N95- 70901

ANALYTICAL AND EXPERIMENTAL STUDIES OF IMPINGING LIQUID JETS

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SUMMARY:

Impinging injectors are a common type of injector used in liquid propellant rocket engines and are typically used in engines where both propellants are injected as a liquid, e.g., engines using LOX/hydrocarbon and storable propellant combinations. The present research program is focused on providing the requisite fundamental understanding associated with impinging jet injectors for the development of an advanced *a priori* combustion stability design analysis capability. To date, a systematic study of the atomization characteristics of impinging liquid jets under cold-flow conditions has been completed. Effects of orifice diameter, impingement angle, pre-impingement length, orifice length-to-diameter ratio, fabrication procedure, jet flow condition and jet velocity under steady and oscillating, and atmospheric- and high-pressure environments have been investigated. Results of these experimental studies have been compared to current models of sheet breakup and drop formation. In addition, the research findings have been scrutinized to provide a fundamental explanation for a proven empirical correlation used in the design of stable impinging injector-based rocket engines.

DISCUSSION:

An extensive series of detailed measurements, including sheet breakup length, drop size distribution and wavelength of apparent structures, were completed to delineate the atomization processes of two impinging water jets as a function of orifice diameter (d_o), impingement angle (2θ), pre-impingement length (l_j), length-to-diameter ratio (L/d_o), jet velocity (U_j) and jet flow condition [1, 2]. These tests were performed under ambient conditions, and the impinging injector used consisted of two precision-bore glass tubes that could be independently modified to obtain the desired geometry. This injector is referred to as the glass tube impinging injector throughout the text. Recent work has focused on evaluating the functional dependence of the measured variables (e.g., drop size) on an injector parameter, d_o/U_j, associated with an empirical correlation used for engine stability prediction. In addition, the measurement program has been expanded to include the effects of fabrication technique and chamber pressure on the impinging jet atomization process.

Finally, a finite difference model is being used to study the effects of jet disturbances and jet-jet interactions on incipient wave formation on the liquid sheet formed by two opposed impinging jets.

An empirical correlation, used by industry in the design of stable impinging injector-based rocket engines, relates the highest sustainable instability frequency to the injector parameter d_o/U_j (orifice diameter/injection velocity) [3]. According to the stability correlation, an increase in the injector parameter, d_o/U_j, leads to an increase in the frequency range over which the engine can operate stably. A general objective of this work is to develop a rational physical explanation for this successful empirical correlation; hence, the experimental results obtained with the glass tube impinging injector are analyzed with regards to the stability correlation. Specifically, the dependence of drop size distribution and atomization frequency on d_o/U_j is examined. It is important to keep in mind that the discussion to follow pertains to cold-flow atomization data, and that, ideally, the impinging jet atomization characteristics should be evaluated under high-pressure and combusting-flow conditions, which will be the next step undertaken in this research program.

The measured drop size number distribution, $f(d_D)$, is plotted as a function of drop size, d_D, and injector parameter, as shown in Fig. 1. The drop size distribution measurements were made using a Phase Doppler Particle Analyzer along the spray centerline (x=0) at an axial location (z) of 41 mm from the impingement point for an orifice diameter of 0.64 mm and an impingement angle of 60°. An increase in mean drop size is noted with increasing d_o/U_j, thus indicating that bigger drops may have a stabilizing effect. Notice that an increase in the injector parameter leads to broader distributions as well. Similar mean diameter and distribution shape trends are observed for different test cases (e.g., different radial positions and impingement angles).

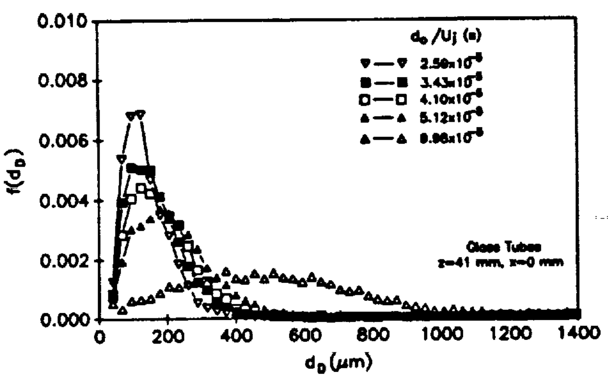

Fig. 1. The number distribution plotted as a function of drop size and injector parameter.

The functional dependence of the periodicity of ligaments detaching from the end of the impinging jet intact sheet on d_o/U_j was examined also. The measured separation distance between adjacent detaching ligaments was converted to an atomization frequency simply by dividing the jet velocity by the separation distance. The assumption that the detached ligament velocity is equal to the jet velocity needs to be substantiated. The calculated atomization frequency associated with the glass tube impinging injector is presented in Fig. 2, along with the highest sustainable combustion instability frequency predicted by the stability correlation. The dependence of the atomization frequency on d_o/U_j is quite similar to the highest sustainable combustion instability frequency;

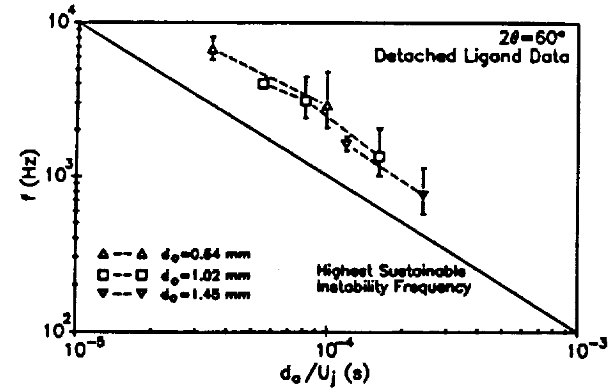

Fig. 2. A comparison between the calculated atomization frequency associated with the glass tube impinging injector and the highest sustainable combustion instability frequency predicted by the empirical correlation [3].

however, the calculated atomization frequency is approximately twice as great. The similar dependencies of maximum possible instability frequency and atomization frequency on d_o/U_j is significant in terms of periodic ligament formation being a key process in combustion instability phenomena.

In practical combustors, injector orifices and pre-impingement lengths are short, and chamber pressures are high. Consequently, a series of cold-flow atomization experiments were undertaken in which sheet breakup length and apparent disturbances on the liquid sheet surface were gauged as a function of jet velocity and chamber pressure for an electro-discharge machined (EDM) impinging injector having an orifice diameter of 0.51 mm, a length-to-diameter ratio and a pre-impingement length-to-diameter ratio of five, and an impingement angle of 60°. From instantaneous spray images, the intact sheet breakup length and the separation distance between adjacent disturbances on the sheet surface were measured.

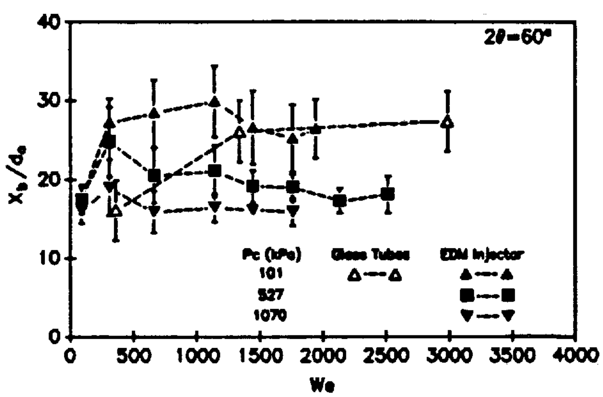

Fig. 3. Nondimensional breakup length as a function of Weber number, chamber pressure and injector type.

A plot of the nondimensional breakup length, x_b/d_o, as a function of Weber number, We ($=\rho_l U_j^2 d_o/\sigma$), is shown in Fig. 3. Each symbol in Fig. 3 represents an average of 17 individual breakup length measurements, while the bars represent the plus/minus standard deviation of those measurements. The breakup length decreases with increasing chamber pressure. In addition, for both the EDM as well as the glass tube impinging injector, the nondimensional breakup length is relatively insensitive to changes in We. Two differences between the glass tube impinging and the EDM injectors are the orifice length-to-diameter ratio and the pre-impingement length. The glass tube impinging injector L/d_o is 80 and l_j/d_o is 40, while the EDM injector L/d_o and l_j/d_o are both equal to five. In spite of these geometric differences between the two injectors, the measured nondimensional breakup lengths are comparable, especially at the higher Weber numbers.

Measurements of the separation distance between adjacent disturbances (disturbance wavelength) on the intact impinging jet sheet surface were made as a function of chamber pressure and injector type. As shown in Fig. 4, the measured disturbance wavelength is observed to be independent of both chamber pressure (up to 1070 kPa) and jet velocity (up to 19 m/s) for the EDM injector. Disturbance wavelength measurements for the glass tube impinging injector were independent of jet velocity (up to 18.5 m/s) as well; however, measurements were only made under ambient pressure conditions. At a pressure of 101 kPa, the measured disturbance wavelengths associated with the glass tube impinging injector are slightly larger than those measured for the EDM injector, which has a smaller orifice length and pre-impingement length as compared to the glass tube impinging injector.

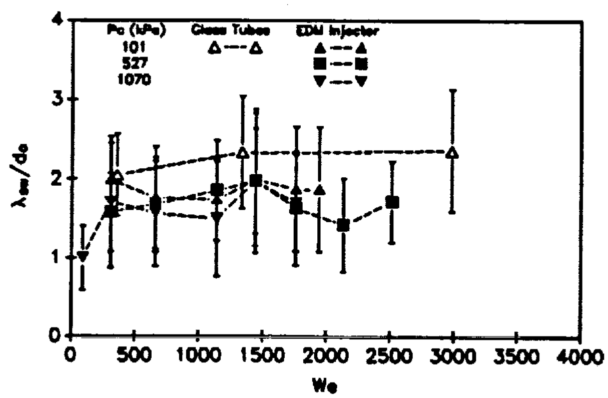

Fig. 4. Nondimensional surface disturbance wavelength as a function of Weber number, chamber pressure and injector type.

The formation of impact waves on the sheet surface emanating from the impingement point has been often observed and is a process which must be clearly understood for the development of an accurate mechanistic impinging jet atomization model. To specifically address this process, modeling efforts have centered on the use of a finite difference Navier-Stokes code (RIPPLE) [4] to investigate the effects of spatial and temporal jet flow oscillations on the primary breakup of the impinging jet fan into ligaments.

Directly opposed axisymmetric jets are chosen for study to simplify the analysis. Harmonic disturbances are imposed on each jet upstream of the impingement point to simulate jet instabilities. The imposed jet disturbances have a radial profile that is proportional to sin ($\pi r/d_0$), with the maximum axial velocity oscillation at the jet periphery being 5% of the mean jet velocity, U_j. The computed free surface contours for two cases, one in which a steady, flat velocity profile exists at both jet inlets, and the second case in which a sinusoidal velocity profile having a frequency of 1000 s^{-1} exists at both jet inlets, are shown in Fig. 5. For the unsteady jet case, the sheet disturbance frequency equaled the frequency of the imposed oscillation on the jet, and the resultant sheet is qualitatively similar to those experimentally observed. This model has some promise of clarifying the process of impact wave formation, and ongoing analytical work is focused on the most appropriate way to simulate pre-impingement jet oscillations.

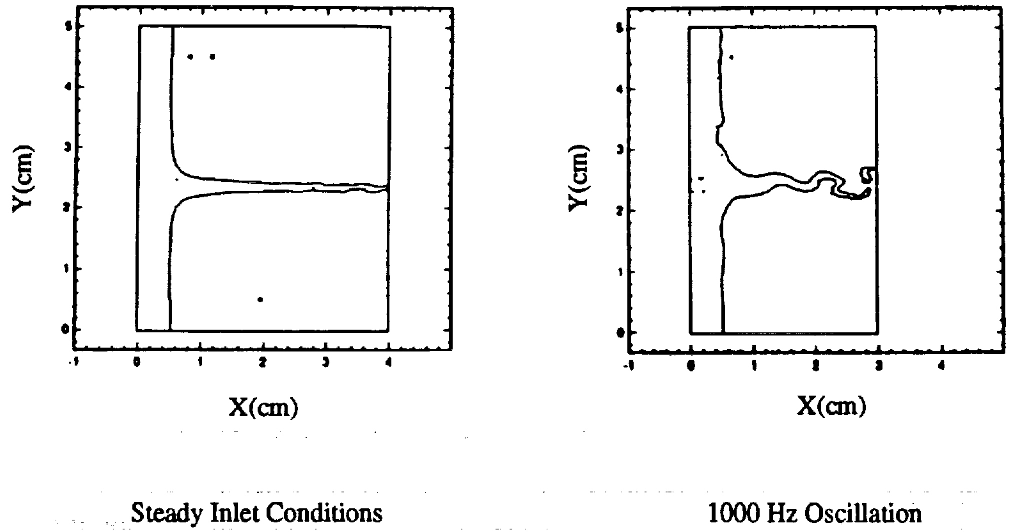

Fig. 5. Computed free surface contours for a steady jet inlet condition and an inlet condition with harmonic disturbances imposed on the jet. The top jet enters at the upper left hand corner with a mean velocity of -10 m/s and the bottom jet enters at the lower left hand corner with a mean velocity of 9.6 m/s. The jet diameter is 10 mm.

ACKNOWLEDGEMENTS:

The authors would like to acknowledge the support of the Air Force Office of Scientific Research, Air Force Systems Command, USAF, under grant number 91-0336, as well as the support of the Penn State NASA Propulsion Engineering Research Center under grant NAGW 1356. In addition, the technical information and feedback provided by the personnel of the Aerojet Propulsion Division is gratefully acknowledged.

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