affected by the magnitude of the imposed one-dimensional oscillation. Variations in Weber number indicate a decrease in both the amplitude and phase lag of the response as *We* is increased.

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Near-Critical Liquid Oxygen Droplet Measurements

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Introduction

SUPERCRITICAL droplet evaporation and combustion are some of the least understood processes occurring in current and future aerospace propulsion systems. They occur in current cryogenic rocket motor chambers when oxygen is injected (in the liquid state at supercritical pressure) into a combusting environment that is above its critical temperature while the injected hydrogen gas is already above its critical pressure and temperature. Supercritical droplet evaporation and combustion will also be present in future high-speed airbreathing propulsion systems where the fuel, whether hydrocarbon based or liquid hydrogen, will be used to cool the engine, avionics, and airframe, and will thus be preheated above its critical temperature before injection into the combustion chamber.

Above the critical pressure and temperature, the distinction between liquid and gas phases breaks down as their densities become similar and dramatic changes in material properties occur. For example, the liquid surface tension and heat of vaporization go to zero and the viscosity decreases significantly while the gas solubility into the liquid phase increases. At the same time, knowledge of the droplet lifetimes is essential for the prediction of combustor performance and stability. The droplet lifetime no longer follows the d^2 law and analysis of the process by standard methods, i.e., solution of the Navier–Stokes equations, is difficult because of the highly transient nature of the problem and the need of numerous submodels to obtain the gas and liquid thermodynamic and transport properties.

The Space Shuttle Main Engine (SSME) is one example of a cryogenic hydrogen/oxygen system that operates supercritically. Although the engine has been operating successfully for decades, no knowledge exists of the behavior or characteristics of the liquid oxygen (LOX) subsequent to its injection into the combustion chamber. It is only within the past 15 years that nonintrusive optical means have existed to make spatially resolved measurements of drop sizes and velocities,[1] and even more recently these techniques have been applied to the high-pressure and temperature environments typical of liquid rocket motor combustion chambers.[2] The question has always existed, however, as to what these techniques would measure as chamber pressures and temperatures passed the critical point of the injected fluids.

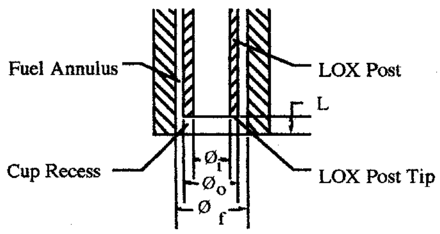
Experimental Approach

Shear Coaxial Injector Element

The shear coaxial injector for the hot-fire experiments (Fig. 1) permits the modification of critical injector dimensions including the gaseous hydrogen-fuel annulus and LOX post exit areas, LOX post tip landwidth and shape, and the recess depth of the LOX post within the fuel annulus. The baseline dimensions of the injector are derived from the dimensions of the prototype injector element of the fuel preburner to the SSME. These dimensions are summarized in Fig. 1. The fuel annulus segment and LOX post are attached to a main propellant feed segment. A Swagelok compression fitting allows the LOX post to be positioned axially within the fuel annulus. The gas is fed into diametrically opposed inlets on the main-propellant feed segment and accumulated within the relatively large volume of the fuel plenum. To determine the injection properties of the gas, the temperature along with the fluctuating and mean components of the pressure are measured in the plenum region. Likewise, the pressure and temperature of the liquid are measured in the supply line at the entrance to the LOX post. The fuel annulus segment contains a threaded insert that forms the o.d. of the fuel annulus. The insert may be replaced between tests without complete chamber disassembly to change the fuel annulus diameter. The effects of gas-to-liquid velocity ratio, density ratio, and mixture ratio on injector performance may then be studied.

Hot-Fire Experiment

The chamber for these experiments is modular in design, allowing for simple variation of the chamber length, location



Baseline Dimensions

Fuel Annulus Diameter, $Ø_f$	5.03 mm
LOX Post Outer Diameter, $Ø_o$	3.76 mm
LOX Post Inner Diameter, $Ø_i$	2.26 mm
Post Tip Land Width	0.76 mm
Recess Length, L	2.54 mm

Fig. 1 Shear coaxial injector element schematic with baseline dimensions.

Received March 7, 1997; revision received Jan. 12, 1998; accepted for publication Jan. 20, 1998.

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of optical access, injector design, and throat diameter. The individual chamber segments include the injector segment, window segment, igniter segment, blank segment, and nozzle segment.[3] With all segments in place the interior length of the combustion chamber measures 25.7 cm. The chamber is mounted together with a hydraulic press and sealed between segments with standard polymer O-rings. The chamber is designed to operate for approximately 4 s at steady-state conditions.

Phase Doppler Interferometry Implementation Issues

An Aerometrics phase doppler particle analyzer (PDPA) was used in these experiments. The environment encountered in subscale cryogenic rocket-engine testing can readily yield sizing errors that impact the performance of phase Doppler interferometry (PDI). The sources of these errors include, but are not limited to, trajectory-dependent scattering effects,[4] multiple particle scattering,[5] nonsphericity of droplets,[6] and variations in the index of refraction.[7,8] Through proper selection of the optical configuration and novel signal-processing techniques,[9] trajectory-dependent scattering and multiple particle scattering may be minimized or eliminated. The issue of sizing errors caused by the passage of prolate/oblate drops or liquid ligaments through the probe volume is rather intractable in that the foundation of PDI relies on the assumption of droplet sphericity. Ligaments traversing the probe volume will most likely be rejected by the signal analyzer. Prolate/oblate droplets can be measured as valid drops, but with an inappropriate size depending on the degree of their deformation.[8] To minimize the errors associated with nonspherical droplets, measurements must be performed from two or three orthogonal directions,[9] an operation that is not readily possible with the existing apparatus.

The critical parameter affecting the present experimental effort is the variation of the refractive index n of the droplet and its surrounding medium with increasing chamber pressure. The influence of changing index of refraction on the performance of the PDPA has been studied numerically by several researchers for both a single and multicomponent fuel droplet.[7,8] The numerical results of both efforts corroborated the trend of increasing slope to the PDPA calibration curve for decreasing refractive index. This trend can likewise introduce sizing errors throughout the drop-size distribution when an incorrect refractive index is used to compute the curves. Both groups performed their calculations at the standard collection angle of 30 deg. However, collection of scattered light at the 30-deg angle becomes impossible at a refractive index less than approximately 1.04. This situation may arise in the present experiment when the chamber pressures approaches the critical pressure for LOX. To allow measurements at higher pressures, a smaller collection angle of 20 deg was selected following a light scattering analysis based on the geometrical optics approximation. A 20-deg collection angle permits refractive indices down to approximately 1.02 while still minimizing the interference of diffractively and reflectively scattered light with the refractive component. At an angle of 30 deg the slope of the calibration curves tend toward a single value for refractive indices less than or equal to 1.165. This behavior is advantageous because an average slope for these refractive indices can be used within the data acquisitions software without introducing significant drop-sizing errors arising from changes in the index of refraction. However, as stated earlier, a 30-deg angle may only be used for refractive indices greater than 1.04. A 20-deg collection angle allows for indices of refraction slightly lower than 1.04, but the calibration curves for 20 deg exhibit incrementally larger slopes with decreasing refractive index. To minimize the effect of changes in refractive index on drop sizing, the 30-deg collection angle was employed for subcritical pressures up to 700 psia and the 20-deg angle for transcritical pressures. The PDPA was calibrated at atmospheric pressure with a reference water spray provided by Aerometrics, Sunnyvale, California.

Results

Table 1 lists the experimental test conditions and measurements. Figure 2 shows the droplet arithmetic mean diameter as a function of the chamber pressure with the velocity ratio held between 10.9 and 13.9. For these tests the mixture ratio, defined as oxygen mass flow rate divided by hydrogen mass flow rate, varied from 3.3 to 4.8 (stoichiometric is 8). The chamber temperature was a function of the mixture ratio, starting at approximately 2900 K for a mixture ratio of 3.3 to 3400 K at 4.8. The velocity ratio was maintained constant by varying the fuel-flow area. The liquid Reynolds numbers ranged from 6.94×10^5 to 9.01×10^5, and the Weber numbers ranged from 1.16×10^5 to 4.25×10^5. Measurements were taken approximately 12 cm downstream from the injector face and 4 mm off axis. The droplet arithmetic mean diameter remains fairly constant at a value of about 40 μm from a chamber pressure of 450 psig up to approximately 600 psig and then begins to drop dramatically down to values around 10 μm at 800 psig. PDPA measurements were still being obtained at 800 psig, 80 psi above the critical pressure of pure oxygen. Facility limitations with the current experiment did not permit testing at higher chamber pressures. It was found that the chamber pressure had no consistent effect on the droplet velocity, which varied between 26 and 31 m/s, indicating the efficacy of the modular injector system in maintaining a constant gaseous hydrogen injection velocity as the chamber pressure was varied. These droplet-size measurements at low pressures agree with those of Pal et al.,[2] who measured an arithmetic mean diameter of 45 μm at a slightly lower pressure (~400 psig).

The same rate of droplet measurement attempts were made by the PDPA regardless of pressure, but the percent validation

Table 1 Experimental test conditions and measurements

Run no.	P_{ch}, psig	O/F	$\dot{m}_{LOX}$ kg/s	T_{LOX} K, injector	V_g/V_l	D_{10}, μm	Valid counts	% Valid
1	450	3.9	0.112	128	12.2	44.0	3266	26
2	450	3.8	0.111	128	12.4	44.2	3281	26
3	572	4.5	0.121	121	12.2	42.0	2566	23
4	574	4.2	0.117	126	12.7	42.7	2169	23
5	576	3.9	0.112	128	13.3	37.9	2285	24
6	588	4.1	0.118	127	12.6	39.3	2268	24
7	634	3.3	0.093	135	15.7	32.7	532	5
8	656	3.5	0.103	135	13.9	33.3	667	7
9	662	3.6	0.105	135	13.4	19.7	1681	14
10	667	3.6	0.106	134	13.5	25.0	897	7
11	758	3.8	0.108	128	13.9	18.7	1420	13
12	765	4.8	0.123	130	11.0	9.7	1059	12
13	784	4.5	0.123	136	10.9	10.1	1298	11
14	800	4.6	0.126	130	11.1	10.8	811	9

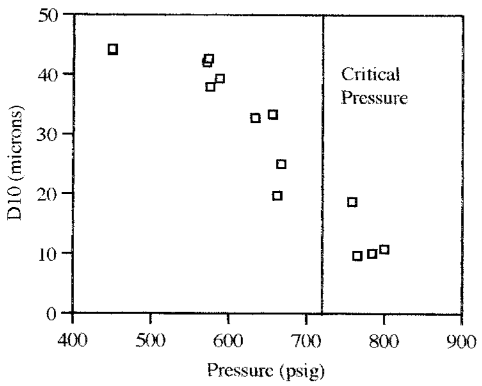

Fig. 2 Arithmetic mean diameter as a function of chamber pressure showing decrease of droplet size with increasing pressure and existence of droplets past the critical pressure of pure oxygen (P_c = 720 psig).

rate dropped with increasing pressure, starting from 26% at 450 psig and going down to 9% at 800 psig. However, the trend was not consistent and the lowest validation rates were not necessarily obtained at the highest chamber pressures, indicating the criticality of a correct optical alignment of the PDPA and a clear optical path through the combustion chamber. Validation rates dropped dramatically when the chamber windows became smudged, cracked, or fogged. These constitute the first ever PDPA droplet measurements for LOX above its critical pressure and temperature, indicating the existence of drops at least slightly above its critical pressure in the pure state, perhaps because of an increase of the critical pressure of oxygen caused by dissolved water vapor or hydrogen.[10] Suspended fuel droplets have been observed experimentally to exist above a fuel's critical pressure and temperature.[11,12]

Conclusions

Experiments were performed with LOX and gaseous hydrogen at elevated pressures with an SSME unielement shear coaxial injector in a subscale rocket combustion chamber. An Aerometrics PDPA was employed to examine the effect of chamber pressure on the LOX droplet size and velocity in the far-field region of the combusting spray. The injector velocity and mixture ratios were held constant and the spray was sampled 12 cm downstream from the injector face and 4 mm off-axis. The droplet arithmetic mean diameter decreased with increasing chamber pressure, whereas no effect on the droplet velocity was measured. For the first time droplet measurements were obtained for chamber pressures 80 psi above the critical pressure of pure oxygen (720 psig), indicating that solubility of hydrogen or water vapor in the oxygen may have increased its critical pressure.

Acknowledgments

This work was supported by the U.S. Air Force Office of Scientific Research Grant F49620-95-1-0184 and NASA Grants NAGW-1356, Supplement 10, and NGT-10034. J.-L. Thomas wishes to acknowledge the financial support of the Societe Europeene de Propulsion. The authors thank the U.S. Army Research Laboratory, Aberdeen, Maryland, for the loan of the Aerometrics PDPA.

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General Numerical Model for Liquid Jet Atomization Applications

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Introduction

NUMERICAL modeling of atomization processes in many liquid-fueled propulsion systems poses a challenge because it requires simultaneous resolution of liquid-gas-droplets dynamics, and the flow regimes considered can range from

Received July 26, 1996; revision received Dec. 2, 1997; accepted for publication March 2, 1998.

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