Validation of a simplified model for liquid propellant rocket engine combustion chamber design

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Abstract. The combustion phenomena inside the thrust chamber of the liquid propellant rocket engine are very complicated because of different paths for elementary processes. In this paper, the characteristic length (L*) approach for the combustion chamber design will be discussed compared to the effective length (Leff) approach. First, both methods are introduced then applied for real LPRE. The effective length methodology is introduced starting from the basic model until developing the empirical equations that may be used in the design process. The classical procedure of L* was found to over-estimate the required cylindrical length in addition to the inherent shortcoming of not giving insight where to move to enhance the design. The effective length procedure was found to be accurate within ±10%.

1. Introduction

The combustion phenomena inside the thrust chamber of the liquid propellant rocket engine (LPRE) are very complicated because of different paths for elementary processes, figure 1 [1]. Previous research from the same group studied the vaporization controlled model for liquid propellant thrust chamber design. It was concluded that for some propellant combination i.e. LOX/Kerosene, vaporization is actually the rate-limiting process and can be used as to find the minimum length required for the combustion chamber, they also found that for other propellant combinations, the chemical reactions are slow that the vaporization is no longer the rate-limiting process [2]. In this paper, the L* approach will be discussed and applied to real case studies, next, the effective length approach will be introduced. This effective length design methodology is developed using the previously developed vaporization-limited model. Similarly, the effective length approach is applied for the same known liquid propellant motors in order to validate the applicability of the effective length and L* approaches.

The characteristic length approach is a classical approach to design a LPRE combustion chamber. This approach depends on tabulated values for L*, table 1 [3] which is defined as the ratio between the volume of the combustion chamber and the nozzle critical area, equation 1 [4]. The chamber volume is that volume enclosed between the injection head and the nozzle critical section as indicated in figure 2. Characteristic length is not a physical length but it is a parameter depending on the perfection of combustion processes.
$L^* = \frac{V_c}{A_{cr}}$  \hspace{1cm} (1)

where $V_c =$ Volume of the chamber (m$^3$), $A_{cr} =$ Critical cross-section area (m$^2$)

Experimental data for the characteristic length is obtained through several tests using motors with different cylindrical lengths. The measurements involve the characteristic velocity efficiency defined as the ratio between experimental and theoretical characteristic velocities, equation 2, [3]. The characteristic velocity is known as the ratio of the product (chamber pressure $\times$ nozzle throat area) to the mass flow rate of gases leaving the nozzle. Such parameters can be measured to determine the experimental characteristic velocity while the theoretical one can be obtained from any thermochemical calculation software for each motor.

$\eta^* = \frac{c^*_e}{c^*_th}$  \hspace{1cm} (2)

where $c^*_e =$ Experimental characteristic velocity (m/s), $c^*_th =$ Theoretical characteristic velocity (m/s).

Similar curves can be obtained with this method by changing the propellant type, injection system, combustion chamber geometry (contraction area ratio), or the mixture ratio. From these curves, the optimum cylindrical length can be determined for the combustion chamber as shown in table 1 [3].

![Processes inside the thrust chamber of LPRE](modified from reference [1].)
Figure 2. Definition of combustion chamber volume $V_c$ [1].

Figure 3. Variation in characteristic velocity efficiency with the chamber cylindrical length [3].

Table 1. Values of characteristic length for different propellant combinations [3]

| Propellant Combination       | $L^*$ (m) |
|------------------------------|-----------|
| Nitric-acid-Hydrocarbon      | 2-3       |
| Nitric Acid-UDMH             | 1.5-2     |
| LOX-Ethyl alcohol            | 2.5-3     |
| LOX-Kerosene                 | 1.5-2.5   |
| Fluorine-Ammonia             | 1-1.5     |

The procedure starts by selecting a value of $L^*$ then find the volume of the chamber. This volume is used to evaluate the value of chamber length depending on volume shape (spherical, cylindrical, or ellipsoidal). Table 2 shows the data for 6 of actual LPREs, shown in figures 4-9, the table summarizes the main data needed for the analysis in this section, namely contraction area ratio $a_c$ (ratio of the combustion chamber area to the critical area), convergent angle $\theta$, critical area $A_{cr}$ and cylindrical length $L_c$. Such values were obtained from available documentation.

Figure 4. Engine LR89-NA-7 [5].

Figure 5. Engine LR79-NA-11 [5].
Figure 6. Engine RD-0110 [5].

Figure 7. Engine H-1 [5].

Figure 8. Engine F-1 [6].

Figure 9. Engine LR87-AJ-3 [5].

Table 2. Main parameters of used engines.

| Engine       | L, mm | $a_c$ | $A_{cr}$, In² | Convergent angle $\theta$° |
|--------------|-------|-------|---------------|---------------------------|
| RD-0110[7]   | 204   | 4.538 | 8.69          | 30                        |
| F1[8]        | 944   | 1.3   | 961.4         | 13                        |
| LR79-NA11[8] | 280   | 1.67  | 206           | 10                        |
| LR89-NA-7[8] | 335   | 1.67  | 206           | 10                        |
| H1[8]        | 270   | 1.62  | 205           | 15                        |
| LR87-AJ-3[8] | 412   | 2.17  | 182.56        | 25                        |

The results of applying L* procedure are shown in table 3, choosing values for $L^* = 1.5$ m and 2.5 m. These are the lower and upper values for the combination of LOX/ Kerosene, given in table 1. It is clear from the last three columns that the actual engines do not comply with the recommended ranges of L*. For the engine RD-0110, the actual length is far below the length calculated using the lowest value of L*. This also is true for the engine LR79-NA-11. This discrepancy adds to the
disadvantages of L* methods where there is no measurable account for the operating parameters on calculated values. Increase in pressure, decrease of injection temperature, or alteration in the efficiency of the injection system are examples of operating parameters in question.

Table 3. Data for 6 LPREs with calculated values of cylinder length using L* method.

| Engine   | L\(_{\text{act}}\) mm | \(V_{c(1.5)}\) m\(^3\) | \(V_{c(2.5)}\) m\(^3\) | L(1.5) mm | L(2.5) mm |
|----------|-------------------------|-----------------------------|-----------------------------|-----------|-----------|
| RD-0110[7] | 204                     | 0.0084                      | 0.014                       | 284       | 504       |
| F-1[8,9,10] | 944                     | 0.931                       | 1.552                       | 905       | 1670      |
| LR79-NA-11[8,9,10] | 280                    | 0.199                       | 0.332                       | 628       | 1227      |
| LR89-NA-7[8,9,10] | 335                    | 0.199                       | 0.332                       | 628       | 1227      |
| H-1[8,9,10] | 270                     | 0.198                       | 0.331                       | 759       | 1376      |
| LR87-AJ-3[8,9,10] | 412                    | 0.177                       | 0.295                       | 605       | 1096      |

The previous data obligate the need for a different procedure to design a liquid propellant combustion chamber which can account for the process in order to find more accurate values and account for both operating conditions and design parameters.

2. Model of relevant chamber parameters

The model used to develop the equations needed for the new methodology is discussed in detail in [2]. The main ideas are reviewed in the following. The model is assuming a one-dimensional steady flow in which propellant vaporization is the rate-controlling process, considering reaction and mixing are infinite fast processes. In addition, there is no reaction in the liquid phase, neglecting secondary breakup. Applying these assumptions would result in the following equations:

\[
\frac{dm_d}{dt} = w = A_S \alpha P_{a,s} \tag{3}
\]

\[
q_v = h A_S (T_c - T_l) Z \tag{4}
\]

\[
\frac{dT_d}{dt} = \frac{1}{m_{c,p,l}} (q_v - w \lambda) \tag{5}
\]

\[
\frac{dV_d}{dt} = -\frac{3}{8} C_D \frac{\rho_m}{\rho_l} \frac{U^2}{r_s} \tag{6}
\]

\[
\frac{u(x)}{u_{jin}} = 1 - \frac{m_f(x)}{m_{f,jin}} \tag{7}
\]

For the nomenclature and more details, interested readers can rely on reference [2]. The equations can be used to find the length required to vaporize the less-volatile component, considering the reaction takes place in gas phase between the more volatile component and the amount vaporized from the less-volatile one. The objective in this research is to develop an empirical equation relating the required length to the operating parameters (combustion pressure \(P_c\), and injection temperature \(T_{in}\)), geometric parameter (contraction ratio \(a_c\)), spray parameter (mass median diameter MMD), and standard deviation \(\sigma_{LN}\). The target is to illustrate the effect on the length required to vaporize 95% of propellant when using conditions other than those applied in a test case. The test matrix used for n-heptane as typical hydrocarbon propellant is considering the variation of injection temperature \(T_{in}\), injection velocity \(V_{in}\), MMD, \(\sigma_{LN}\), \(P_c\) and \(a_c\) as shown in table 4.
Table 4. Operating and design parameters used in the parametric study.

| T<sub>in</sub> (°C) | V<sub>in</sub> (m/sec) | MMD (μm) | σ<sub>LN</sub> | P<sub>c</sub> (bar) | a<sub>c</sub> |
|----------------------|-------------------------|-----------|----------------|-----------------|------------|
| 220                  | 15                      | 100       | 1.25           | 10              | 1.65       |
| 280                  | 30                      | 150       | 2.3            | 20              | 3.15       |
| 380                  | 60                      | 450       | 3.6            | 40              | 12.6       |

2.1. Mass median droplet size effect

Table 5. Effect of MMD on L<sub>95%</sub>.

| MMD (μm) | L<sub>95%</sub> (mm) |
|----------|----------------------|
| 100      | 110.73               |
| 150      | 196.10               |
| 450      | 946.88               |

The length required to vaporize a given fraction of the total mass of the spray is proportional to the 1.46 of the mass median droplet size. a result which is intuitively accepted as the larger the size of a droplet, the longer the length it needs to vaporize.

2.2. Geometric standard deviation effect

For higher standard deviation, the percent of the spray vaporization and vaporization rate near the injector increases because of the large number of small droplets, and the required length to vaporize propellant is longer because of the larger droplets. The length required to vaporize a given fraction of the total mass of the spray is proportional to the 0.77 of the geometric standard deviation.

Table 6. Effect of geometric standard deviation on L<sub>95%</sub>.

| Standard deviation (σ<sub>LN</sub>) | L<sub>95%</sub> (mm) |
|-------------------------------------|---------------------|
| 1.25                                | 113.23              |
| 2.3                                 | 196.10              |
| 3.6                                 | 335.47              |

2.3. Injection droplet velocity effect

The maximum vaporization rate is obtained with a low initial velocity. The higher the initial velocity, the more mass vaporized before the minimum point is reached. However, the larger the velocity, the larger the spray travel before complete vaporization. This yields the results that the length required to vaporize a given percentage of the total mass is proportional to 0.86 power of initial velocity.

Table 7. Effect of injection velocity on L<sub>95%</sub>.

| Droplet Injection velocity (V<sub>in</sub>) (m/sec) | L<sub>95%</sub> (mm) |
|---------------------------------------------------|---------------------|
| 15                                                | 126.28              |
| 30                                                | 196.01              |
| 60                                                | 353.80              |

2.4. Chamber pressure effect

The higher the chamber pressure, the higher the vaporization rate and amount vaporized in a given length. The length required to attain a given high percentage of mass vaporized is inversely proportional to 0.54 power of chamber pressure. This would not be attained if it was made use of the d<sup>2</sup>-law of Spalding [11]. The pressure dependence is introduced via the droplet equation and vaporization equation. Experimentally, it was found that burning rate dependency on pressure is related to fuel (0.25 for furfuryl alcohol, 0.4 for benzene, 0.37 for hydrazine in air and 1 for hydrazine decomposition) [12].
Table 8. Effect of chamber pressure on L₉₅%.

| Gas pressure (bar) | L₉₅% (mm) |
|-------------------|-----------|
| 10                | 298.89    |
| 20                | 196.01    |
| 40                | 128.41    |

2.5. Contraction area ratio effect

It is the ratio of cylindrical chamber cross-section area to the nozzle throat area. Small contraction ratio yields high gas velocities at the end of the combustion chamber, which encourages vaporization. The higher the contraction ratio, the more mass is vaporized before the minimum point is reached.

Table 9. Effect of contraction ratio on L₉₅%.

| Contraction ratio | Final gas velocity (m/sec) | L₉₅% (mm) |
|------------------|---------------------------|-----------|
| 1.65             | 382.06                    | 160.50    |
| 3.15             | 188.20                    | 192.40    |
| 12.6             | 46.51                     | 373.59    |

Reduction in contraction ratio decreased the length of the combustor needed for complete vaporization. This effect, however, was not constant throughout the vaporization period. During the initial vaporization phase, an inverse effect of contraction ratio was noticed. Inversion occurs in the region where combustion gas velocity begins to exceed drop velocity. This analytical result is similar to the experimental effect, where efficiency improves with an increase in contraction ratio for the low-efficiency region and the inverse effect becomes evident as efficiency increases [13]. The calculation shows that the length required to vaporize 95% of the mass is proportional to 0.48 power of contraction ratio.

2.6. Droplet temperature effect

A higher initial liquid temperature is moderately beneficial, as droplet spends less time reaching the wet-bulb temperature which simply is the droplet temperature at which all heat flux goes to vaporize droplet and no more heating or droplet temperature increase. The calculation shows that the percentage of mass vaporized is inversely proportional to 0.51 power of initial droplet temperature.

Table 10. Effect of droplet injection temperature on L₉₅%.

| Droplet Temperature (K) | L₉₅% (mm) |
|-------------------------|-----------|
| 220                     | 212.57    |
| 280                     | 196.10    |
| 380                     | 165.35    |

For a summary, it is concluded that the chamber length required for a given percent of propellant vaporized increases with larger drop sizes and higher injection velocity, decrease with higher final gas velocity, higher chamber pressure, and higher initial temperature.

2.7. Empirical correlation

The above discussion can be used to derive a correlation relating the chamber length required to vaporize 95% of propellant. The resultant correlation for heptane can be expressed as:

\[
L = 0.196 \left( \frac{MMD}{150} \right)^{1.46} \left( \frac{V}{30} \right)^{0.86} \left( \frac{\sigma_{LN}}{2.3} \right)^{0.77} \left( \frac{a_t}{3.15} \right)^{0.48} \left( \frac{P_c}{20} \right)^{0.54} \left( \frac{T_I}{280} \right)^{0.51}
\]

(8)
The above correlation has an error band of ±10% in comparison with the data from the solution of differential equations as in [2]. This correlation may be compared with the correlation given in [14] that expressed the empirical equation for the geometric standard deviation of 2.3 only. From the above equations, it may be evident that the data could be expressed by an "effective length" rather than the actual length. This length can be expressed by:

$$L_{eff} = L \frac{P_c^{0.54} T_0^{0.51}}{MMD^{1.46} \nu^{0.86} \sigma_{LN}^{0.77} \alpha_c^{0.48} (1.1861 \times 10^8)}$$

(9)

The advantage of the effective length over actual length is that it combines the actual length, design and operating parameters. Effective length can be considered as a generalized or universal length. Effective length can be expressed as percentage propellant vaporized as in the following section.

2.8. The relation between mass vaporized and effective length

Variation percentage mass vaporized vs. effective length for different parameters is shown in figure 10. From that figure, it is clear that there is a stacking of data in a central stream except for a very large change in standard deviation (the outlier dashed line in the figure). Nevertheless this outlier arises only in the very low-efficiency motors, those with low percentage mass vaporized. Taking advantage of such a stack to fit a generalized equation for variation of effective length with percentage mass vaporized, the following relation can be written.

$$L_{eff} = 5.7 \times 10^{-8} M\%_{vap}^4 - 8 \times 10^{-6} M\%_{vap}^3 + 3.17 \times 10^{-4} M\%_{vap}^2$$

$$+ 0.0017 M\%_{vap} + 0.0347$$

(10)

![Figure 10](image.png)

Figure 10. The spread of data and fitted mass % -effective length relation-dashed line indicates ±15 % variation from the fitted equation (10).

3. The Methodology

The methodology is described in the flow chart shown in figure 11, and can be summarized in the following steps:

- Start with targeting characteristic velocity efficiency (defined in equation 2).
Using thermochemical calculations to find the theoretical characteristic velocity at both the theoretical mixture ratio and at vaporized mixture ratio.

- Find the required percentage mass vaporized (consider the propellants are one gas or volatile and the other has low volatility) using equation 11, which relates characteristic velocity efficiency to the percentage of vaporized propellant through two terms \( \left( \frac{C^*_{th}}{F_{vap}} \right) O_{vap} \) and \( \% M_{vap} \). That dictates using look-up table technique to find \( \% M_{vap} \) rather than direct substitution in figure 12 [2]

\[
\eta_{C^*} = \frac{\left( \frac{C^*_{th}}{F_{vap}} \right) O_{vap} \eta_{vaporized}}{\left( \frac{C^*_{th}}{F_{injected}} \right) O_{f}} = \frac{\left( \frac{C^*_{th}}{F_{vap}} \right) O_{vap} \eta_{vaporized}}{\left( \frac{C^*_{th}}{F_{injected}} \right) O_{f}} \% M_{vap}
\]  

\( \eta_{C^*} \)

- Find the effective length using equation 10.

- The effective length equation represents a relation between chamber length, operating parameters, and injection system design.

- From injection system cold flow test or from empirical correlations found in literature, find the MMD, injection velocity for the injector elements.

- From the regenerative cooling or other cooling system constraints, find the injection temperature.

- Choose the operating pressure according to structural constraints or feeding cycle constraints.

- Use equation 9 to find the desired cylindrical length; this length satisfies the target characteristic velocity efficiency and takes into account the operating and design constraints.

![Thermochemical calculation look-up table](image1)

**Objective \( \eta_{C^*} \)**

\( C^*_\text{act} \)

\( M\% \)  

Eq (11)

\( L_{eff} = A_0 M\%^4 - A_1 M\%^3 + A_2 M\%^2 - A_3 M\% + A_4 \)

**Injection head design**

**MMD/SMD**

\( V_{inj} \sigma_{LS} \)

**L_{eff} = \frac{P_c 0.61 + T_{inj} 0.46}{MMD 1.42 V 0.75 \sigma_{LS} 1.11 A c 0.43 C} \frac{P_c}{T_{inj}} \)

**Operating conditions**

**Figure 11.** Flow chart for the proposed methodology.

### 4. Application

The effective length methodology is applied for the same test case mentioned in table 1. The data needed to find MMD for the injection head is shown in table 11. The temperature of injection liquid depends on the layout of cooling achieved by fuel or oxidizer. In some cases, temperature is known or otherwise, it will be assumed to be around 350 - 400 K. MMD is calculated for swirl injector [2,15] and for impingement injector [2].
Figure. 12 Relation between C* efficiency and % propellant vaporized [2].

\[ SMD = 2.25\sigma^{0.25} \mu_L^{0.25} \Delta P_L^{-0.5} \rho_g^{-0.25} \]  

(12)

\[ MMD = 1.2 \ SMD \]  

(13)

\[ MMD = 8.41 \times 10^5 \frac{D_j^{0.57}}{V^{0.85}} \]  

(14)

The details of the injector and injection head for the cases studied are shown in figures 13-18, the calculations of the needed data are summarized in table 12.

**Table 11.** Data for injection parameters for case studies.

| Engine      | Element type         | Injector diameter \( \text{mm} \) | Number primary element | \( \Delta P_{\text{inj}} \) \( \text{bar} \) | \( \dot{m} \) \( \text{kg/s} \) |
|-------------|----------------------|------------------------------------|------------------------|---------------------------------|-----------------|
| RD-0110[4]  | bi-swirl injector    | bi-swirl injector 13 5.41 - -    | 6.96 4.27 6.6 15.7    | F O F O F O F O F O           |
| F1[7]       | Like doublet         | Like doublet 6.15 7.14 702 714 58 40 1715 4070 |
| LR79-NA11[7]| Like doublet & triplet| Like doublet 2.87 1.6 582 335 22.4 19.2 202 456 |
| LR89-NA-7[7]| Like doublet & triplet| Like doublet 2.87 1.6 582 335 18 13.8 211 458 |
| H1[7]       | Like doublet         | Like doublet 3.05 2.08 612 365 11.5 8.5 240 537 |
| LR87-AJ-3[7]| Like doublet         | Like doublet 3 2.08 610 560 27 11 183.3 412.7 |
Figure 13. RD-0110 main injector [7].

Figure 14. Engine RD-0110 injection head [7].

Figure 15. Engine H-1 injection head [5].

Figure 16. RD-0110 main injector [7].

Figure 17. F-1 injection head [6].

Figure 18. LR87-AJ-3 injection head [5].
Table 12. Data needed for the $L_{\text{eff}}$ methodology.

| Engine     | $\eta_c$ | M% | $L_{\text{eff}}$ (mm) | $P_c$ (bar) | $T_{\text{inj}}$ (k) | MMD (μm) | $V_{\text{inj}}$ (m/s) | $L_{\text{cal}}$ (mm) |
|------------|----------|----|-----------------------|------------|---------------------|----------|----------------------|---------------------|
| RD0110     | 95       | 95 | 1018.9                | 68.16      | 350                 | 298      | 11.38                | 164                 |
| F1         | 95       | 95 | 1018.9                | 77.6       | 350                 | 988      | 30.35                | 1011                |
| LR79-NA11  | 95       | 95 | 1018.9                | 40.54      | 350                 | 177.1    | 95.6                 | 316                 |
| LR89-NA-7  | 94.7     | 95 | 1018.9                | 38.78      | 350                 | 170.7    | 99.84                | 313                 |
| H1         | 94.8     | 95 | 1018.9                | 48.61      | 350                 | 295.9    | 64.59                | 410                 |
| LR87-AJ-3  | 94.7     | 94 | 964                   | 43.92      | 350                 | 359.4    | 49.35                | 5*9                 |

The classical $L^*$ methodology is applied; in addition to the effective length methodology applied with different target characteristic velocity efficiency. Table 13 and figures 19-20 show the results. The comparison between the classical $L^*$ approach vs. the real data is shown in figure 19. As mentioned before, all the engines do not comply with that recommended range of $L^*$. However, applying the effective length approach with different target characteristic velocity efficiencies (92.5%, 95% and 97.5%) show a far better agreement with that of real values, figure 20.

Table 13. Comparison between the $L^*$ approach and $L_{\text{eff}}$ approach.

| Engine     | $L_{\text{act}}$ (mm) | $L_{\text{eff}}(L^*=1.5)$ (Mm) | $L_{\text{eff}}(L^*=2.5)$ (Mm) | $L_{\text{cal}}(92.5\%)$ (mm) | $L_{\text{cal}}(95\%)$ (mm) | $L_{\text{cal}}(97.5\%)$ (mm) |
|------------|------------------------|---------------------------------|---------------------------------|-------------------------------|-------------------------------|-------------------------------|
| RD0110     | 204                    | 284                             | 504                             | 143                           | 164                           | 188                           |
| F1         | 944                    | 905                             | 1670                            | 881                           | 1011                          | 1162                          |
| LR79-NA11  | 280                    | 628                             | 1227                            | 275                           | 316                           | 363                           |
| LR89-NA-7  | 335                    | 628                             | 1227                            | 273                           | 313                           | 360                           |
| H1         | 270                    | 759                             | 1376                            | 357                           | 410                           | 471                           |
| LR87-AJ-3  | 412                    | 605                             | 1096                            | 487                           | 529                           | 642                           |

It is clear from the previous figure that the effective methodology shows better agreement with the real data, with the powerful advantage that it can propose insight on how to change design parameters to fit the design in a certain geometrical envelope, which is an inherent shortcoming in the classical $L^*$ methodology. However, the proposed methodology has an inherent assumption of vaporization limited engines which is an accurate assumption in a well-mixed propellant with a large difference in volatility. However, these assumptions are not valid for engines with mixing limited situations [16] such as the case in the gas generator, or low-cost engine with high flow rate injectors [17] or in cases where the propellants have similar volatility such combination MMH/NTO, but this is left for future work.
5. Conclusion
The complete modelling of processes inside the liquid propellant thrust chamber is a formidable task. However, the insightful engineer can rely on the concept of the “rate-limiting process” in order to find...
an engineering equation to design a motor. In this paper, the classical procedure of L* was found to over-estimate the required length. In addition, it does not give insight to where to move to enhance the design. An "effective length" procedure was proposed to find the cylindrical length of the thrust chamber. Validation of this methodology was performed on actual liquid motors, and the results showed a better agreement than the classical L* method.

References
[1] Harrje D and Reardon F 1972 Liquid Propellant Rocket Combustion Instability NASA Special Publication-194
[2] Belal H et al. 2019 IOP Conf. Ser.: Mater. Sci. Eng. 610 012088
[3] Barrere M et al. 1960 Rocket Propulsion Elsevier Publishing Company, New York
[4] Joseph Himpan, 1950 The Calculation of the Volume of Rocket Combustion Chambers Aircraft Engineering and Aerospace Technology, Vol. 22 Iss 7 pp 191–193
[5] http://www.astronautix.com/
[6] Anthony Young 2008 The Saturn V F-1 Engine Powering Apollo into History Springer-Praxis Books In Space Exploration
[7] Vigor Yang and William E Anderson 1995 Liquid Rocket Engine Combustion Instability Volume 169 Progress In Astronautics And Aeronautics AIAA
[8] Liquid rocket engine injectors 1976 I Liquid rocket engine nozzles NASA Space Vehicle Design Criteria (Chemical Propulsion) SP-8120
[9] Turbopump Systems For Liquid Rocket Engine 1974 NASA Space Vehicle Design Criteria (Chemical Propulsion) SP-8107
[10] Turms, S 2012 Introduction to Combustion, 3rd edition.
[11] Williams A 1973 Combustion of droplets of liquid fuels: A review Combustion and flame Vol. 21 pp 1-31
[12] Heidmann M 1959 Propellant vaporization as a criterion for rocket engine design; Experimental effect of chamber diameter on liquid oxygen-heptane performance NASA TN D-65
[13] Priem R 1958 Propellant vaporization as a criterion for rocket engine design; Calculation of chamber length to vaporize various propellants NASA TN-3883
[14] Simmons H 1977 The Correlation of Drop-Size Distributions in Fuel Nozzle Sprays-Part I Journal of Engineering for Power
[15] Yang V 2004 Liquid Rocket Thrust Chambers Aspects of Modelling, Analysis, and Design Chapter 20, AIAA Progress in Astronautics and Aeronautics, Vol 200
[16] Berque J, Sion M, and Thomas JL 1999 Tricoaxial injector technology development Progress In Astronautics And Aeronautics AIAA 1999-2492