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Modeling of a blow-down propulsion system

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Lockheed Martini Group

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Nomenclature

Acronyms

LRE	Liquid Rocket Engine
LOX	Liquid Oxygen
RP-1	RP-1 fuel
AM	Additive Manufacturing

Symbols

$\boldsymbol{a}$	[m/s]	Speed of sound
$\boldsymbol{A}$	[m^2]	Area
$\boldsymbol{B}$	[-]	Blow-down ratio
$\boldsymbol{c_P}$	[J/kg K]	Specific heat at constant pressure
$\boldsymbol{c_T}$	[-]	Thrust coefficient
$\boldsymbol{c^*}$	[m/s]	Characteristic velocity
$\boldsymbol{C_d}$	[-]	Discharge coefficient
$\boldsymbol{D}$	[m]	Diameter
$\boldsymbol{E}$	[m/s]	Erosion rate
$\boldsymbol{f}$	[-]	Darcy friction factor
$\boldsymbol{h}$	[W/m^2 K]	Convective heat transfer coefficient
$\boldsymbol{H}$	[m]	Height
$\boldsymbol{i}$	[-]	First iteration index
$\boldsymbol{I_{sp}}$	[s]	Specific impulse
$\boldsymbol{I_{tot}}$	[N s]	Total impulse
$\boldsymbol{j}$	[-]	Second iteration index
$\boldsymbol{k}$	[m^{-1}]	Curvature
$\boldsymbol{K}$	[-]	Pressure loss coefficient
$\boldsymbol{L}$	[m]	Length
$\boldsymbol{L^*}$	[m]	Characteristic length
$\boldsymbol{m}$	[kg]	Mass
$\boldsymbol{\dot{m}}$	[m/s]	Mass flow rate
$\boldsymbol{M}$	[-]	Mach number
$\mathbb{M}$	[kg/mol]	Molar mass
$\boldsymbol{N}$	[-]	Number of
$\boldsymbol{O/F}$	[-]	Oxidizer to fuel ratio
$\boldsymbol{\overline{O/F}}$	[-]	Mean O/F ratio
$\boldsymbol{p}$	[Pa]	Pressure
$\boldsymbol{\Delta p}$	[Pa]	Pressure loss / difference
$\boldsymbol{Pr}$	[-]	Prandtl number
$\boldsymbol{\dot{q}}$	[W/m^2]	Heat flux
$\boldsymbol{\dot{Q}}$	[W]	Heat transfer rate
$\boldsymbol{r}$	[-]	Recovery factor
$\boldsymbol{R}$	[J/kg K]	Specific gas constant
$\boldsymbol{\mathcal{R}}$	[J/mol K]	Universal gas constant
$\boldsymbol{Re}$	[-]	Reynolds number
$\boldsymbol{Re'}$	[-]	Modified Reynolds number
$\boldsymbol{t}$	[s]	Time
$\boldsymbol{\Delta t}$	[s]	Time step
$\boldsymbol{T}$	[K]	Temperature
$\mathbb{T}$	[N]	Thrust
$\boldsymbol{u}$	[m/s]	Velocity
$\boldsymbol{V}$	[m^3]	Volume
$\boldsymbol{\Delta V}$	[m^3]	Volume change
$\boldsymbol{\alpha_{AM}}$	[deg]	Deposition angle of AM
$\boldsymbol{\alpha_{con}}$	[deg]	Convergent semi-aperture angle
$\boldsymbol{\beta}$	[%]	Injector pressure drop as percentage of initial combustion chamber pressure
$\boldsymbol{\gamma}$	[-]	Heat capacity ratio
$\boldsymbol{\varepsilon}$	[-]	Area ratio
$\boldsymbol{\lambda}$	[-]	Nozzle losses coefficient
$\boldsymbol{\mu}$	[Pa s]	Dynamic viscosity
$\boldsymbol{\rho}$	[kg/m^3]	Density
$\boldsymbol{\sigma}$	[-]	Correction factor across boundary layer

Subscripts

aw	Adiabatic wall
c	Combustion chamber
cea	From CEAM software
con	Convergent
e	Nozzle exit
eff	Effective
f	Final
fd	Feeding lines
fu	Fuel
i	Initial
id	Ideal
inj	Injector
max	Maximum
min	Minimum
ox	Oxidizer
p	Propellants
pr	Pressurizer gas
r	Real
t	Nozzle throat
tc	Thrust chamber
tk	Tank
tot	Total
wg	Gas side wall

1 Introduction and literature overview

1.1 Blow-down heritage

1.2 Additive manufacturing state of art

1.3 Analysis of losses

The model of the system was based on some ideal assumption of the propulsion process, but in the nozzle some irreversible processes and losses are present. Therefore some of them were analyzed and compared with the ideal case to achieve a better understanding of what really happens in the nozzle. The losses considered are specifically the ones caused by 2D flow, throat erosion and boundary layer. Considering 2D flow means that the propellants exit velocity is slightly misaligned from the nozzle axis, especially near its edges. Therefore only part of the flow will contribute to the thrust of the engine. The throat erosion is mostly caused by the exhaust gasses passing through it with high velocity and temperature, thus causing the material of the nozzle to erode and fail more easily. This effect causes an unwanted expansion of the throat area during the mission consequently increasing the rate at which the combustion chamber pressure decreases over time. The boundary layer loss is caused by the presence of a boundary layer between the nozzle wall and the flowing gasses. It is present along the whole nozzle but its effects are particularly evident in the throat, as it is the smallest part of the nozzle. This effect is accentuated even more by general dimensions of the considered system.

2 Modeling of propulsion system

Initial considerations (req + hyp / assumptions + constraints + criteria)
Flowchart

2.1 Tanks sizing

2.2 System dynamics

3 Results analysis

4 Nozzle losses

In order to calculate and evaluate the nozzle losses, further modifications and calculations were added to the model previously presented in **REFERENCE** . In particular 2D, throat erosion and boundary layer losses were considered.

4.1 Losses calculations

Each loss term has been calculated as follows:

- **2D losses**: for a parabolic Rao nozzle this loss can be computed in a similar way as a conical nozzle by applying Equation 1

$$\lambda = \frac{1}{2}\left[1+\cos\left(\frac{\delta+\theta_e}{2}\right)\right] \tag{1}$$

  where δ is the cone angle of an fictitious conical nozzle with the same divergent length and area ratio[1].

- **Throat erosion losses:** this effect is due to the increasing throat area over time whose behavior can be obtained by considering a constant erosion rate for simplicity. Since this loss is time dependent it needs to be considered inside the dynamic model of the system (**REFERENCE**).

$$D_t^{(i+1)} = D_t^{(i)} + 2E_t\Delta t \tag{2}$$

  Usually the erosion rate is calculated through experimental measurements of the propulsion system, in this case a suitable erosion rate has been searched for in literature. Due to the smallness of the system, no acceptable rates were found, therefore, an increase of 2% of the initial throat radius over the entire burn was assumed[1][2]. This gives an erosion rate of about **REFERENCE** .

- **Boundary layer losses:** to determine this contribution the effect of the boundary layer in the throat of the nozzle must be estimated. To achieve this the thermophysical properties of the exhaust gasses at the throat must be recovered from the CEAM outputs of the nominal design (**REFERENCE**). From them the throat Reynolds number can be obtained.

$$Re_t = \frac{\rho_t D_t u_t}{\mu_t} \tag{3}$$

Introducing the curvature of the throat, recovered from the Rao nozzle geometry, a modified Reynolds number is derived as follows:

$$k_t = 0.382 \frac{D_t}{2} \tag{4}$$

$$Re' = \sqrt{\frac{D_t}{2k_t}} Re_t \tag{5}$$

Now it is possible to calculate the throat discharge coefficient from which the real mass flow and effective throat area can be calculated.

$$C_{d,t} = 1 - \left(\frac{\gamma_t + 1}{2}\right)^{\frac{3}{4}} \left[3.266 - \frac{2.128}{\gamma_t + 1}\right] \frac{1}{\sqrt{Re'}} + 0.9428 \frac{(\gamma_t - 1)(\gamma_t + 2)}{Re' \sqrt{\gamma_t + 1}} \tag{6}$$

$$\dot{m}_r = C_{d,t} \dot{m}_{id} \tag{7}$$

$$A_{t,eff} = \frac{\dot{m}_r c^*}{p_c} \tag{8}$$

4.2 Effects on the nominal design

Including all the losses in the dynamic model has a significant effect on the evolution of the throat area as can be seen in **REFERENCE** .
Also, in this case the real case is not performing well as the ideal one. The result is a combination of both the erosion losses and boundary layer losses. It is possible to note that boundary layer losses are more prevalent in the beginning of the simulation, instead at the end the erosion one becomes visible. This is due to the fact that the nozzle erosion effects are more relevant when the throat has increased a lot. For this case the total impulse is 2173.157 KNs for the ideal case and 2139.825 KNs for the non-ideal one. By using the same justifications done in the previous section the difference in burning time can be justified. As in the only throat erosion case, also in this case there is a small difference in the burning times, with a 3716 s for the ideal one and 3679 s for the non-ideal, the same justification can be done.
[immagini grafici]

5 Additive manufacturing influences

6 Cooling analysis

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