φ_L	Max Rich Limit φ_R
ethane	C_2H_6	0.81	1.65	0.69	2.00
propane	C_3H_8	0.93	1.45	0.70	1.90
n-butane	n-C_4H_{10}	0.88	1.50	0.70	2.03

Early in this work, detonation transition was attempted with a 0.914 m spiral. Stoichiometric n-heptane/air was successful, but stoichiometric isooctane/air was not, again suggesting the earlier transition for n-heptane mentioned above. For a spiral length of 1.22 m, however, isooctane/air detonations were successfully transitioned. Typically, longer spirals extend the useful equivalence ratio range, but at a cost of extra weight.

Time to transition a deflagration into a detonation was a third parameter of interest. This is defined as the time from an initial combustion driven pressure rise in the closed end of the tube to the arrival of the combustion wave at probe 2. This time is in effect the spiral transit time and is shown in Fig. 14. Again, no fuel temperature dependence was observed. Although the time data does not indicate whether a detonation occurred, detonations correlate with shorter times. Several important features stand out in Fig. 14. The first is that measured times reach a minimum near an equivalence ratio of one. This has been noted before[31] and suggests that the minimum detonation initiation energy for hydrocarbon fuels occurs at or near the stoichiometric equivalence ratio. The lower detonation initiation energy reflects that the detonation transitions fastest at unity equivalence ratio and takes the least amount of time to traverse the spiral. The n-heptane was the fastest to generate a detonation and the isooctane slowest. Most of detonations were observed at transition times on the order of 2.6 ms or less. At longer times, detonations, as defined by wave speed, did not occur.

The shape of the curve in Fig. 13 is also of interest. When compared to total combustion time in Fig. 12, the spiral transit time is much flatter over the range of equivalence ratios. Both the shape of the curve and the magnitude of the error bars in Fig. 12 are dominated by the time for the initial pressure rise in the closed end of the head, defined as ignition time. The time for the combustion wave to transit the spiral (Fig. 14) is only about 1/4 that needed to generate ignition. Thus, reducing the ignition time would be a positive step in shortening the detonation initiation process.

In all the foregoing results, the absence of fuel injection temperature dependence implies an absence of liquid droplets. The fuel injection envelope predictions (Figs. 2 and 3) support the assumption that given adequate time (or mixing length), ambient temperature fuel mixed with air at 311 K will achieve 100% vapor.

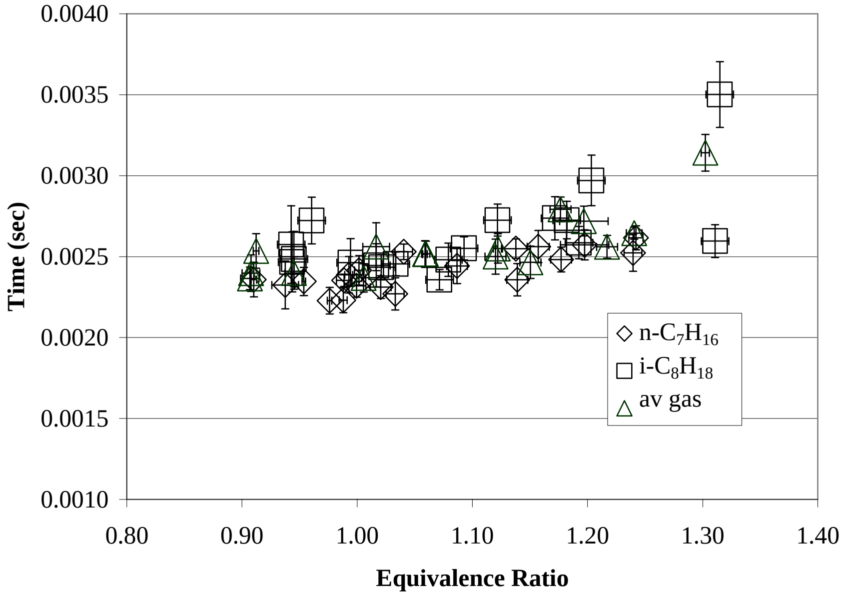

Fig. 14. Spiral transit time for high vapor pressure fuels.

Low vapor pressure JP-8/air

JP-8 combustion results were strongly influenced by both fuel and air temperature. This influence is shown in Fig. 15 for four fuel temperatures and two air temperatures (indicated by the circles and ellipse in Fig. 4). Lower combustion times occur with the fully vaporized high fuel temperatures (refer to Fig. 4), indicated by a curve shift to the left (leaner). The shift is due to unvaporized (liquid) fuel not combusting in the short time (~12 ms) to ignite and DDT the fuel/air mixture. One can see this from the best fit lines from Fig. 15 replotted in Fig. 16. The unheated (307 K) JP-8 line has been shifted by 0.15 to indicate the amount of fuel remaining in liquid form during combustion. The 0.15 shifted characteristic infers that with fully vaporized fuel either the same ignition and deflagration to detonation time can be achieved using 15% less fuel or, the total time to achieve the desired detonation wave at $\varphi = 1$ is reduced from 14 ms to 10 ms.

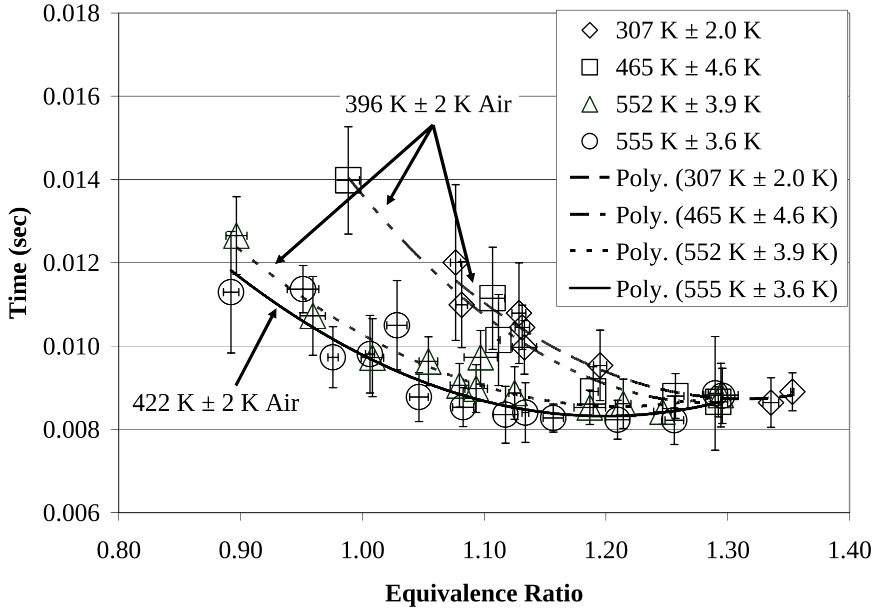

Fig. 15. Total time from spark deposit to combustion wave arrival at probe 2 for JP-8 and air.

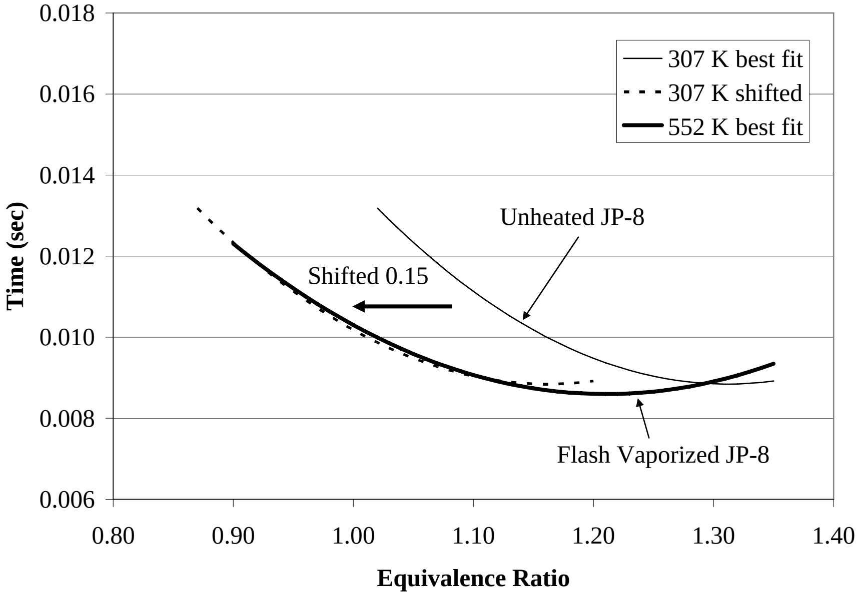

Fig. 16. Best fit lines for total time from spark deposit to combustion wave arrival at probe 2 for JP-8 and 394 K air.

Figure 17 shows spiral transit time, the time from initial pressure rise in the closed end of the tube to the combustion wave arrival at probe 2, for various equivalent ratios and fuel temperatures. The spiral transit time was relatively independent of fuel temperature. The primary effect of the JP-8 fuel temperature was on the minimum lean ignition limit. The circled temperatures in Fig. 17 denote the leanest φ for ignition for three fuel temperatures, given the 22 ms time limit on the fire phase of the cycle. For example, the 307 K fuel temperature could not operate leaner than φ = 1.07, whereas the lean limit at 552 K was 0.89. Like the earlier high vapor pressure fuels, flash vaporized JP-8 reaches a minimum spiral transit time at φ = 1.05 which correlates well with the minimum detonation initiation energy required for that mixture condition.

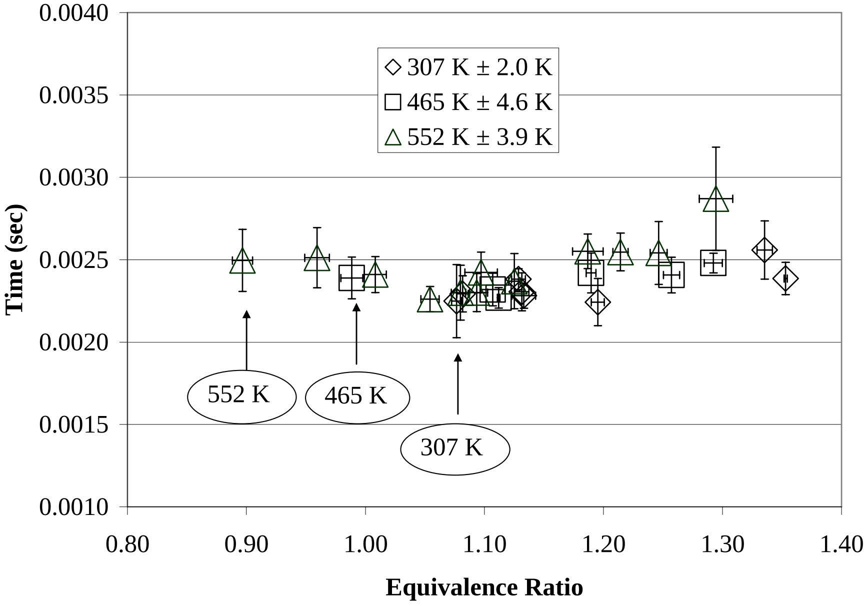

Fig. 17. Spiral transit time for JP-8 and air at three fuel temperatures into 396 K (± 2 K) air. Arrows denote the leanest mixture for ignition for the three fuel temperatures.

Wave speeds for JP-8/air mixtures detonated with (552 K case) and without (307 K and 465 K) full flash vaporization are shown in Fig. 18, agreeing well with the predicted CJ results. The two lower temperature fuels, presumably containing liquid droplets (refer to Fig. 4) required a considerably richer mixture than the flash vaporized case to achieve detonation and CJ speed. Like the high vapor pressure fuels, the detonation wave speed standard deviations increase for the leaner and richer detonability limits. The flash vaporized JP-8 detonability range was 0.90 to 0.95 at the lean limit and greater than 1.3 (1.3 was highest tested) at the rich limit.

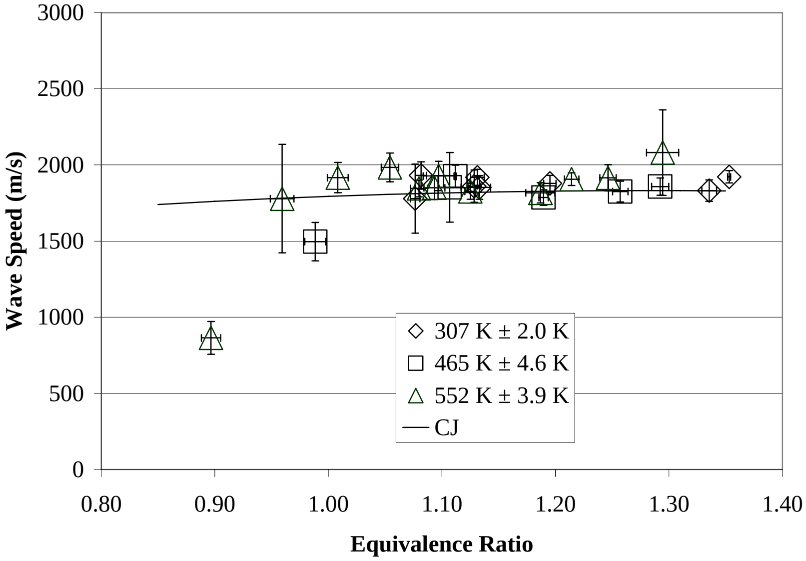

Fig. 18. Average combustion wave speed between sensors 2 and 3 for three fuel temperatures into 396 K air. The lean equivalence ratio detonation limit is reduced as fuel injection temperature is increased.

Conclusions

This is the first reported successful effort to flash vaporize and detonate a wide variety of liquid hydrocarbon fuels with air, including the low vapor pressure JP-8, in a working pulsed detonation engine. Detonations were achieved over a wide operating equivalence ratio, without oxygen enhancement, or a pre-detonator. Fuel injection temperature had no measurable influence on the combustion for the aviation gasoline, i-C_8H_{18}, and n-C_7H_{16} due to both the high vapor pressure of the fuels as well as the long mixing length. The low vapor pressure JP-8 droplet effects on the ignition of the fuel were characterized as primarily an equivalence ratio shift to a higher (fuel rich) condition. For JP-8 fuel temperatures at levels that insured flash vaporization (> 530 K), the combustion data collapse to near that of the performance of the high vapor pressure n-heptane.

The FVS and the associated fuel injection scheme gave comparable ignition and detonation results even with a much shorter mixing length. The FVS also validated the ability to safely heat fuel to temperatures over 330 °C without thermal oxidative and endothermic reactions damaging the fuel system.

The conditions required to successfully flash vaporize and achieve a mixture without droplets were modeled. The JP-8 and air modeling showed that for 300 K fuel and 422 K air at a manifold pressure of 2 bar, the enthalpy available in the fuel and air was insufficient to completely evaporate the fuel. Likewise, for 300 K air, no fuel temperature (short of endothermic temperatures) could sufficiently ensure complete fuel vaporization. The fuel and temperatures used during this research were both above and below the predicted flash vaporization region. The resulting combustion results validated the temperature and pressure envelope required to provide a droplet free mixture.

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