Aphlex 1B Injector Characterization

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(Initial revision 29 February, 2020; received 29 February, 2020)

1 Nomenclature

Symbols				**Acronyms**		
ϵ	=	Expansion ratio		CEA	=	Chemical equilibrium with applications
γ	=	Ratio of specific heats				
ρ	=	Density	g/cm^3	$COTS$	=	Commercial off-the-shelf
C^*	=	Characteristic velocity	m/s	DAQ	=	Data acquisition & control
C_d	=	Discharge coefficient		FOD	=	Foreign object debris
C_v	=	Valve flow coefficient		$GLOW$	=	Gross lift-off weight
f_d	=	Friction factor		$MECO$	=	Main engine cut-off
F_t	=	Thrust	N	$P\&ID$	=	Plumbing and instrumentation diagram
g_0	=	Acceleration due to gravity	m/s^2			
I_{sp}	=	Specific impulse	s	PT	=	Pressure transducer
$\dot{m}$	=	Mass flow rate	kg/s	TC	=	Thermocouple
O/F	=	Oxidizer-to-fuel ratio		SF	=	Safety factor
Q	=	Volumetric flow rate	L/s	VDC	=	Direct current voltage

Note: Subscripts follow the convention outlined in Rocket Propulsion Elements. Unless otherwise specified, subscript 0 indicates at stagnation or impact conditions, 1 indicates conditions at the nozzle inlet or combustion chamber, t indicates the nozzle throat, 2 is at the nozzle exit, and 3 is at ambient conditions.

2 Injector Characterization

Design Parameters			
Name	Value	Unit	Uncertainty
Propellant (Fuel)	Ethanol (C_2H_5OH, 95%)	N/A	N/A
Propellant (Oxidizer)	Nitrous oxide (N_2O)	N/A	N/A
O/F, Oxidizer/fuel ratio	4	N/A	±1%
F_t, Nominal thrust	1.50	kN	±0.1%
$\dot{m}_{total}$, Mass flow rate	0.6945	kg/s	N/A
$\dot{m}_f$, Fuel $\dot{m}$	0.1389	kg/s	N/A
$\dot{m}_o$, Oxidizer $\dot{m}$	0.5556	kg/s	N/A
p_{inj}, Δp across injector	25 (% of P_c)	N/A	N/A
P_c, Chamber static pressure	1.5×10^6	Pa	±0.1%
P_e, Ambient pressure	9.5540×10^4	Pa	±0.1%
T_c, Chamber static temperature	3025.98	K	±0.01%
M, Exhaust molecular mass	24.861	kg/mol	±0.01%
γ, Specific heat ratio	1.1537	N/A	±0.001%

Table 1: Summary of exhaust gas properties and fluid parameters.

The following section outlines the characterization and design process for Aphlex 1B's injector system, based on design parameters as shown in Table 1.

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2.1 Diameter Ratio

The injector types considered were the triplet (fuel-centered) unlike impinging injector and the like-on-like doublet impinging injector, due to 1) our limited manufacturing capabilities 2) a fairly unbalanced O/F ratio 3) both types exhibiting good mixing and atomization properties and 4) the abundance of historical experience and data with both injector types. NASA's SP-8089 conference document on liquid engine injector design suggests that the best way to characterize both the individual orifice geometries and the overall injector geometry for unlike impinging injectors is through diameter ratios. Vigorous cold flow and other empirically testing methods at the time were used and have found correlations between the driving orifice diameter ratio with the optimum mixing efficiency. The correlation found was

$$\left(\frac{d_c}{d_{ou}}\right)^2 = M\left[\frac{\rho_{ou}}{\rho_c}\left(\frac{\dot{m}_c}{\dot{m}_{ou}}\right)^2\right]^{0.7} \tag{2.1}$$

where d_c is the diameter of center orifice, d_{ou} is the diameter of an outside individual orifice, M is an experimentally-determined mixing factor coefficient, ρ represents liquid density, and $\dot{c}$ and $\dot{m}_{ou}$ are the center mass flow rate and outside mass flow rate respectively. It is cited that for a 2-on-1 element type, M has a value of 1.6. Using Equation 2.1, we find that our controlling diameter ratio is

$$\frac{d_c}{d_{ou}} = \sqrt{M\left[\frac{\rho_{ou}}{\rho_c}\left(\frac{\dot{m}_c}{\dot{m}_{ou}}\right)^2\right]^{0.7}} = \sqrt{1.6\left[\frac{772.25\ kg/m^3}{789\ kg/m^3}\left(\frac{0.1389\ kg/s}{0.5556\ kg/s}\right)^2\right]^{0.7}} = 0.4757$$

Since this diameter ratio is not reasonably near 1.22 (as suggested by NASA SP-8089), we can assume this correlation would not be accurate and that there will be potentially drastic losses in mixing efficiency. Thus, this suggests that a like-on-like system is required. Since like-on-like elements will have a 1 to 1 diameter and momentum ratio, we can begin determining the pressure drop and mass flow rate through each individual orifice. Rocket Propulsion Elements (RPE) provides and equation for the volumetric flow rate Q (and therefore $\dot{m}$ since ρ is constant) as shown below:

$$\dot{m} = Q\rho = C_d A\sqrt{2\rho\Delta p} \implies \Delta p = \left[\left(\frac{\dot{m}}{C_d A}\right)^2\right]/2\rho \tag{2.2}$$

where C_d is a dimensionless discharge coefficient that is experimentally determined and a function of the orifice geometry, A is the area of the orifice, and Δp is the pressure drop across the orifice. Flow velocity is similar:

$$v = Q/A = C_d\sqrt{2\Delta p/\rho} \tag{2.3}$$

Since C_d is a measured parameter, initial design calculations must assume a value. RPE suggests a C_d value of around 0.88 for a 1 mm diameter orifice in a short tube with a rounded entrance (L/D > 3.0), and 0.9 for a similar configuration with a 1.57 mm diameter. Accordingly, a C_d value of 0.9 was chosen for the oxidizer and a C_d value of 0.88 was chosen for the fuel. For the orifice sizing, NASA SP-8089 found that smaller orifice sizes attributed to better mixing in all scenarios, although only to a certain extent (orifice diameters <0.03 inches saw insignificant improvements in mixing). Due to limited manufacturing capabilities, a minimum hole size of 1 mm was chosen. Using the previously calculated diameter ratio, this means the minimum diameter must be applied to the fuel (center) orifice and that the surrounding (oxidizer) orifices must have a diameter of 1 $mm/0.7045 = 1.419\ mm$. Using this information, a design parameter of an overall injector pressure drop that is 25% of chamber pressure, and Equation 2.2, the mass flow rate across a single oxidizer and fuel orifice are 13.083

$$\dot{m}_o = 0.9 * (\pi * ((1.58\ mm/2) \times 10^{-3})^2)\sqrt{2(772.25 kg/m^3)(1.5 \times 10^6\ Pa * 0.25)} = 0.0425\ kg/s$$

$$\dot{m}_f = 0.88 * (\pi * ((1.00\ mm/2) \times 10^{-3})^2)\sqrt{2(789 kg/m^3)(1.5 \times 10^6\ Pa * 0.25)} = 0.0168\ kg/s$$

The same pressure drops can be used for each orifice due to Bernoulli's principle and the law of conservation of energy, similar to how voltage stays constant across a parallel circuit. The corresponding injection velocities (Equation 2.3) are

$$v_o = 0.9\sqrt{(2(1.5 \times 10^6\ Pa)(0.25))/(772.25\ kg/m^3)} = 28.048\ m/s$$

$$v_f = 0.88\sqrt{(2(1.5 \times 10^6\ Pa)(0.25))/(789\ kg/m^3)} = 27.132\ m/s$$

Dividing the mass flow rate by the individual orifice mass flow rates gives the total orifice count for each propellant:

$$Number\ of\ oxidizer\ orifices = \dot{m}_o/\dot{m}_{oi} = (0.4865\ kg/s)/(0.0170\ kg/s) = 13.083$$

$$Number\ of\ fuel\ orifices = \dot{m}_f/\dot{m}_{fi} = (0.139\ kg/s)/(0.0339\ kg/s) = 8.262$$

[Still need to figure out angle of impingement, distance from injector face, though this is expected to be 60 degrees and around 3 cm respectively. Need to note that L/D is greater than 3 (or more), and that higher is better.]