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OVERVIEW OF THE SCRAMJET COMBUSTION CHAMBER LENGTH

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Abstract. *Scramjet is an airbreathing aeronautical engine that uses the oblique/conical shock waves generated during the hypersonic flight, to promote compression and deceleration of freestream atmospheric air at the inlet of the scramjet. One the most important and critical component of the scramjet is the combustion chamber. Physical and chemical aspects limit the length of the combustor to a minimum where the air and fuel must have enough time to mix, to react and to release the heat to the supersonic airflow. This paper intends to overview some of the available literature for a simple, first approach, equations that can predict the minimal allowable length of a scramjet combustion chamber.*

Keywords: *combustion chamber, hypersonic aerospace vehicle, scramjet, hypersonic airbreathing propulsion*

1. INTRODUCTION

In order to reduce the costs to space access it is necessary to achieve new and more efficient ways to reach orbit. One of the most promising technologies is airbreathing hypersonic propulsion, specifically supersonic combustion ramjets also known as scramjets. There are several challenges in the developments of such engines. Due to the supersonic nature of the reactor there is a minute amount of time for the several physical and chemical processes to occur. Most of these processes can be studied on hypersonic ground test facilities and in order to experiment scramjet engines using these facilities is necessary to work with reduced size models. There are physical limitations for the minimal length of such engines to guarantee a proper fuel to air mixing, complete combustion reaction and heat release to occur. This paper is an overview of several references that mention the length and basic combustor geometry calculation and prediction of scramjet engines.

2. REACTOR GEOMETRY

The scramjet reactor, after the compression stage, can be described with four components: the isolator, injector block, constant area combustion chamber and divergent combustion chamber as shown at Figure 1. This paper considers a simple section area with rectangular shape, ignoring any effects caused by the sharp corners of the duct.

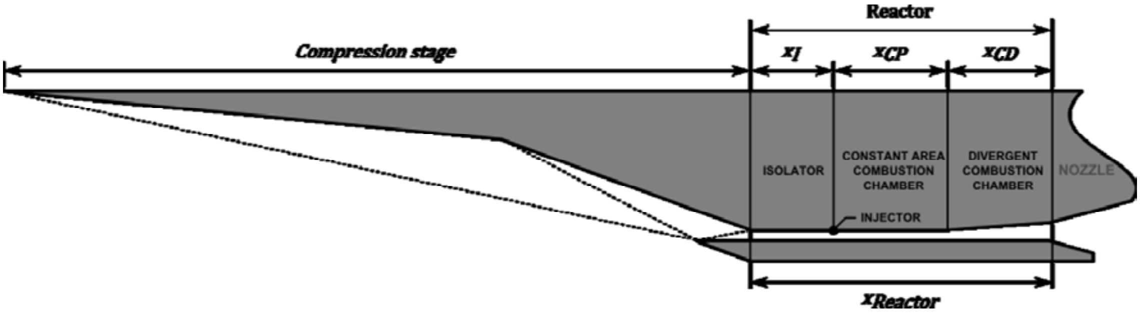

Figure 1. Chamber length geometry.

2.1 Isolator

The isolator is a duct that in general plays no role other than protecting the inlet flow from adverse back pressure (Segal, 2009). The isolator also compresses the flow as a result of weak oblique shock waves generated by the separated flow at the walls (Heiser and Pratt, 1994) as shown at Figure 2.

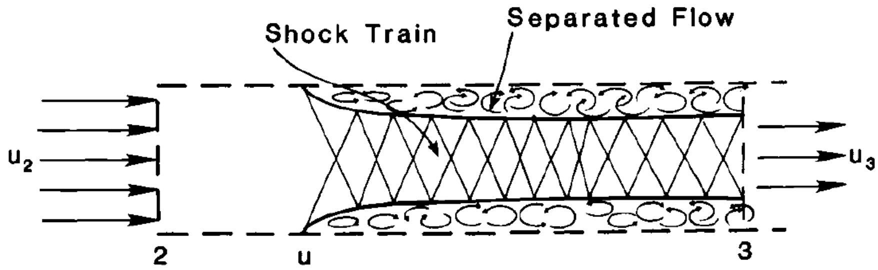

Figure 2. Shock train generated by the separeted flow inside a constant area duct. (Heiser and Pratt,1994).

Heiser and Pratt (1994) suggest an empirical relation between the entrance Mach number, M_2, pressure ratio, p_3 / p_2, length, L, height, H, boundary layer momentum thickness, θ, and the inlet Reynolds number, Re_θ.

$$\frac{L}{H} = \frac{\sqrt{\frac{\theta}{H}}}{\sqrt[4]{Re_\theta}} \frac{\left[50\left(\frac{p_3}{p_2}-1\right)+170\left(\frac{p_3}{p_2}-1\right)^2\right]}{M_2^{\,2}-1} \tag{1}$$

The Mach number at the exit of isolator is given by (Heiser and Pratt, 1994):

$$M_3 = \left[\frac{\gamma^2\, M_2^{\,2}\left(1+\frac{\gamma-1}{2}\,M_2^{\,2}\right)}{\left(1+\gamma\, M_2^{\,2}-\frac{p_3}{p_2}\right)^2}-\frac{\gamma-1}{2}\right]^{-\frac{1}{2}} \tag{2}$$

The confined area by the separated flow can be determined from conservation of momentum (Heiser and Pratt, 1994):

$$\frac{A_{3_c}}{A_2} = \frac{1}{\gamma\, M_3^{\,2}}\left[\frac{p_2}{p_3}\left(1+\gamma\, M_2^{\,2}\right)-1\right] \tag{3}$$

Equation 3 is plotted on Figure 3 for an entry Mach number $M_2 = 2$ and a ratio of specific heats $\gamma = 1.4$ (Heiser and Pratt, 1994).

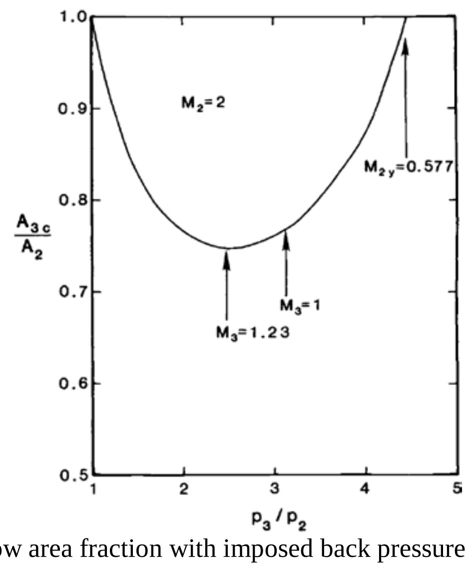

Figure 3. “Variation of confined flow area fraction with imposed back pressure ratio, for isolator Mach number and ratio of specific heats $\gamma = 1.4$” (Heiser and Pratt, 1994).

According to Tu and Segal(2010) and Segal (2009) the isolator length can be determined by:

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$$\frac{X}{D_H} = \frac{1}{4K}\frac{g_1^{\,2}}{\gamma\, f_1}\left[\frac{p_r - 1}{\left(f_1 - p_r\right)\left(f_1 - 1\right)} + \frac{1}{f_1}\ln\frac{p_r\left(f_1 - 1\right)}{f_1 - p_r}\right] + \frac{\gamma - 1}{2\,\gamma}\ln p_r \tag{4}$$

where:

$$f_1 = \frac{F_1}{p_1\,A_1} \tag{5}$$

$$g_1 = \frac{\dot{m}\sqrt{\left(\gamma - 1\right)\,H_0}}{p_1\,A_1} \tag{6}$$

$$p_r = \frac{p_{out}}{p_{in}} \tag{7}$$

where $4K = 44.5$ is the constant friction coefficient at the duct entrance. According to Tu and Segal (2010), Equation 4 "was found to predict the shock train length accuracy with 20% over a broad range of experimental results, including ducts of various shapes (round and rectangular), entrance Mach numbers ranging from 1.5 to 5, order of magnitude variation in the entrance Reynolds number, and different friction coefficients". For circular ducts Segal (2009) refers to Equation 8 as based on experimental data of a circular duct. Tu and Segal (2010) also refer to this equation:

$$\frac{X}{\sqrt{D}} = \frac{\sqrt{\theta}}{\sqrt[4]{Re_\theta}}\frac{1}{M_1^{\,2} - 1}\left[50\left(p_r - 1\right) + 170\left(p_r - 1\right)^2\right] \tag{8}$$

2.2 Fuel and air mixing, injector block.

The mixing of fuel and air processes are determining factors that lead to heat release and thrust generation. The main reason for this characteristic is the milliseconds of fluid residence within a scramjet reactor (Segal, 2009). Therefore, the injector block design and resulting mixing length is a critical aspect of a scramjet reactor design. For gaseous fuel injection there are three main mechanisms: parallel injection within the flow, normal injection from the walls and vortex generator or hyper mixer injectors (Segal, 2009; Heiser and Pratt, 1994).

2.2.1 Parallel injection

The axial injection uses the shear layer formed by the two parallel streams of air and fuel to mix the reactants, as shown at Figure 4,

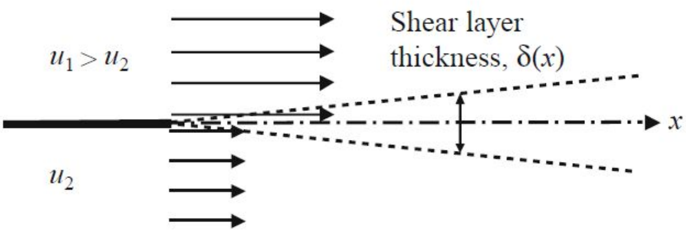

Figure 4. "Schematic of shear-layer thickness development" (Segal, 2009).

The axial injection requires long distances to achieve the molecular mixing required for combustion if compared to the wall, perpendicular type of injector (Segal, 2009). Heiser and Pratt (1994), Segal (2009) and Kliche and Mundi (2011) use an empirical solution for the mixing length.

$$L_{mix} = b_{mix} \times 0{,}179 \times C_{mix} \times e^{1{,}72\times\phi} \text{ for } \phi \le 1 \tag{9}$$

$$L_{mix} = b_{mix} \times 3{,}333 \times C_{mix} \times e^{-1{,}204\times\phi} \text{ for } \phi > 1 \tag{10}$$

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where b_{mix} is the height of the reactor and C_{mix} is a factor varying from 25 to 60 for fully turbulent to a fully laminar shear layer. The usual value is around $C_{mix} = 46$ (Heiser and Pratt, 1994) and $C_{mix} = 40$ (Kliche and Mundi, 2011). The mix efficiency along the axial distance is given by:

$$\eta_m = \frac{x}{x_\phi} = \frac{x}{L_{mix}} \tag{11}$$

Murthy (2000) proposes, for axial injectors in a step at the wall, this efficiency and length relation:

$$\eta_m = 1 - e^{\frac{\ln(1-\eta_{max})}{L_{mix}} x} \tag{12}$$

2.2.2 Perpedicular Injection

Perpendicular injectors, Figure 5, have shorter mixing distances if compared to axial injectors but results in large momentum losses (Segal, 2009). Diskin and Northam (1987), Tomioka et al. (2006) and Segal (2009) suggest an experimental correlation between the combustor geometry and fuel equivalent ratio to calculate the mixing efficiency at any distance in the direction of the flow from the fuel injection position, X':

$$\eta_{mix} = 1,01 + 0,176 \times \ln \frac{x'}{x'_\phi} \tag{13}$$

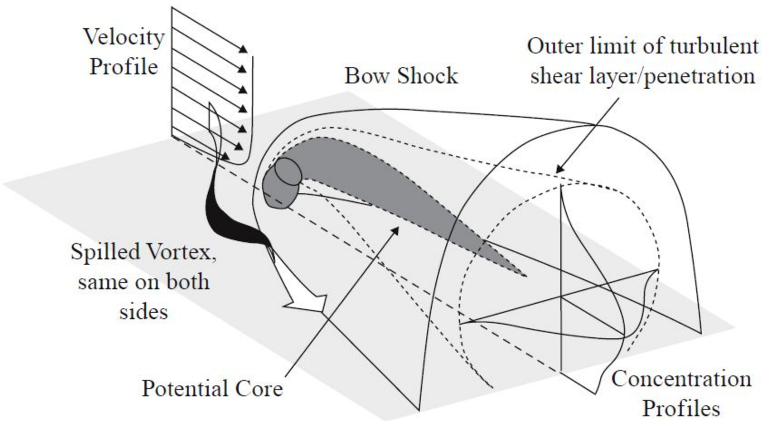

Figure 5. “Model of a transverse, underexpanded jet in a supersonic airstream” Segal (2009).

The length for a complete mixing, x'_ϕ, is given by (Tomioka et al. 2006):

$$\frac{x'_\phi}{x'_{\phi_{Ref}}} = 0,1791 \times e^{\left(1,72 \times \frac{\phi}{\phi_{Ref}}\right)} \tag{14}$$

Heiser and Pratt (1994) have a different empirical relation:

$$\eta_{m,90^\circ} = \left\{ \frac{x}{L_m} + \frac{1}{(50 + 1000 \times \alpha)} \right\}^{\alpha} \tag{15}$$

where α is a fit parameter which varies from $\alpha = 0,17$ for “widely spaced” injectors to $\alpha = 0,25$ for “closely spaced” injectors. $L_m = x'_\phi$ is the distance needed for complete mixing and is given by Equations 13 and 15. Diskin and Northam (1987) suggest the length required for a complete mixing ($x_l = L_m$) is:

$$x_l = 60\ G \tag{16}$$

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This is valid for sonic perpendicular or parallel injectors from both walls of a two-dimensional duct with the spacing between injectors, s, that is equal to the distance of the opposite walls, G, and with injectors diameter of:

$$d = \frac{s}{15} \tag{17}$$

For injectors with an angle Heiser and Pratt (1994) and Segal (2009) suggest the linear interpolation between parallel and transverse injector results.

2.2.3 Vortex generator injector

The hyper mixer or vortex generator injectors have series of small ramp structures, relieved or exposed as shown at Figure 6 and Figure 7, with injectors that generate an oblique shockwave over it. This creates a pressure ratio between the flow over the ramps and the flow besides them, inducing the formation of vortexes that increase the mix efficiency.

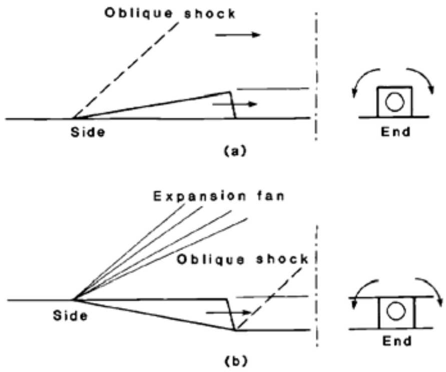

Figure 6. “Geometry of wall-mounted, unswept ramp fuel injectors. (a) Raised ramp. (b) Relieved or exposed ramp. Side elevation: view is along z axis. End elevation: view is upstream, along x axis” (Heiser and Pratt, 1994).

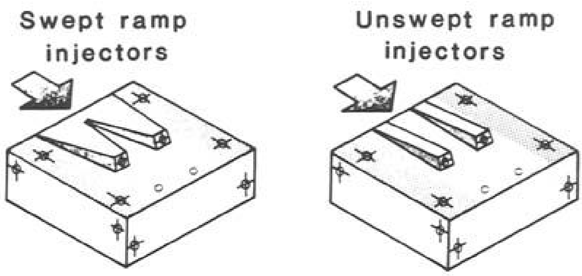

Figure 7. “Perspective view of swept and unswept ramp fuel injectors” (Heiser and Pratt, 1994).

The efficiency of an axial vortex mixing with raised ramps of 10º and injectors with 30º is given by (Heiser and Pratt, 1994):

$$\eta_{m,\,AV} = \frac{1 - e^{\frac{-A\, x_{Mix}}{x_\phi}}}{1 - e^{-A}} \tag{18}$$

where A=1.77 for unswept and A=3.4 for swept type injectors and $L_m = x_\phi$ is given by Equations 09 and 10. Heiser and Pratt (1994) also suggest A=4.9 for higher freestream Mach number. Anderson et al. (1990) show an empiric relation for gaseous hydrogen injection for vortex generator injectors:

$$\eta_{mixing} = 0.485 \times \left(\frac{x_{mix}}{d} \times q_r^{-0.671} \right)^{0.149} \tag{19}$$

where q_r is the ratio of dynamic pressure of the injector and the main flow with suggested values of 0.5, 1 and 1.5, and d is the diameter of the injectors.

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2.3 Combustion chamber

A constant area combustion chamber can lead to a quick pressure raise, which is very difficult to control and can lead the inlet to unstart (Segal, 2009). To avoid this effect one can use a divergent combustion chamber to keep the pressure constant during the combustion process along the flow, compensating the heat release effect (Heiser and Pratt, 1994). Diskin and Mundi (1987) found that the combination of a section with constant area followed by a section with divergent flow path can lead to a better mixing and flame holding characteristics, improving the overall efficiency. Diskin and Mundi (1987) suggest the length of 2.22 times the half height if the chamber. Heiser and Pratt (1994) propose that a half angle between 4º and 5º to the diverging part. To design the combustion chamber length one must consider the length needed to mix the fuel and air, then the length to allow enough time for ignition and reaction of the fuel air mixture. Essentially the combustor length, from the point of fuel injection to the end of the combustion process, is the sum of the needed lengths for mixing, ignition and reaction. Figure 8 shows the time scale in chemically flows.

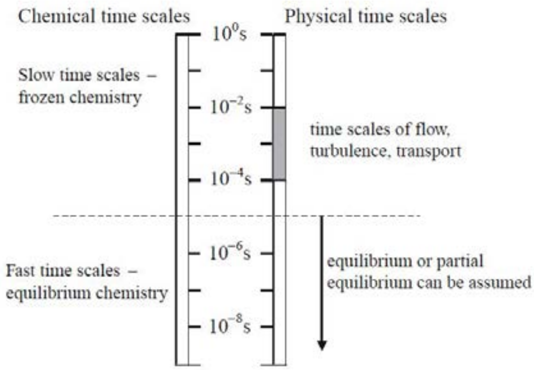

Figure 8. “Time scales in chemically reacting flows” (Segal, 2009).

After the first portion of air and fuel is mixed at flammable proportions there is an ignition delay to the start of the reaction. When the combustion is already started there is a time for the reaction to occur and release the energy to the flow. One can say that the flame takes place between the distance needed for the ignition delay after the injector block until the sum of the mixing length with the ignition delay and reaction lengths. Paull and Stalker (1990) propose that time required for 95% of the combustion to occur is the sum of the ignition delay time with the reaction time, given by:

$$t_i = \frac{8\times10^{-9}\times e^{\frac{9600}{T}}}{P} \tag{20}$$

$$t_r = \frac{0.000105\times e^{\frac{-.,12\times T}{1000}}}{P^{1,7}} \tag{21}$$

where P is the mix pressure in atmospheres and T is the temperature in Kelvin. Heiser and Pratt (1994) also propose an empirical ignition delay equation:

$$t_i \approx 4.510^{-9}\,\frac{p_0}{p}\,e^{\frac{10^4}{T}} \tag{22}$$

Segal (2009) shows another empirical relation for the ignition delay:

$$t_{ign} = \frac{1}{k\times[O_2]} \tag{23}$$

where:

$$k = 5,52\times10^{16}\times T^{-0,7}\times e^{\frac{-8580}{T}} \tag{24}$$

and the reaction time is a function of the wall pressure distribution along the axial length of the combustor, P_b :

$$t_r = 3,25 \times 10^4 \times P_b^{-1,6} \times e^{\frac{-0,8 \times T_{st}}{1000}} \quad (25)$$

$$P_b = \frac{1}{x_l} \times \left\{ \int_{x_1}^{x_2} \left[P_w(x) \right]^n \times dx \right\}^{\frac{1}{n}} \quad (26)$$

3. CONCLUSION

The result of this overview is implemented at an in house developed computational code for scramjet engine design and performance prediction. The mix efficiency and combustion delays calculation are the inputs for the one-dimensional Rayleigh flow for combustion prediction. The program is used to design the both ground and flight experimental hypersonic vehicles, that are been developed by the Prof. Henry T. Nagamatsu Laboratory of Aerothermodynamics and Hypersonics, at the Institute for Advanced Studies (IEAv). The outputs from the different solutions proposed in the present overview will be compared with future supersonic combustion experiments.

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