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AXISYMMETRIC SINGLE SHEAR ELEMENT COMBUSTION INSTABILITY EXPERIMENT

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SUMMARY

The combustion stability characteristics of a combustor consisting of a single shear element and a cylindrical chamber utilizing LOX and gaseous hydrogen as propellants are presented. The combustor geometry and the resulting longitudinal mode instability are axisymmetric. Hydrogen injection temperature and pyrotechnic pulsing were used to determine stability boundaries. Mixture ratio, fuel annulus gap, and LOX post configuration were varied. Performance and stability data were obtained for chamber pressures of 300 and 1000 psia.

INTRODUCTION

Currently, a rigorous calculation of the combustion stability of a large liquid rocket engine is not feasible. Computationally these calculations are infeasible due to the inherent three dimensionality of the most common instability mode shapes and the fact that flight engines typically contain several hundred injection elements. Parallel computing may offer some hope of resolving this computational dilemma. However, even if sufficient computational resources were brought to bear on the problem, the lack of validated models for atomization, droplet dynamics, and droplet combustion in a rocket combustor environment would still prevent a rigorous solution from being obtained. One of the problems of validating such models for combustion instability is that the majority of existing experimental data is for three dimensional, multi-element geometries. The ability to do "numerical experiments" to develop and validate new models without gross simplifications of the actual phenomena is severely limited by the existing experimental database. Complex multi-element geometries also make it difficult to apply diagnostics to obtain data for model validation. Finally, the cost of obtaining data from multi-element hardware is prohibitive.

TEST ENGINE

The test engine consisted of a single, coaxial injection element and a heat sink chamber (Figure 1). The chamber was 2.055" in diameter and was 18.25" in length from the injector face to the nozzle throat. The chamber consisted of a short injector section, a long main chamber assembly made of Hastalloy, and the throat section. A schematic representation of the engine is provided in Figure 1. The throat diameter was .592" and .296" for 300 and 1000 psia respectively. The chamber was instrumented with an array of seven high frequency, piezoelectric, pressure transducers. Three transducers were located circumferentially around the chamber 1.75" downstream of the injector face. The remaining four transducers were placed axially along the chamber. In addition to the high frequency pressure transducers, an array of nine static pressure transducers were placed axially along the chamber.

The injection element consisted of a two piece LOX post assembly and a faceplate with an opening for the fuel annulus. The injection element was designed to be modular. Fuel annulus diameter (D_f) could be varied by changing the faceplate. LOX post orifice location and injection tip diameter could be varied by interchanging pieces of the two piece LOX post assembly. Three LOX post configurations were selected for testing (Figure 2.). All three configurations are 9.24" in length and are fed by a 1" diameter dome. This length was chosen so that the resonance of the LOX post would match the resonance of the chamber (approximately 1800 Hz).

LOX post configuration 1 in Figure 2 has a simple .9375" diameter tube with no orifice and was selected for its low LOX side pressure drop. Configuration 2 has a .0625" diameter orifice at the top of the tube. Configuration 2 represents the preferred configuration of engine manufacturers. Configuration 3 which has a .0625" diameter orifice at the bottom of the tube is similar to a design used in the Lewis LOX/H_2 instability test programs of the 1960's.

RESULTS

The most interesting stability behavior of this test program was encountered with configuration 3 (orifice at the bottom of the LOX post) and a fuel annulus diameter of .235". With this configuration, instabilities with amplitudes greater than 10% of chamber pressure were obtained. All of the instabilities encountered with this configuration were spontaneously unstable. The oscillations are present from the beginning of mainstage and persist throughout the run with little frequency shift. This can clearly be seen in Figure 3 which displays the frequency content and relative amplitude (pressure) of the oscillation as the test progresses (time axis). The second harmonic is clearly present and a trace of the third harmonic appears to be present also. To ensure that the two dimensionality of the oscillations was not being corrupted, Tests 286 and 292 were digitized at a sufficiently high rate to resolve the first tangential mode for this combustor (17,100 Hz). There was no indication that a tangential mode of oscillation was occurring.

The waveforms produced by the unstable test cases are fairly complex. For test 286, very pronounced beating occurred. Beating is occurring between oscillations at approximately 1780 Hz and 1858 Hz. These modes probably correspond to the natural modes of the chamber and the LOX post. A higher beat frequency also appears to be occurring and is produced by the first and second harmonics of the chamber oscillation. The oscillations appear to be limit cycle oscillations and do not appear to be very steep fronted. A number of the tests with this configuration had significant oscillation amplitudes but were not classically unstable. Figure 4. shows a plot of oscillation amplitude versus mixture ratio for configuration 3 with a fuel annulus diameter of

.235". Injector pressure drop or hydrogen injection temperature effects are not shown on the plot, resulting in some of the scatter. However, the appearance of distinct operation regimes is clear. In particular, a tuning region between a mixture ratio of approximately 5 to 6 exists in which classic instabilities occur. Retaining the same LOX post configuration but decreasing the fuel annulus diameter to .210" and .205" resulted in generally stable operation. Although an oscillation is present, its amplitude is between 3 and 5 percent of chamber pressure.

Configurations 2 and 3, both with orifices, had very high pressure drops. Eliminating the orifice, and utilizing a straight tube post (configuration 1) lowers the LOX side pressure drop. The tests are generally stable. While the LOX side pressure drop is down, the fuel side pressure drops as a percentage of chamber pressure for the configurations are relatively high (greater than fifteen percent). The only test with an oscillation approaching significant amplitude, also has the minimum fuel side pressure drop. It would have been interesting to test this configuration with a larger fuel annulus gap.

By changing the throat diameter from .592" to .296", tests were run at a nominal chamber pressure of a 1000 psi with the same injection element hardware and propellant flowrates that were used at 300 psi. A chamber pressure of 1000 psi was selected because it is above the critical pressure of pure liquid oxygen. When configuration 3 was run at 1000 psi the tests were very stable. In the majority of tests no organized oscillation is even detectable. It is interesting to note that when configuration 3 was tested at 1000 psi with a fuel annulus diameter of .235", the tests were stable. The same configuration was unstable at 300 psi. It is stable at 1000 psi even though the LOX and fuel side pressure drops as a percentage of chamber pressure are much lower than they were at 300 psi.

Bomb tests were performed during the test program (10 bomb tests are included in the tables). The bomb was triggered one half to one second before the end of a two second duration test. This timing provided ample time for a disturbance to organize and also permitted useful data to be taken before the bomb was triggered. Bomb overpressures ranged from 30 to 120 percent of chamber pressure. None of the bomb tests initiated an instability or altered the strength of an existing oscillation.

COMPUTATIONAL MODELS

A computational model of the test engine was made by modifying the KIVA II computer code.[4] The LOX tube flow was modeled using the one-dimensional "water hammer" equations. The LOX tube model provided the spray velocity and mass flowrate boundary conditions. The fuel side was modeled using a lumped parameter approach with the property variations during hydrogen temperature ramping being taken into account. The fuel side model provided a velocity boundary condition for KIVA II. A constant mass flowrate was imposed upstream of the LOX and fuel sides of the injection element. No attempt was made to resolve the atomization process computationally. A "blob" injection model with a dropsize correlation based on the work of Wu and Faeth[5] and a stochastic breakup model was employed. Results from the model for a stable, ambient temperature test and an unstable low temperature test are presented in Figure 5. The simulation of the high temperature test case exhibits small amplitude pressure oscillations whose frequency content is dominated by the first longitudinal oscillation. The low temperature simulation produces first longitudinal oscillations of an amplitude similar to those obtained experimentally for Test 286. It also appears as if beating is beginning to occur between the first and second harmonics (between 4.5 and 5.5 milliseconds in Figure 5). While the preliminary results look encouraging, the simulation should be carried out for longer than a few milliseconds. The initial goal is to reproduce the stability (and corresponding performance) map shown in Figure 10. with a single dropsize correlation.

CONCLUDING REMARKS

The data obtained in this test program provide a unique set of test cases for the validation of combustion instability codes, particularly CFD based models. Ultimately, it is hoped that validated instability codes could be used to design and predict the stability characteristics of future single element tests, a step on the path to reliable stability design codes for large liquid rocket engines.

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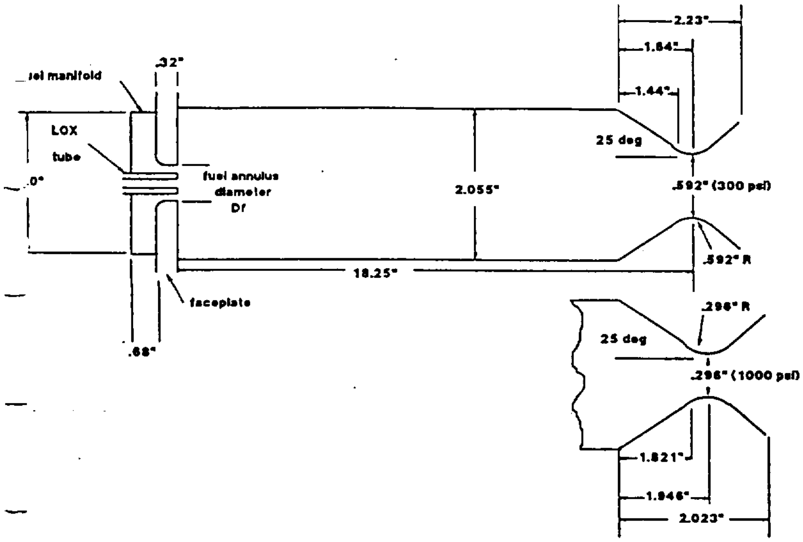

Figure 1. - Schematic Representation of Combustion Chamber Hardware

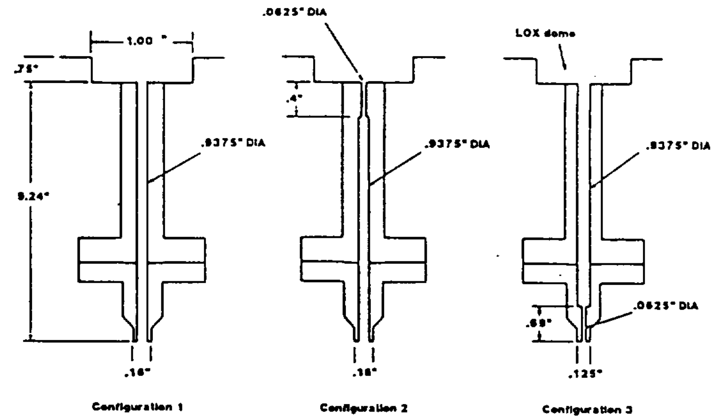

Figure 2. - Schematics of LOX Post Configurations

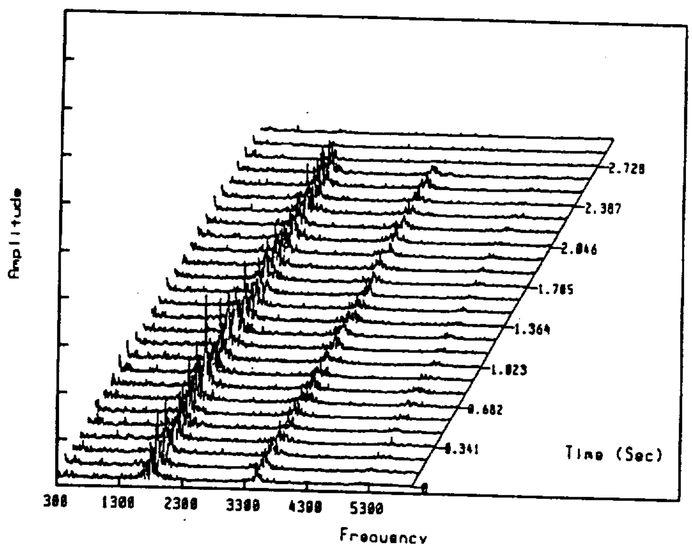

Figure 3. - Cascade Plot of Pressure for Unstable Test 292.

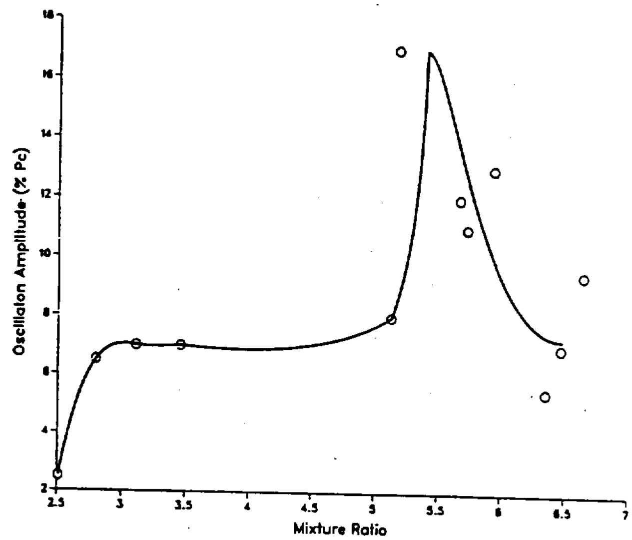

Figure 4. - Variation of Oscillation Amplitude with Mixture Ratio (Configuration 3, Df - .235")

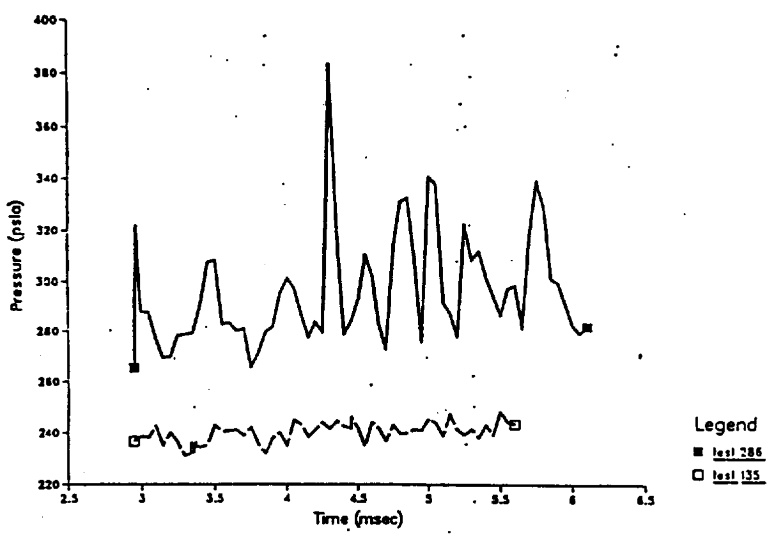

Figure 5. - Computed Pressure Trace for Stable and Unstable Test Cases.