N94-23042

SPRAY FORMATION PROCESSES OF IMPINGING JET INJECTORS

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SUMMARY:

A study examining impinging liquid jets has been underway to determine physical mechanisms responsible for combustion instabilities in liquid bi-propellant rocket engines. Primary atomization has been identified as an important process. Measurements of atomization length, wave structure, and drop size and velocity distribution were made under various ambient conditions. Test parameters included geometric effects and flow effects. It was observed that pre-impingement jet conditions, specifically whether they were laminar or turbulent, had the major effect on primary atomization. Comparison of the measurements with results from a two-dimensional linear aerodynamic stability model of a thinning, viscous sheet were made. Measured turbulent impinging jet characteristics were contrary to model predictions; the structure of waves generated near the point of jet impingement were dependent primarily on jet diameter and independent of jet velocity. It has been postulated that these impact waves are related to pressure and momentum fluctuations near the impingement region and control the eventual disintegration of the liquid sheet into ligaments. Examination of the temporal characteristics of primary atomization (ligament shedding frequency) strongly suggests that the periodic nature of primary atomization is a key process in combustion instability.

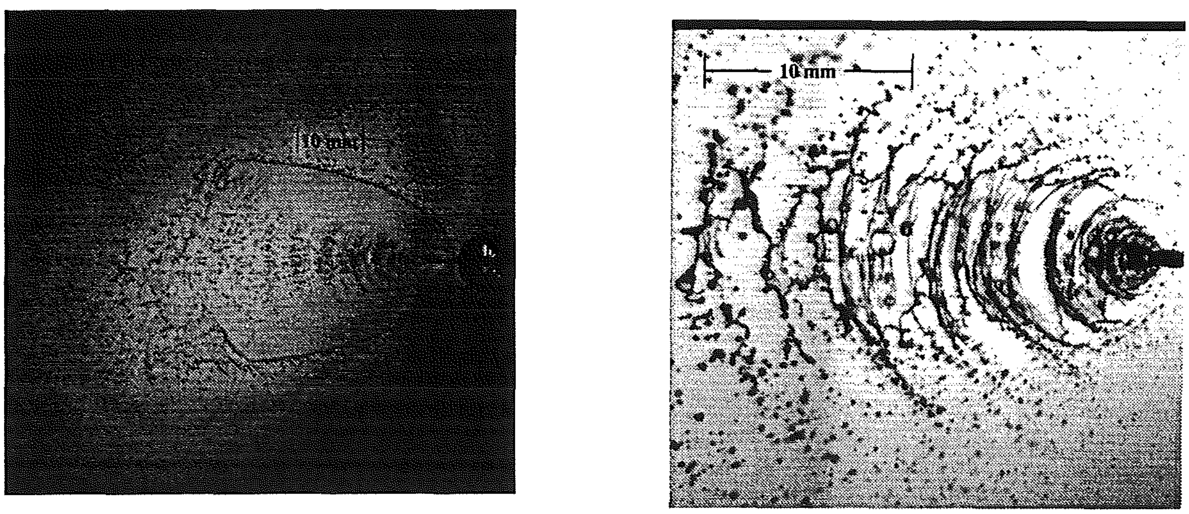
TECHNICAL DISCUSSION:

The present study is concentrated on defining the operative mechanisms of combustion instability in rocket engines that use impinging jet injectors. General information regarding the combustion process in rocket engine combustors of all types is also an important byproduct of this research. A review and characteristic time analysis[1] identified the combustion processes of primary atomization, secondary atomization, inter-propellant mixing, and droplet heating and vaporization as potential key mechanisms of combustion instability. Most of the effort to date has centered around an extensive characterization of primary atomization under cold-flow and atmospheric pressure conditions, with recent work emphasizing high-pressure and forced oscillatory conditions. A parallel effort in developing an accurate model of primary atomization is ongoing. More detail of the work can be found in References 1, 2, and 3.

There are two clear reasons for emphasizing atomization at the outset of the study: (1) atomization provides the initial conditions for subsequent combustion processes by its determinant effect on drop size and velocity; and (2) the periodic nature of primary atomization (ligament shedding) has pronounced similarities to combustion oscillations in rocket engines in terms of both frequency range and the way in which the frequencies of both combustion instability and ligament shedding are dependent on injector operational and geometric parameters.

The three classical cases of jet flow, namely fully-developed laminar jet flow, fully-developed turbulent jet flow, and "plug" jet flow have been studied because of their well-characterized velocity and turbulence intensity profiles. Fully-developed laminar flows could be obtained at high Reynolds by carefully contouring the orifice inlet. Absolute plug flow conditions were approached by using orifices with length-to-diameter ratios of five. Orifice length-to-diameter ratios used in practical injectors are typically about three. Undeveloped flows through the short orifices were observed to have either laminar or turbulent characteristics. In addition to changing flow condition and L/d_o, other test parameters varied included half-impingement angle, θ, orifice diameter, and free jet length prior to impingement.

The flow condition of the jet before impingement, i.e., whether it was laminar or turbulent, had the major effect on atomization. To illustrate the importance of the initial conditions of the liquid jet, consider the instantaneous images of the sheets formed by laminar and turbulent impinging jets shown in Fig. 1. These images were taken under quiescent conditions and at atmospheric pressure. Although the jet Reynolds numbers for both the laminar and turbulent cases are similar, the resultant sheets are distinctively different.



(a) (b)

Fig. 1. Instantaneous images of sprays formed by two impinging water jets injected through precision bore glass tubes at full impingement angles, 2θ, of 60°. (a) Resultant sheet formed by two laminar impinging jets emanating from 0.51 mm inner diameter, L/d_o=375 tubes. The jet velocity was 13.1 m/s and the jet Reynolds number was 6680. (b) Resultant sheet formed by two turbulent impinging jets emanating from 0.64 mm inner diameter, L/d_o=80 tubes. The jet velocity was 12.2 m/s and the Reynolds number was 7810.

In the laminar case, Fig. 1a, small ripples on the surface of the sheet are seen near the impingement point, and after some distance the sheet suddenly disintegrates into droplets. In many of the images of laminar impinging jets, incipient breakup occurred at mid-span of the sheet. Drops are also seen shedding off the edge of the sheet.

In the turbulent case, Fig. 1b, larger waves are apparent at jet impact. Downstream, the sheet disintegrates into ligaments, with incipient breakup consistently occurring at the edges, where the sheet is thinnest. Periodicity is indicated by waves on the liquid sheet and by the spacing between the detached ligaments. Examination of the detached liquid structures reveals irregular liquid shapes that contract into roughly cylindrical ligaments. The cylindrical ligaments appear to contract further into irregularly-shaped drops that will eventually take a nearly spherical shape. The ligament-to-droplet formation process is most likely controlled by surface tension-driven instabilities. The turbulent sheet is not as symmetric as the laminar sheet, and, by comparing upstream and downstream points near the edge of the turbulent sheet there appears to be relatively large-scale displacement of the sheet in the image plane, indicating large scale jet unsteadiness. Examination of opposite edges at the same downstream location leads to the same conclusion regarding asymmetry and large-scale jet unsteadiness. Thus, this phenomena is in all probability three-dimensional.

A mechanistic model of primary atomization that can accurately predict the effects of injector design and operation on breakup length, atomization frequency, and drop size and velocity distributions is critically needed by engine designers. The theoretical model that has been used to date by most researchers in this area[4,5,6] is based on linear stability analysis of aerodynamically-induced wave growth on the surface of a thinning, viscous liquid sheet. This model can be used to predict breakup length, the periodic structure of breakup, and drop size. Details of our implementation of the model as well as a more detailed comparison with the present experimental results can be found in References 2 and 3.

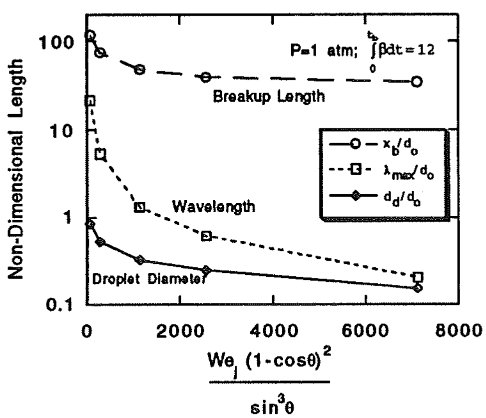


Fig. 2. Non-dimensional lengths as a function of geometrically scaled jet Weber number as predicted by aerodynamic instability model. Lengths normalized by orifice diameter.

In the course of analyzing results from the aerodynamic stability model, a non-dimensional scaling parameter based on the jet Weber number, $We_j=\rho_j v_j^2 d_o/\sigma$, and the half-impingement angle, θ, was identified: $We_j(1-\cos\theta)^2/\sin^3\theta$. Use of this parameter collapses the theoretical dependence of breakup length, fastest-growing wavelength, and drop size on orifice diameter, impingement angle, and velocity into a single curve dependent on the scaling parameter. Results from the model are shown in Fig. 2, where non-dimensional lengths, normalized by the orifice diameter, d_o, are plotted against the geometrically scaled jet Weber number.

Experiments were performed at atmospheric conditions using impinging jet injectors made of either precision bore glass tubes or twist-drilled orifices in a brass block. The latter injector unit was also used in experiments at high pressure and under oscillatory conditions forced by an acoustic driver. Length measurements of the intact sheet and of periodic structures were made from images such as

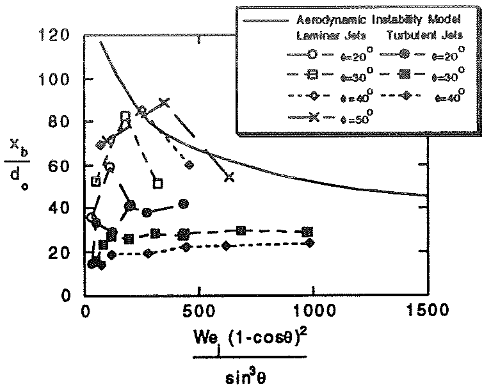


Fig. 3. Non-dimensional breakup length as a function of geometrically scaled jet Weber number. Comparison of measurements with aerodynamic instability model predictions.

those shown in Fig. 1. Results from breakup length measurements along with comparisons of the measured non-dimensional breakup length with predictions from the aerodynamic instability model are shown in Fig. 3. Again the differences between the turbulent impinging jet case and the laminar impinging jet case are evident. The non-dimensional breakup length of the turbulent impinging jets appears to have some dependence on impingement angle, but appears to be relatively independent of jet Weber number. There is a strong dependence on jet Weber number for the laminar impinging jet case. Laminar impinging jet breakup may be modeled relatively well by the aerodynamic instability model, but again, the turbulent impinging jet breakup shows little dependence on the geometrically scaled jet Weber number. It appears that turbulent impinging jet breakup, which is clearly dependent on orifice diameter and impingement angle, is related to the sheet thickness, which also is determined by orifice diameter and impingement angle .

The measured distance of the separation between periodic structures for turbulent impinging jets normalized by orifice diameter is shown in Fig. 4 as a function of jet velocity. The "wavelength" appears to be primarily dependent on orifice diameter and independent of jet velocity. The observation of independence from jet velocity is contrary to the aerodynamic instability model predictions. The distance between detached ligaments is approximately constant at about four orifice diameters, and the distance between surface wave structures is constant at about two orifice diameters. There was a large spread in the data, with a standard deviation of +/- 35%.

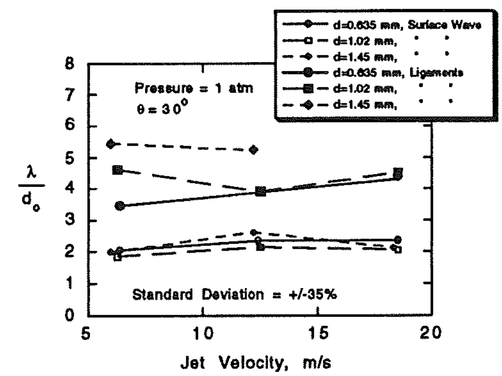


Fig. 4. Measured non-dimensional distance between adjacent surface wave structures and between adjacent ligaments.

The wavelength data was converted to atomization frequency simply by dividing the jet velocity by the measured wavelength; earlier studies showed that measured drop velocities were nearly equal to the jet velocity.[2] These atomization frequencies, as well as those obtained by Heidmann et al.[7] using a different experimental method, are quite similar to the maximum possible combustion instability frequency given by the Hewitt Stability Correlation[1] in that the respective frequencies are linearly dependent on the parameter d_o/v_j and also have a similar magnitude. The similarity between the maximum possible instability frequency as indicated by the stability correlation and atomization frequency as indicated by measurement is significant and suggests that primary atomization is the key process in combustion instability.

The energy release process must certainly be considered in an analysis of combustion instability. In liquid rocket engine combustion, vaporization is the rate-limiting step. The vaporization process is controlled in large by the drop size. Accurate measurements of the drop size distribution are necessary to develop an accurate understanding of the problem of combustion instability. An argon-ion based, two-component Phase Doppler Particle Analyzer

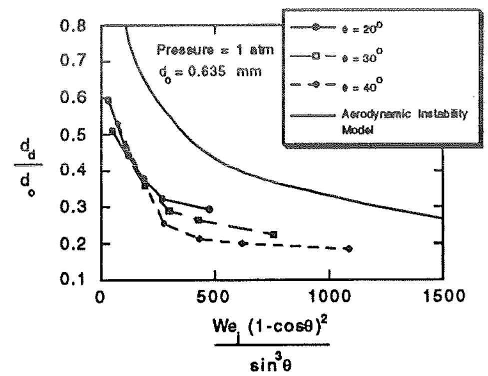


Fig. 5. Non-dimensional drop diameter as a function of geometrically scaled jet Weber number. Comparison of PDPA Measurements with predictions from aerodynamic instability model.

(PDPA) was used for making drop size and velocity measurements. A description of the theoretical and operating principles of the PDPA are given elsewhere.[3] Non-dimensional arithmetic mean drop diameters (D_{10}) are presented in Fig. 5 for the turbulent impinging jet case. A comparison of measured D_{10} with the monodisperse drop size predicted by the aerodynamic instability model is also shown. The model predictions match the experimental trend quite well, and, as the model predicts, the measurements collapse into a single curve when plotted against the geometrically scaled jet Weber number. An empirical correlation for normalized drop size as a function of the geometrically scaled jet Weber number, $We_j f(\theta)$, was obtained with a correlation coefficient of 0.964: $\frac{d_D}{d_o} = 2.217 \cdot \{We_j f(\theta)\}^{-0.354}$.

Recent experimental work has focused on making spray measurements (e.g., breakup length and drop size/velocity distributions) in a rectangular, transparent acoustic chamber. The interior dimensions of the chamber are 254 mm in width, 305 mm in height and 102 mm in depth. A twist-drilled impinging injector is inserted into the chamber top-plate, while an Altec Lansing compression driver attaches to a chamber side-wall. Use of the compression driver allows for the excitation of the first (1W), second (2W) and third (3W) resonant modes in the 254 mm width dimension of the chamber at frequencies on the order of several thousand hertz under ambient temperature conditions for air and helium environments. These modes and frequencies were chosen because of their similarity to typical rocket instability characteristics. Visual access to the spray field formed by the impinging injector is primarily afforded by two clear plexi-glas side-walls.

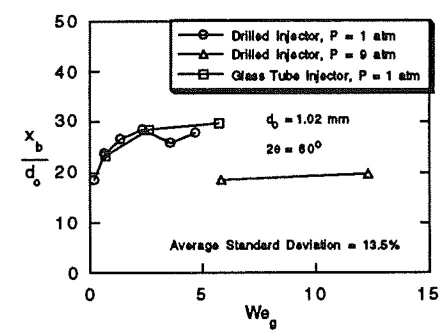


Fig. 6. Non-dimensional breakup length as a function of the gas Weber number and injector type. Breakup length measurements for the twist-drilled injector were taken at pressures of one and nine atm.

Initial measurements of the breakup length have been made within the aforementioned acoustic chamber in a high-pressure environment. Specifically, the spray breakup length was measured from instantaneous images, much like the one shown in Fig. 1b, at chamber pressures of one and nine atmospheres. A plot of the non-dimensional breakup length, x_b/d_o, as a function of We_g $(=\rho_g v_j^2 d_o/\sigma)$ is shown in Fig. 6. The non-dimensional breakup length observed for the twist-drilled injector is quite similar to that of the glass tube breakup length data at a chamber pressure of one atmosphere, despite the fact that the glass tube length-to-diameter ratio is eight times greater than that of the twist-drilled injector. In both cases, the breakup length gradually increases with increasing gas Weber number. Also, the observed breakup length for the twist-drilled injector noticeably decreases with an increase in chamber pressure.

Ongoing work is focused on obtaining further drop size/velocity measurements using the Phase Doppler Particle Analyzer for various injector orientations within the acoustic chamber under high-pressure and oscillatory conditions. In addition, work continues on the development of an accurate primary atomization model that is able to to account for the important physics occurring at the jet impingement point. After the completion of the high-pressure, acoustic cold-flow atomization and spray characterization studies, future efforts will focus on the initiation of experiments under combusting, high-pressure, and oscillating conditions.

ACKNOWLEDGEMENTS:

Funding for this work was provided by the Air Force Office of Scientific Research, Grant No. 91-0336, Dr. Mitat Birkan, Program Monitor, and by the Propulsion Engineering Research Center, Contract NAGW 1356 Supplement 5. The authors also gratefully acknowledge the help from Mr. Ross Hewitt of Aerojet Propulsion Division, Gencorp, and Mr. Jeffrey Phipps in identifying critical technical issues and initiating this cooperative project with Aerojet.

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