Liquid Engine Design: Effect of Chamber Dimensions on Specific Impulse

Developing a correlation for Isp comparing equilibrium and frozen chemistry combustion processes.

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Abstract

•Which assumption of combustion chemistry—frozen or equilibrium—should be used in the prediction of liquid rocket engine performance calculations? Can a correlation be developed for this?

•A literature search using the LaSSe tool, an online repository of old rocket data and reports, was completed. Test results of NTO/Aerozine-50 and Lox/LH2 subscale and full-scale injector and combustion chamber test results were found and studied for this task.

•NASA code, Chemical Equilibrium with Applications (CEA) was used to predict engine performance using both chemistry assumptions, defined here.

- •Frozen- composition remains frozen during expansion through the nozzle
- •Equilibrium- instantaneous chemical equilibrium during nozzle expansion

•Chamber parameters were varied to understand what dimensions drive chamber C* and Isp

- •Contraction Ratio is the ratio of the nozzle throat area to the area of the chamber.
- •L' is the length of the chamber
- •Characteristic chamber length, L*, is the length that the chamber would be if it were a straight tube and had no converging nozzle.

•Goal: Develop a qualitative and quantitative correlation for performance parameters—Specific Impulse (Isp) and Characteristic Velocity (C*)—as a function of one or more chamber dimensions—Contraction Ratio (CR), Chamber Length (L') and/or Characteristic Chamber Length (L*). Determine if chamber dimensions can be correlated to frozen or equilibrium chemistry.

Space Flight Test Stand 116 at Marshall Center

NTO/Aerozine- 50 Test Results

The study revealed that for hypergolic propellants a phenomenon known as reactive stream blowapart can occur, especially for low injector density and high momentum ratios. The impinging streams create non-uniform mixture ratio distributions which lowers the C* efficiency as shown by the blue curve in Figure 2. If the momentum ratio was lower, this effect would go down and the distribution C* efficiency would improve to a point where as the chamber length increases, the vaporization portion of the C* efficiency improves and the two curves would meet and be optimized.

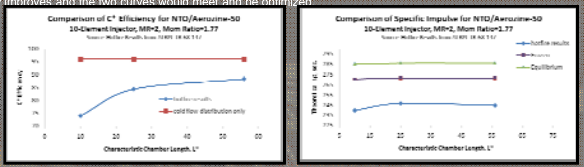


Figure 2. C* Eta and Isp vs. L* for a 10-element injector flowing liquid Nitrogen Tetroxide (N2O4) and 50%-50% Hydrazine (N2H4) and Unsymmetrical Dimethylhydrazine (UDMH) at a momentum ratio of 1.77, MR=2, and CR=3.

Lox/H_2 Test Results

A comparison was made between the 58-element injector for fuel injection temperature and momentum ratio. For the cold injection points, shown as the dashed blue line on Figure 3, the H2 injection temperatures were about 110 °R while the solid blue line are for H2 injection temperatures around 265 °R. The 40-element injector points shown were also at about 265 °R. From this, it appears going from 40-element to 58-element for similar inlet conditions, increases C* efficiency about 0.6% to 0.7% points for chamber lengths between 12.2 inches and 18.2 inches as shown in Figure 4. The table below shows the actual dimensions of the subscale chambers used for injector performance testing at MSFC's Test Stand 116 during the summer and fall of 2006.

L^*	L_{cyl}	L_{conv}	Total Chamber Length, in.
11.7	7. 32	4.91	12.23
15.7	11.32	4.91	16.23
16.9	13.32	4.91	18.23

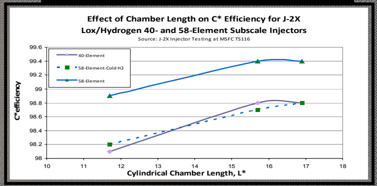


Figure 3. C* Eta vs. L* for a 40- and 58-element injectors at 6.0 Mixture Ratio. Cold H2 Injection points are at 110 °R and 0.68 Momentum ratio while the Nominal Injection points are at 265 °R and

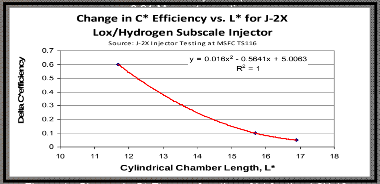


Figure 4. Change in C* Eta as a function of L* for the J-2X 40-element subscale injector flowing Liquid Oxygen (O2) and Hydrogen (H2) at nominal injection temperatures.

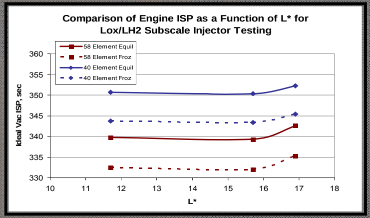


Figure 5. CEA Ideal vacuum Isp vs. L* showing CEA's inability to vary L*. *Note: Variation in Isp due to very small MR and fuel injection temperature differences. All curves become flat when MR and Temp are the same for all L* cases.

Parameters

Contraction Ratio

Assuming a fixed throat, the area and volume of a chamber can be changed by varying the CR. CEA was run at various CR's for known engines to determine the impact on chamber performance. Both chemistry assumptions were run and it was learned that CR has essentially no impact when assuming equilibrium chemistry as shown in Figure 1. I learned that CEA adjusts the chamber length to hold the total chamber area and volume constant—known as the fixed area combustor (FAC) option (See drawing). CEA does not allow the frozen chemistry assumption when running the FAC option; only for the infinite area (IAC) option.

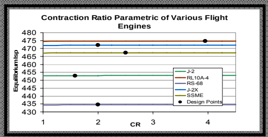
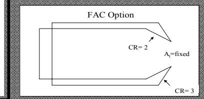


Figure 1. Ideal Frozen Specific Impulse for typical values of Chamber Contraction Ratio.

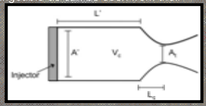
$$CR = A'/A_t$$
$$L^* = V_c/A'^*CR$$



Chamber Volume

Because CEA does not allow for L* or L' changes, a literature search was used to find test data of chamber dimensions vs. engine performance parameters.Both chamber length (L') and characteristic chamber length (L*) are somewhat interchangeable as can be seen from their definitions:

$$L^* = V_c/A_t$$
$$V_c = A' L' + A' L_c(1 + \sqrt{A_t/A'} + A_t/A')$$



where Vc = Chamber Volume, At = Throat Area, A' = Chamber Area, L' = Cylindrical Chamber Length section, Lc = Convergent Section Length.

For a given injector operating at constant momentum ratio, increasing L* should cause combustion efficiency to increase continuously until a chamber length is reached which causes the propellants to be 100% vaporized. Then any additional increases in L* should cause efficiency to increase only negligible amounts because of small-scale turbulent mixing of the combustion gases.

Other Parameters

$$\eta C^* = \eta C^* \text{ distribution} * \eta C^* \text{ vaporization} / 100$$

After analyzing the test data, it was determined that for both NTO/Aerozine-50 and Lox/Hydrogen fueled engines there were other factors besides just L' and L* that also effect C* and Isp. Essentially, the combustion efficiency, ηC^*, is a function of the combined effects of both propellant mixing and propellant vaporization.

Using the MSFC subscale injector test data, CEA was run at the test conditions to calculate the ideal vacuum Isp assuming a 2.0 area ratio nozzle. Figure 5 shows the results of the test data that indicate the measured Isp is more like the CEA prediction for equilibrium chemistry. Figure 5 also shows the effect of changing the injector density while all other parameters are the same—about 3.5% increase in performance for a 31% increase in injector density—or about 0.11% for a 1% change. This appears to be self-limiting since one cannot achieve a C* efficiency greater than 1.

The table below summarizes the effect of various chamber and injector parameters on engine performance for Lox/Hydrogen propellants.

Parameter	**Δ change**	**Δ Isp**
Injector density	1%	0.11%
Chamber L* †	2nd order equation	(0.016L*)^2 – 0.5641L* + 5.01
Chamber Contraction Ratio	0.1 units	Unknown due to CEA limitations
Fuel Injection Temp	1 deg	0.007%

†Similar trend for L', A', and Vc.

Conclusion

1) The C* efficiency trend is similar for both cryogenic and hypergolic propellants. As L' increases, the rate of change of C* efficiency decreases. It is impossible to precisely correlate C*, C* eta, or Isp to L' or L* alone, since test data clearly shows that Injector Type, Injector Density, Momentum Ratio, Fuel Injection Temperature, Chamber Pressure, and Mixture Ratio also affect these performance values.

2) To properly correlate engine performance to chamber dimensions, one needs to be able to vary the chamber length and volume. Since the CEA model only allows Contraction Ratio variability and the model adjusts the L' to hold L* constant, it was not possible to develop a correlation between L* and frozen or equilibrium chemistry-based Isp.

3) The effect of other chamber and injector parameters on C* and Isp was completed, specifically for NTO/Aerozine-50 and LOX/Hydrogen propellant combinations. These trends can be used qualitatively to size a subscale injector for Lunar Lander Descent or Ascent Engine applications.