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Modeling of a blow-down propulsion system

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Nomenclature

Acronyms

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

Symbols

a	[m/s]	Speed of sound
A	[m^2]	Area
B	[-]	Blow-down ratio
c_P	[J/kg K]	Specific heat at constant pressure
c_T	[-]	Thrust coefficient
c^*	[m/s]	Characteristic velocity
C_d	[-]	Discharge coefficient
D	[m]	Diameter
E	[m/s]	Erosion rate
f	[-]	Darcy friction factor
h	[W/m^2 K]	Convective heat transfer coefficient
H	[m]	Height
i	[-]	First iteration index
I_{sp}	[s]	Specific impulse
I_{tot}	[N s]	Total impulse
j	[-]	Second iteration index
k	[m^{-1}]	Curvature
K	[-]	Pressure loss coefficient
L	[m]	Length
L^*	[m]	Characteristic length
m	[kg]	Mass
$\dot{m}$	[m/s]	Mass flow rate
M	[-]	Mach number
$\mathbb{M}$	[kg/mol]	Molar mass
N	[-]	Number of
O/F	[-]	Oxidizer to fuel ratio
$\overline{O/F}$	[-]	Mean O/F ratio
p	[Pa]	Pressure
Δp	[Pa]	Pressure loss / difference
Pr	[-]	Prandtl number
$\dot{q}$	[W/m^2]	Heat flux
$\dot{Q}$	[W]	Heat transfer rate
r	[-]	Recovery factor
R	[J/kg K]	Specific gas constant
$\mathcal{R}$	[J/mol K]	Universal gas constant
Re	[-]	Reynolds number
Re'	[-]	Modified Reynolds number
t	[s]	Time
Δt	[s]	Time step
T	[K]	Temperature
$\mathbb{T}$	[N]	Thrust
u	[m/s]	Velocity
V	[m^3]	Volume
ΔV	[m^3]	Volume change
α_{AM}	[deg]	Deposition angle of AM
α_{con}	[deg]	Convergent semi-aperture angle
β	[%]	Injector pressure drop as percentage of initial combustion chamber pressure
γ	[-]	Heat capacity ratio
ε	[-]	Area ratio
λ	[-]	Nozzle losses coefficient
μ	[Pa s]	Dynamic viscosity
ρ	[kg/m^3]	Density
σ	[-]	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 $3.189 * 10^{-2}\ \frac{\mu * m}{s}$ **REFERENCE** .

- **Boundary layer losses:** to determine this contribution the effect of the boundary layer in the throat of the nozzle must be estimated, this was done by using the . 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** .
As expected the result of the simulation is that the case that consider nozzle losses is less performing respect to the ideal case. This is supported by analyzing the total impulse values, that are 2173.157 KNs for the ideal case and 2139.825 KNs for the non-ideal one. Moreover, it is possible to note that boundary layer losses are more prevalent in the in the simulation, this is totally expected because throat erosion losses typically do not affect much the performance of liquid propulsion system. Futhermore, it can be noted that there is a small difference in the burning time of the two simulation, with a 3716 s for the ideal case and 3679 s for the non-ideal one. The cause of this effect can be attributed to the presence of the throat erosion that allow to discharge all the propellant quicker. Lastely, it is also worth noting that the values found for the discharge coefficients are compatible with the value found in the literature **REFERENCE** [fig ,presa da slide maggi]with similar modified Reynolds number, the value range are respectably $0.9804 - 0.9697$ and $1.48 * 10^4 - 6.15 * 10^3$.
[immagini grafici]

5 Additive manufacturing influences

6 Cooling analysis

Bibliography

[1] G.P.Sutton. “Rocket Propulsion Element”. In: (2017).

[2] Mohd Aizat Iz’aan Mohd Ali et al. “INVESTIGATION ON NOZZLE THROAT EROSION IN HYBRID ROCKET MOTOR DUE TO NOZZLE EXPANSION RATIO”. In: (2023).