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FUNDAMENTAL ROCKET INJECTOR / SPRAY PROGRAMS AT THE PHILLIPS LABORATORY

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INTRODUCTION

The performance and stability of liquid rocket engines is determined to a large degree by atomization, mixing, and combustion processes. Control over these processes is exerted through the design of the injector. Injectors in liquid rocket engines are called upon to perform many functions. They must first of all mix the propellants to provide suitable performance in the shortest possible length. For main injectors, this is driven by the tradeoff between the combustion chamber performance, stability, efficiency and its weight and cost. In gas generators and preburners, however, it is also driven by the possibility of damage to downstream components, for example piping and turbine blades. This can occur if unburned fuel and oxidant later react to create hot spots. Weight and cost considerations require that the injector design be simple and lightweight. For reusable engines, the injectors must also be durable and easily maintained. Suitable atomization and mixing must be produced with as small a pressure drop as possible, so that the size and weight of pressure vessels and turbomachinery can be minimized. However, the pressure drop must not be so small as to promote feed system coupled instabilities. Another important function of the injectors is to ensure that the injector face plate and the chamber and nozzle walls are not damaged. Typically this requires reducing the heat transfer to an acceptable level and also keeping unburned oxygen from chemically attacking the walls, particularly in reusable engines. Therefore the mixing distribution is often tailored to be fuel-rich near the walls. Wall heat transfer can become catastrophically damaging in the presence of acoustic instabilities, so the injector must prevent these from occurring at all costs. In addition to acoustic stability (but coupled with it), injectors must also be kinetically stable. That is, the flame itself must maintain ignition in the combustion chamber. This is not typically a problem with main injectors, but can be a consideration in preburners, where the desire to keep turbine inlet temperatures as cool as possible can make it advantageous for the preburners to operate as far from stoichiometry as can be tolerated. For some missions such as Single Stage To Orbit, all of the above requirements must be maintained over a throttleable range, for example 5:1 to 10:1. Finally, the injectors must be ignitable during startup where pressures and temperatures are far from design conditions, and ignition transients must be minimized in order to avoid damage to engine components.

In order to satisfy these various constraints, the injector designer must be able to perform design tradeoff studies, and it is important that this be done with minimal time and costs. In fact, it can easily be argued that reducing engine development time and costs is essential to maintaining U.S. competitiveness in space. The Propulsion Directorate of the Phillips Laboratory has invested in a number of programs to advance liquid rocket engine technology, and several of these are directed at improving design tools for liquid rocket injectors. The purpose of the presentation will be to describe some of these latter programs.

OVERALL APPROACH

The overall approach of the design-oriented programs is to first give consideration to fundamental mechanisms, and to initiate programs to study these mechanisms if they are not sufficiently well understood. The results are incorporated into models, and the models are validated using suitable subscale experiments. The validated models are then incorporated into design-oriented CFD codes. This includes efforts to make these codes user-friendly, such as equipping them with graphical user interfaces. Although priority is given to Air Force customers, in many instances the technology developed has broader commercial or other applications, and efforts are made to make the technology available to these other applications where appropriate. The ultimate goal is to reduce engine development time and costs by a factor of two. The overall program is accomplished by a mixture of in-house programs, externally funded programs, and cooperative efforts with other industry, government, and academic laboratories. A representative sample of these is summarized below.

INJECTOR CHARACTERIZATON AT HIGH PRESSURES

Engine development programs have typically had to resort to a large number of expensive large subscale and full scale hot fire tests. Although the need for these cannot be entirely eliminated, cold flow testing is by comparison much cheaper, and useful for providing initial conditions for code predictions, as well as for performing comparative studies of different injector designs. The Phillips Lab injector characterization facility is capable of performing cold flow testing of full scale single injector elements at chamber pressures up to 2000 psi. The injector chamber is equipped with four sapphire windows for optical access, and is supported by an array of optical diagnostics including an Aerometrics phase doppler particle analyzer (PDPA), a Malvern Fraunhoffer diffraction instrument, a Greenfield image-based sizing instrument, and the coaxial beam particle analyzer of Grissom [1]. In addition, the vessel is equipped with a 27 element traversable linear patternator for mass distribution measurements. The facility is currently being used to study manifold effects on the atomization characteristics of a single orifice, as shown in Fig. 1. The manifold upstream of the orifice is designed to produce a well characterized turbulent cross flow, and the effects of cross velocity, orifice size, orifice L/D, chamber pressure, and injector ΔP are being studied.

PRIMARY AND SECONDARY ATOMIZATION AND DROPLET COMBUSTION

A number of programs have been directed at improving the understanding of these fundamental mechanisms as they apply to liquid rocket engines. Much of the work has been concerned with the effect of acoustic waves and the ability to couple with combustion instabilities, but steady state effects are also of concern. External programs have used shock tubes to study the effect shock strength and wave shape on liquid jets [2] and droplets [3]. Anderson and Winter [3] have applied the time and sub-micron resolution capability of the Morphology Dependent Resonant (MDR) drop sizing technique to effectively perform instantaneous vaporization rate measurements of droplets behind a shock wave. The results in Fig. 2 show the diameter decrease in fractions of a micron as a function of time in microseconds for different shock strengths and different fluids. Vaporization rates are shown to increase with increasing shock strengths and more volatile fluids, as expected, and the rates measured are found to be substantially higher than steady state models would predict. These programs compliment an internal program to experimentally study the vaporization and combustion behavior of supercritical droplets. Injection in many liquid rocket engines occurs at pressures exceeding the critical pressure of the propellant. Liquid oxygen, for example, is typically injected at a supercritical pressure, but at a subcritical temperature. It then undergoes a transition to a supercritical state as it is heated in the combustion chamber. The mechanism by which this occurs is not well understood; consequently most rocket CFD codes still use correlations based on subcritical studies. The approach will be to study droplets in free fall in a supercritical environment. Figure 3 shows the droplet generator developed for this project. The generator was designed to produce a monodisperse stream of widely spaced droplets (>100 diameters), using a variety of fluids including cryogenic fluids, at pressures up to 1500 psi. The piezoelectric droplet generator is theoretically capable of operating either in an acoustically excited breakup mode, a drop-on-demand mode, or with a shroud in an aerodynamic stripping mode in the absence of excitation. Most likely operation in a hybrid fashion combining two or more modes will produce the most success. The generator is currently undergoing testing. This project will also use a high pressure acoustic driver developed under an SBIR grant to acoustically excite the droplets. Unlike alternative methods such as using a rotating toothed wheel at the exit of a choked orifice, the acoustic driver is piezoelectrially driven and is capable of operating with no mean flow. Initial tests in a high pressure impedance tube show that sound pressure levels reaching 160 dB (1 atm. ref.) can be produced at 1000 psi. Efforts are underway to increase the output of the driver.

ADVANCED LIQUID ROCKET ENGINE MEASUREMENTS

This program is designed to cultivate recent developments in combustion diagnostics and determine the extent to which they can be "hardened" to apply to more realistic rocket environments, including high pressures and high temperatures. Such techniques would serve to validate codes under more realistic conditions, as well as to provide tools for diagnosing problems that may be encountered during testing. Efforts to date have been largely limited to planar laser sheet Mie scattering, but future efforts will seek creative, innovative approaches to obtain badly needed realistic data.

1. Grissom, W.M., "A Coaxial Beam Drop Sizing Instrument for Dense Sprays," Proceedings of the 5th International Conference on Liquid Atomization and Spray Systems, paper 69, July 1991.
2. Ateshkadi, A., Eastes, T.W., and Samuelsen, G.S., "Primary Breakup of a Liquid Jet in a Transverse Shock-Induced Flow," AIAA/SAE/ASME/ASEE 29th Joint Propulsion Conference & Exhibit, paper 93-2335, June 1993.
3. Anderson, T.J., and Winter, M., "Measurements of the Effect of Acoustic Disturbances on Droplet Vaporization Rates," AIAA 30th Aerospace Sciences Meeting & Exhibit, paper 92-0108, January 1992.

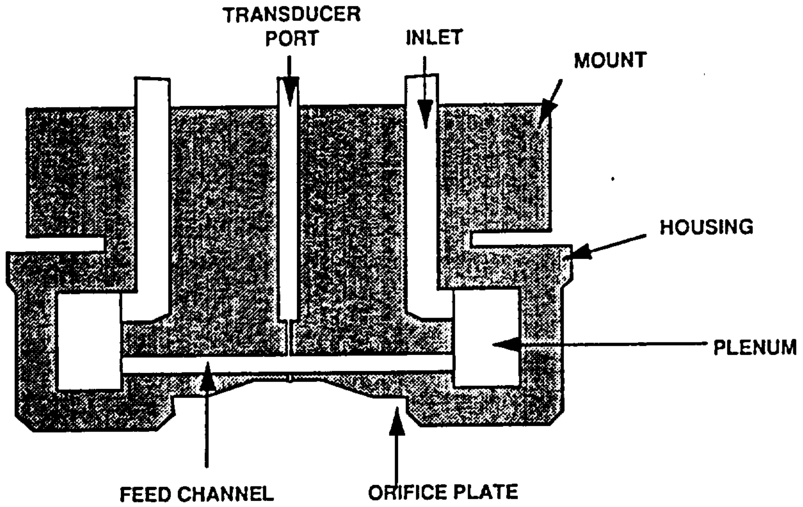

Figure 1.
Apparatus to study the effect of manifold cross flow on an orifice injector.

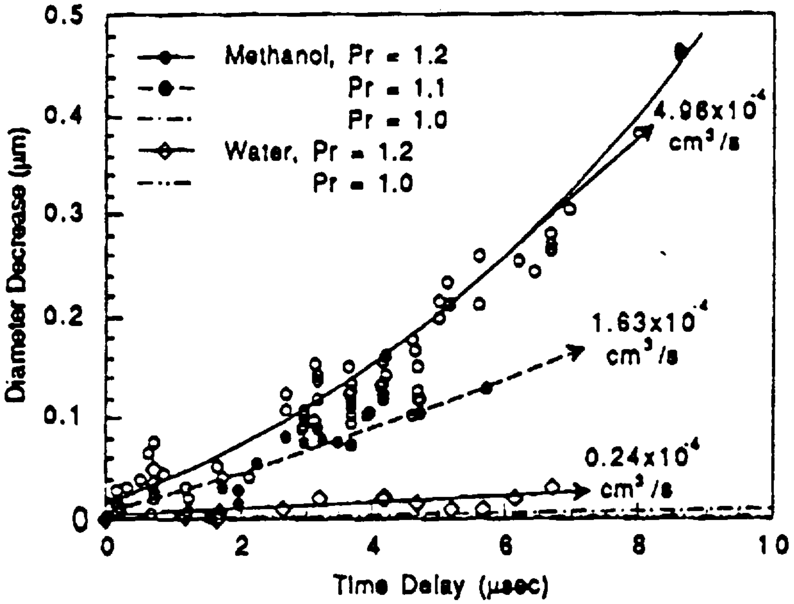

Figure 2.
Droplet vaporization rate measurements behind a shock wave (Winter/UTRC).

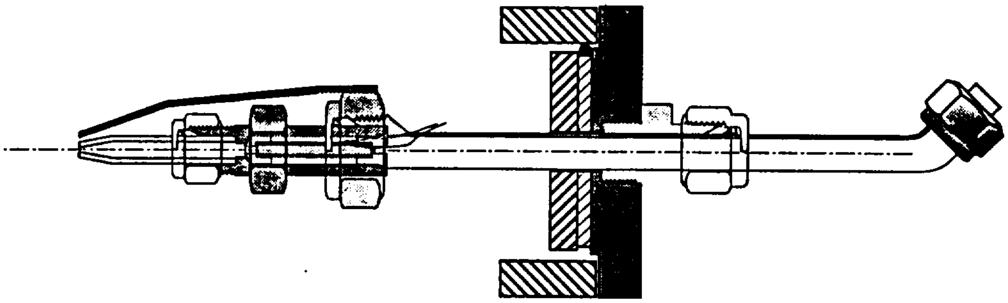

Figure 3.
Hybrid droplet generator for cryogenic fluids at high pressures.