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Advanced nozzle concept trade-off and selection criteria based on launcher mission constraints

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Abstract
In previous studies [3] it has been shown that the operational efficiency is one of the key demands of space transportation systems. In this context, performance losses caused by non-adaptation of the flow in the expansion process represent the largest loss source for conventional rocket nozzles, with losses up to 15%. The reason is that these nozzles can be adapted or optimally designed only for a single trajectory point along the entire ascent phase. In contrast, Advanced Nozzle Concepts (ANCs) such as, among others, expansion-deflection and plug/ aerospike nozzles are able to adapt to different altitudes. The latter concept adapts even theoretically up to its geometric expansion ratio. By increasing the engine performance through a reduction of the adaptation losses, the payload, for example, can be increased [2]. Driven by this goal, ANCs have been explored for many years.

However, the best ANC is very closely related to the architecture and mission constraints of the overall launcher system. These are, for example, the application such as main stage/ -upper stage operation, the launcher class covering for instance the number of stages, and the thrust range or the propellant combination that has to be used. At the end of this investigation, it is expected to provide an application-driven critical assessment and a detailed trade- off analysis and discussion of the ED nozzle and to analyze different selection criteria based on launcher architecture and mission constraints. These results will be largely based on the evaluation of literature studies that have already been carried out (both numerically and experimentally) but also own analyses.

For every space propulsion engineer this investigation will be helpful and necessary to select possible ED nozzles tailored on the specific system requirements. This preliminary assessment can then be followed by further analyses including for example CFD assessments of critical aspects such as flow separation and heat fluxes in critical regions. After a verification and validation of the numerical simulations the design process can be finally completed by defining a system level integration methodology of the ANCs that will also include a novel upper stage application.

This work is framed within the ASCenSIon (Advancing Space Access Capabilities - Reusability and Multiple Satellite Injection) H2020 ITN consortium. The purpose of the ASCenSIon project is to develop a program that focuses on several specific cutting-edge space research, particularly on launcher systems that are (partially) reusable and capable of injecting multiple payloads into multiple orbits [1]. More than providing design concepts, the network aims to identify and advance critical technologies, such as for example the nozzle design, to prove a feasibility of these concepts. ASCenSIon is funded from the EUs Horizon 2020 research and innovation programme under Marie Skłodowska-Curie grant agreement.

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1. Introduction

Advanced Nozzle Concepts (ANCs) may offer an alternative solution to conventional bell nozzles. The most promising candidates are the Plug and the Expansion-Deflection (ED) nozzles whereas this paper is just referring to the later one. The reason for the interest in ANCs is that these show the advantage of self-adaptation to the ambient and therefore facilitate a higher performance than conventional rocket nozzles that show losses related to adaptation of up to 15% compared to the ideal case [7]. However, on the one hand, these ANCs theoretically only adapt up to their geometric expansion ratio [8]. On the other hand, it is known that the altitude compensation capabilities of the ED nozzle are inferior to those of the Plug nozzle due to aspiration and overexpansion losses [9]. Nevertheless, the interest for the ED nozzle increased lately since previous studies [10] on the A5E/ESC-B launch system have shown that the same thrust as for a bell type thrust chamber can be reached with shorter nozzles. Thus, the ED nozzle enables a higher thrust to weight ratio which makes it very interesting for vacuum applications since payload gains result making the space access cheaper and much more accessible.
For this paper an upper stage ED nozzle has been designed for vacuum applications with an in-house code based on a specific reference engine. Then for this ED nozzle a preliminary parametric analysis has been done for several configurations. Therefore, the performance was analyzed by numerical simulations and compared to comparable conventional TIC nozzles aiming to find the best performing ED design.

2. Development of an Expansion Deflection Nozzle

The ED nozzle in this paper has been designed with a self-developed MATLAB code applying the Angelino method [4] which is an analytical approximation of the numerical Method of the Characteristics (MoC) providing isentropic expansion. The Angelino method is an ideal method meaning that it assumes straight characteristic lines, constant specific heat ratio γ, and zero friction effects. Moreover, it is a one-dimensional method, meaning that flow divergence is also not taken into consideration. In the following, the tool is used to design an ED nozzle for upper stage applications.

2.1 Full length ED and TIC nozzle design for Vacuum applications

For applying the Angelino method to calculate the ED contouring but also the flow properties along the characteristic lines (e.g., temperature, pressure, density), the following input parameters have to be used:

- Chamber pressure p_c
- Chamber temperature T_c
- Specific gas constant R_s
- Specific heat ratio γ
- Lip wall radius R_c (see Figure 1)
- Relative base radius $\lambda = \frac{R_b}{R_e}$
- Exit Mach number of external expansion M_e
- Exit Mach number of internal expansion M_i
- Throat area A_t

A parameter that is not directly embedded into the contouring code but still giving a geometrical constraint for the design is the exit radius R_e. In case of the ED nozzle the maximal lateral dimension is located around the exit, just like for conventional nozzles. This results in the fact that the maximum permissible dimensions of the ED nozzle correspond also to those of the conventional nozzle. The reference application for this paper is a specific conventional nozzle which is the LM10-MIRA oxygen/ methane expander cycle engine [11][5]. Finally, the exit radius $R_e = 0.65m$ applies.

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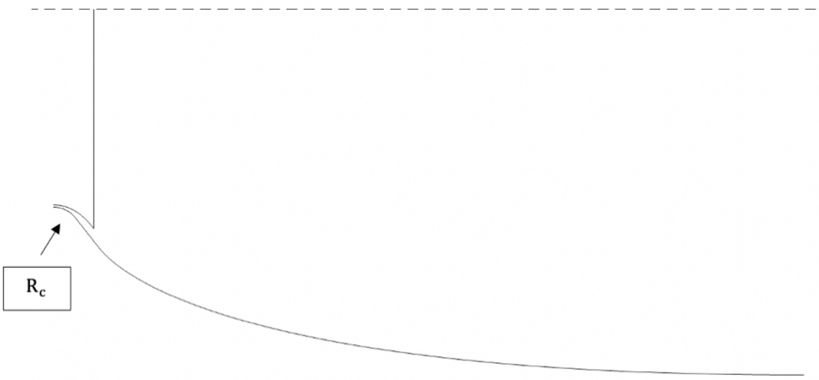

Figure 1. Location of the lip wall radius R_c for a generic ED nozzle

Selecting of the throat area A_t

In addition to the exit radius R_e also the throat area A_t is selected based on the reference bell nozzle with an expansion ratio of $\varepsilon = 160$.

- Expansion ratio $\varepsilon = 160$
- Exit radius $R_e = 0.65m$

$$\boxed{A_t \approx 8.3e - 3\ m^2}$$

Selecting the parameters p_c , T_c , R_s , γ

These parameters are related to the propellant set up of the liquid rocket engine already mentioned (see [11]) as listed in the following:

- Fuel = Methane
- Oxidizer = Oxygen
- Chamber pressure $p_c = 60\ bar$
- Mixture ratio of oxidizer and fuel $o/f = 2.8$

Based on these parameters the CEA code [6] was applied assuming a frozen point at the throat location. On the one hand, the flow properties for different positions in the nozzle are outputted which are useful for the simulation set up and Angelino code input (chamber temperature T_c). On the other hand, the species and the respective mass fractions after the freezing point are known. Based on that information the thermophysical properties of the exhaust gas mixture such as the specific heat capacity c_p , dynamic viscosity μ , heat conductivity k as well as enthalpy h and entropy s as a function of temperature can be calculated as well as the molecular weight. Since for the Angelino code a constant value for the specific heat ratio γ is assumed the value at the throat has been chosen. The specific gas constant R_s is obtained from the molecular weight.

As the input for the Angelino code the parameters are following:

$$\boxed{\begin{array}{c} p_c = 60\ bar \\ T_c = 3366.5\ K \\ R_s = 422.118\ J/(kg\ K) \\ \gamma = 1.2054 \end{array}}$$

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Selecting the geometrical parameters R_c , λ , M_e and M_i

The lip wall radius R_c was chosen to be sufficiently high in order to avoid flow separation after the nozzle throat but not too large to avoid an excessive increase of the length of the internal expansion of the ED nozzle to provide a relatively small total length.

The relative base radius λ and the Mach numbers M_e and M_i are selected simultaneously. This means that for different base radiuses the exit Mach number was found for that the exit radius of the ED nozzle is equal to $R_e = 0.65m$, see Equation 1. This exit radius is as already explained the selected geometrical constraint of the nozzle. The Mach number at the end of the internal expansion M_i is chosen in order to have a tangential flow at the throat meaning that the flow is parallel to the symmetry axis.

$$R_e = \sqrt{\frac{\varepsilon(M_e,\gamma)\cdot A_t}{\pi\cdot(1-\lambda^2)}} \rightarrow M_e = f(R_{e,},\gamma, A_t, \lambda) \tag{1}$$

Finally, for every base radius one ED nozzle can be calculated with its own length that is a further output of the code. The length of the external expansion ${}^{x_{ext}}/_{R_e}$ is measured from the edge of the base till the nozzle exit and results from the following Equation 2 for the assumption that the flow after the last external characteristic is fully axial.

$${}^{x_{ext}}/_{R_e} = \frac{\lambda - 1}{tan(asin(M_e{}^{-1})} \tag{2}$$

In Figure 2 it is shown that the exit Mach number Me (see Equation 2) can be approximated as a polynomial of 6. Order and is decreasing with increasing base radius in order to satisfy the conditions for R_e, γ and A_t (see Equation 1). Finally, the result is that the length of the external expansion decreases approximately linearly over the base radius, see Figure 2.

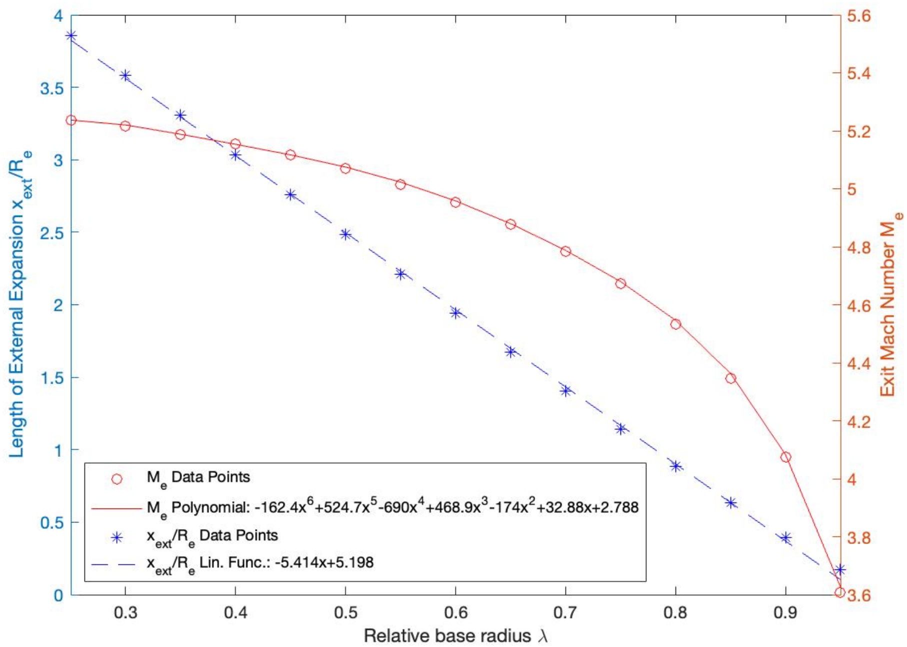

Figure 2. Exit Mach number and External expansion length over the relative base radius

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For the calculation of the length of the internal expansion ${x_{int}}/{R_e}$ first the starting point of the last internal characteristic on the outer wall has to be calculated according to Equation 3:

$$ {x_{Last}}/{R_e} = \frac{-\lambda - {y_{Last}}/{R_e}}{tan(\Theta + asin({1}/{M_i}))} \tag{3} $$

Whereas

$$ {y_{Last}}/{R_e} = -\sqrt{\lambda^2 - M_i \cdot sin(-(\Theta + asin({1}/{M_i})) \cdot \frac{\varepsilon(M_i,\gamma)}{\varepsilon(M_e,\gamma)} \cdot (1 - \lambda^2)} \tag{3a} $$

And

$$ \Theta = \nu(M_i,\gamma) - \nu(M_e,\gamma) \tag{3b} $$

Since there is a tangential flow at the throat the length if the internal expansion ${x_{int}}/{R_e}$ finally follows by Equation 4

$$ {x_{int}}/{R_e} = {x_{Last}}/{R_e} + (\frac{R_c}{R_e}) \cdot sin(\Theta) \tag{4} $$

Figure 3 shows that the length of the internal expansion also decreases with increasing base radius. The evolution of the length of the internal expansion can approximated by a polynomial of 6. Order. Since the length of the internal expansion is negligible small compared to the external part it has almost no influence on the behavior of the total nozzle length as a function of the base radius. Therefore, also the total nozzle length will decrease almost linearly with increasing base radiuses as the external part.

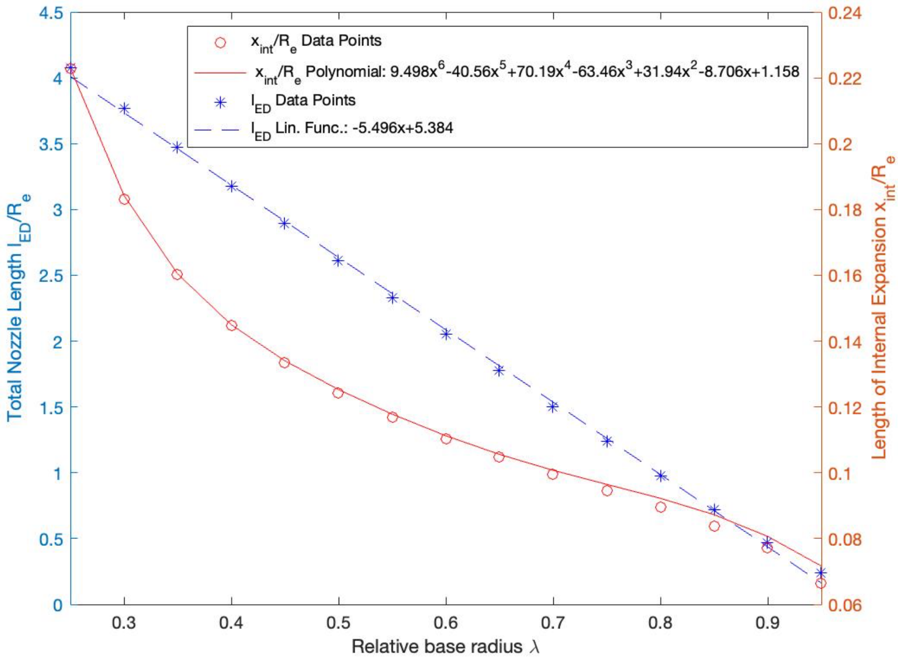

Figure 3. Length of internal expansion and total nozzle over the relative base radius

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For every ED nozzle a corresponding TIC nozzle can be designed with the Method of Characteristics having the same exit radius R_e , nozzle length and throat area as the ED nozzle. Hence, any of those TIC nozzles would have an expansion ratio of $\varepsilon = 160$. It is important to note that the TIC nozzles equivalent to the ED nozzles with high relative base radiuses λ will be also relatively short and therefore of quite conical shape. It can therefore be assumed that these TIC nozzles will have particularly high divergence losses unlike the respective ED nozzle. Because of that, for the ED and TIC nozzle comparison an ED nozzle with relatively high $\lambda = 0.6$ is selected to assess whether the ED nozzle is more efficient under these conditions. In the following the last parameters are summarized:

$$R_c = 0.05m$$
$$\lambda = 0.6$$
$$M_e = 4.9518416$$
$$M_i = 1.33271m$$

In the following Figure 4 the full-length ED and TIC nozzles are shown. In case of the ED nozzle the wall contouring before the throat is not part of the Angelino calculation. Therefore, two cosine functions have been used to calculate the wall contouring.

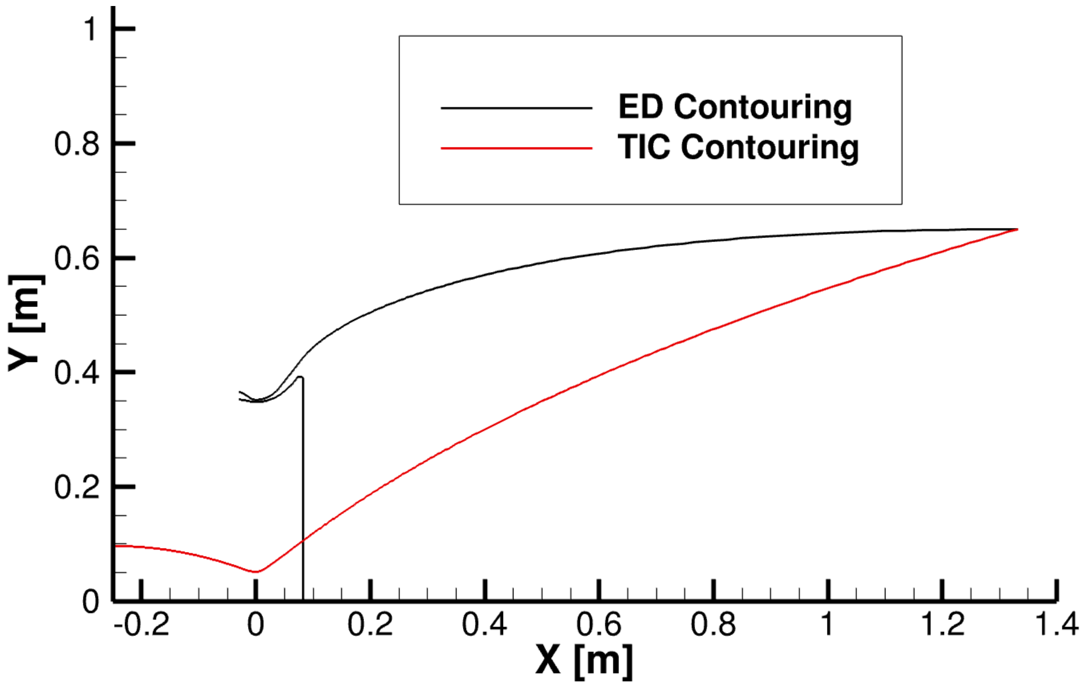

Figure 4. ED and TIC nozzle contouring (Full-length)

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2.2 Comparison of Full-length ED and TIC nozzle for Vacuum applications

After designing the full-length ED and TIC nozzle contours, numerical simulations have been carried out and the corresponding thrust values have been evaluated to compare the nozzle performances.

Numerical Set up

In order to reduce the size of the computational domain and the necessary resources, 2D axisymmetric simulations have been performed with OpenFOAM using the pressure-based solver *rhoPimpleFoam* with x as the symmetry axis. Due to the fact that sharp corners at the base of the ED nozzle can cause numerical instabilities, a rounded lip with a radius of $r_{Lip} = 0.00623m$ has been chosen, as shown in Figure 5. The boundary conditions are the same for both nozzle types.

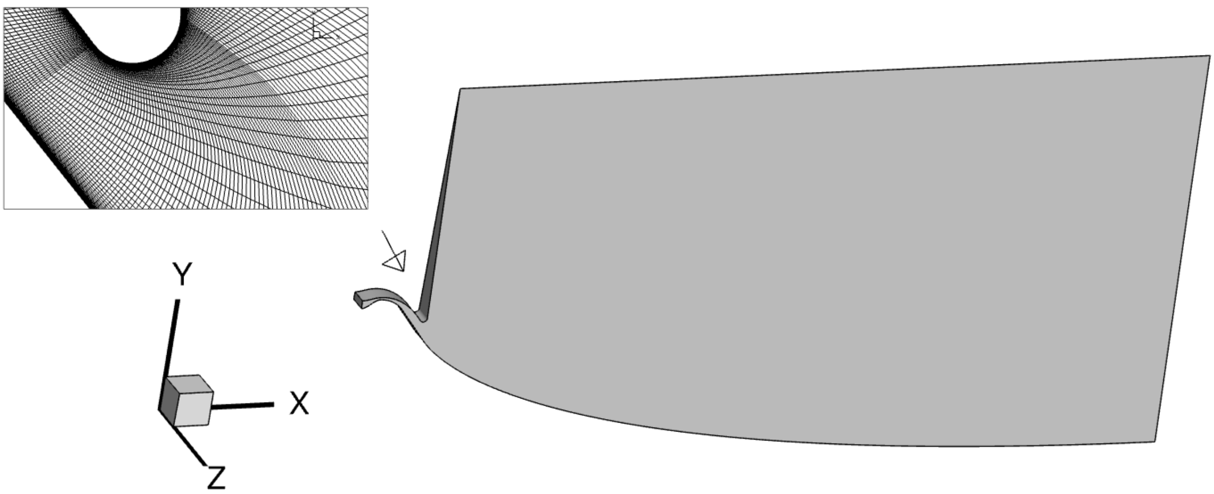

Figure 5. ED domain and mesh around the lip

The walls are modelled as isothermal walls with a constant temperature of 700 K. As well as the velocity on the walls is concerned, the no-slip condition is applied. The conditions in the chamber of the ED as well as TIC nozzles are the same that have already been applied for the ED design with the Angelino code, $\boldsymbol{P_c = 60\ bar}$, $\boldsymbol{T_c = 3366.5\ K}$. The outlet pressure in the far-field after the outlet $\boldsymbol{P_0}$ was set to 10 Pa since a pressure value of zero could lead to numerical instabilities.

The thermophysical properties, meaning the specific heat capacity c_p , the dynamic viscosity μ , the heat conductivity k and the specific heat ratio γ of the exhaust gas are calculated for the mixture and fixed to constant values computed at the throat location. Turbulence is accounted for by the Spalart Allmaras turbulence model.

For the ED as well as TIC nozzle the simulations have been performed on 3 grid levels whereas the number of cells in x and y direction has been varied by the refinement factor r=2. As a result, the total number of cells quadruples between the different grid levels. For the fine meshes the TIC nozzle is resolved by 108000 and the ED nozzle by 42000 Cells. The Mach number contours for both nozzles are shown in Figure 6. In case of the ED nozzle a full supersonic outflow is visible indicating that the nozzle is working in closed wake regime. This means that also the base pressure will remain unaffected by the conditions outside the nozzle.

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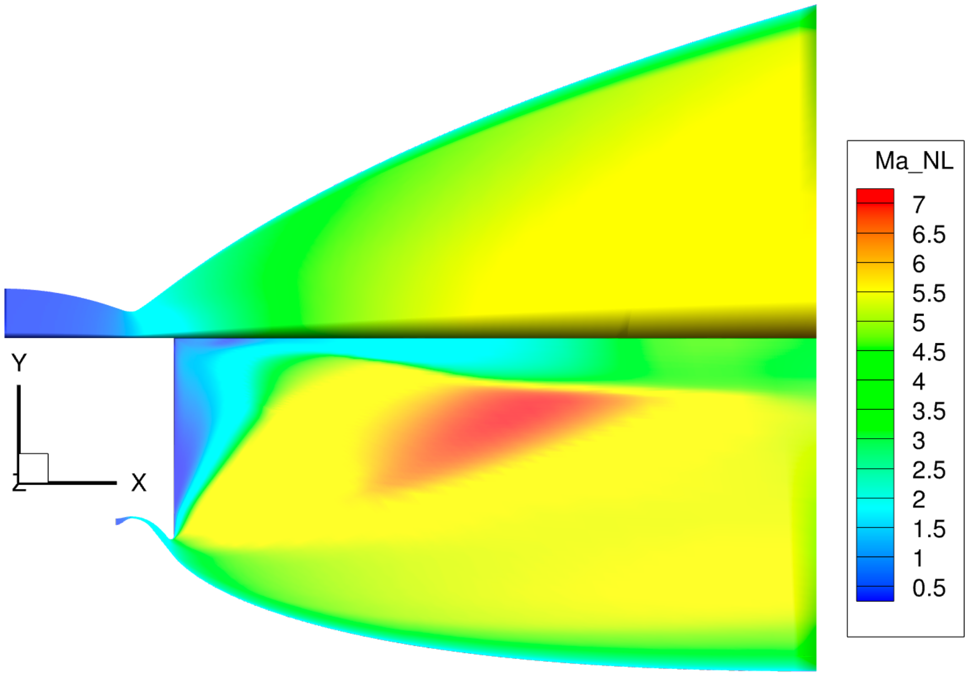

Figure 6. Mach number field of the TIC and ED nozzle

Evaluation of Thrust

In the first place the axial thrust values for the full-length ED and TIC nozzle have been computed by applying Equation 5 to the nozzle exit area.

$$F_x = \int \rho {U_x}^2 + (P_e - P_0)\ dA \tag{5}$$

From the numerical simulations the thrust values in Table 1 are obtained, showing that the full-length TIC is superior to the full-length ED nozzle. This shows clearly that the divergence losses of the TIC nozzle are still not high enough to deliver less thrust than the ED nozzle. At this point it also has to be mentioned that the ED nozzle has more surface than the TIC nozzle contributing also to friction performance losses.

Table 1. Comparison of the axial thrust of the full-length ED and TIC nozzle

Full-length nozzle	F_x [kN]
ED	91.54
TIC	93.13

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2.3 Comparison of Truncated ED nozzles compared to comparable TIC nozzles for Vacuum applications

As already demonstrated in section 2.2 the ED nozzle is inferior to the TIC nozzle when considering the full length. This led to the assumption that the ED nozzle may reveals its full potential when applying truncation. In Figure 7 an additional TIC nozzle is shown that has been developed equivalent to the length and radius of an ED nozzle that has been truncated to 58% of its original full length. This truncation point was chosen randomly.

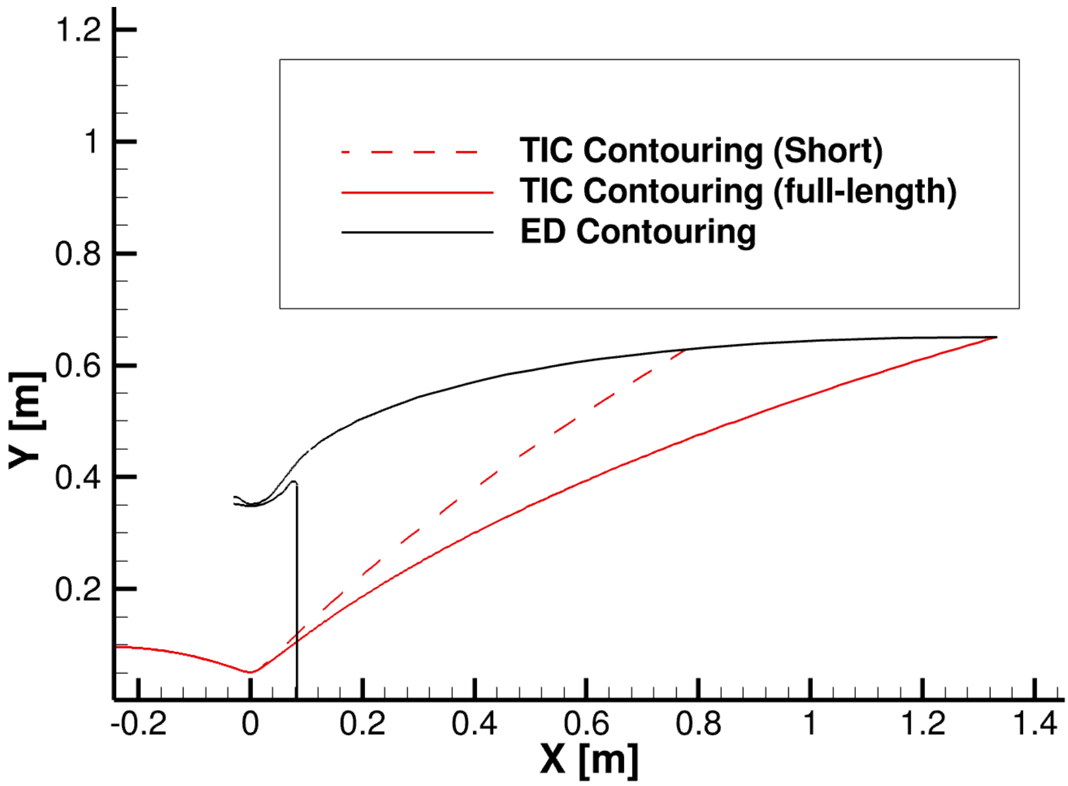

Figure 7. Shorter TIC compared to the full-length ED and TIC nozzle

As visible in Figure 7 the short TIC nozzle, shown as the red dashed line, has a slightly lower expansion ratio than its longer version coming to $\varepsilon_{TIC,short} \approx 150$. For still the same throat area A_t and chamber pressure p_c the ideal thrust and thrust coefficient, that is a function of the expansion ratio ε and the specific heat ratio γ is decreasing with respect to the longer TIC, see the following Equation 6. In addition, there will also be higher divergence losses due to a more conical nozzle shape.

$$F = A_t \cdot CF_{vac}(\varepsilon, \gamma) \cdot p_c \tag{6}$$

Then also the thrust for the truncated ED nozzle and the shorter TIC nozzle has been evaluated. These thrust values are shown together with the full-length values in Table 2. The results clearly show a superior performance for the ED nozzle when shorter nozzle lengths are considered. This is due to the higher divergence losses of the shorter TIC nozzle as mentioned before.

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Table 2. Comparison of the axial thrust of the full-length ED and TIC nozzles as well as those equivalent to 58% of full length

Full-length nozzle	F_x [kN]	Shorter Nozzles	F_x [kN]
ED	91.54	ED	89.49
TIC	93.13	TIC	86.06

If this ED and TIC nozzle performance comparison is also conducted for further nozzle lengths between the 58% of the full length and the full length (100%) it becomes clear that the ED nozzle becomes more efficient than the TIC nozzle if the truncation is more than $\approx 25\%$, hence very short configurations. This is shown in the following Figure 8.

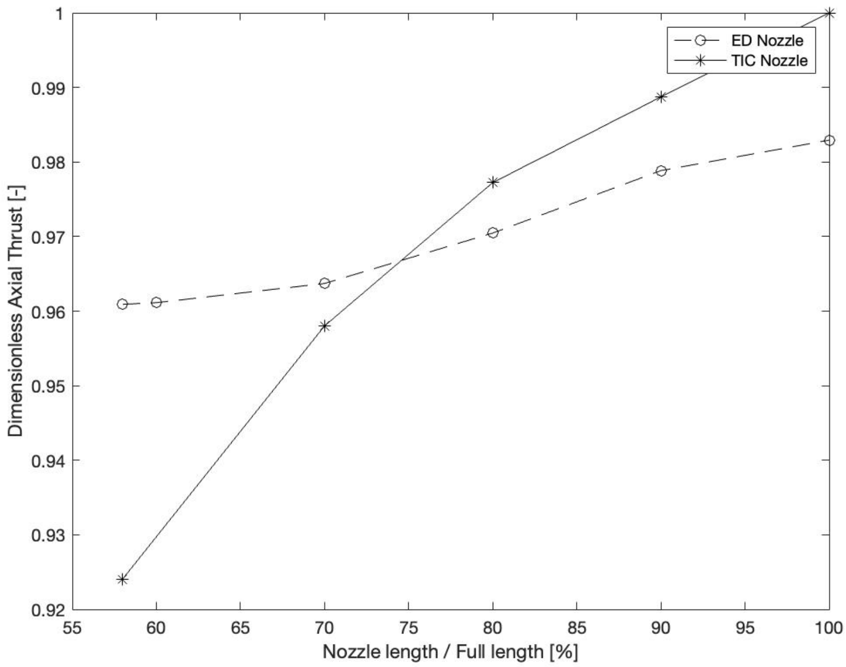

Figure 8. ED and TIC nozzle axial thrust as a function of the nozzle length

Performance optimization analysis for the TIC nozzle

So far it could be shown that the ED nozzle delivered more axial thrust than the TIC nozzle when two nozzles have the same length equivalent to 58% of the total length and the same exit radius enabling a TIC expansion ratio of $\varepsilon \approx 150$. However, in order to broaden this comparison, it must be checked whether the best TIC nozzle possible was used for this nozzle length. Therefore, the short TIC nozzle from Figure 7 has been redesigned for different values of the expansion ratio $\varepsilon = 30, 60, 90$ and 120 (see Figure 9). Since the throat area A_t and length remain unchanged the desired TIC expansion ratios are set by reducing the exit radius.

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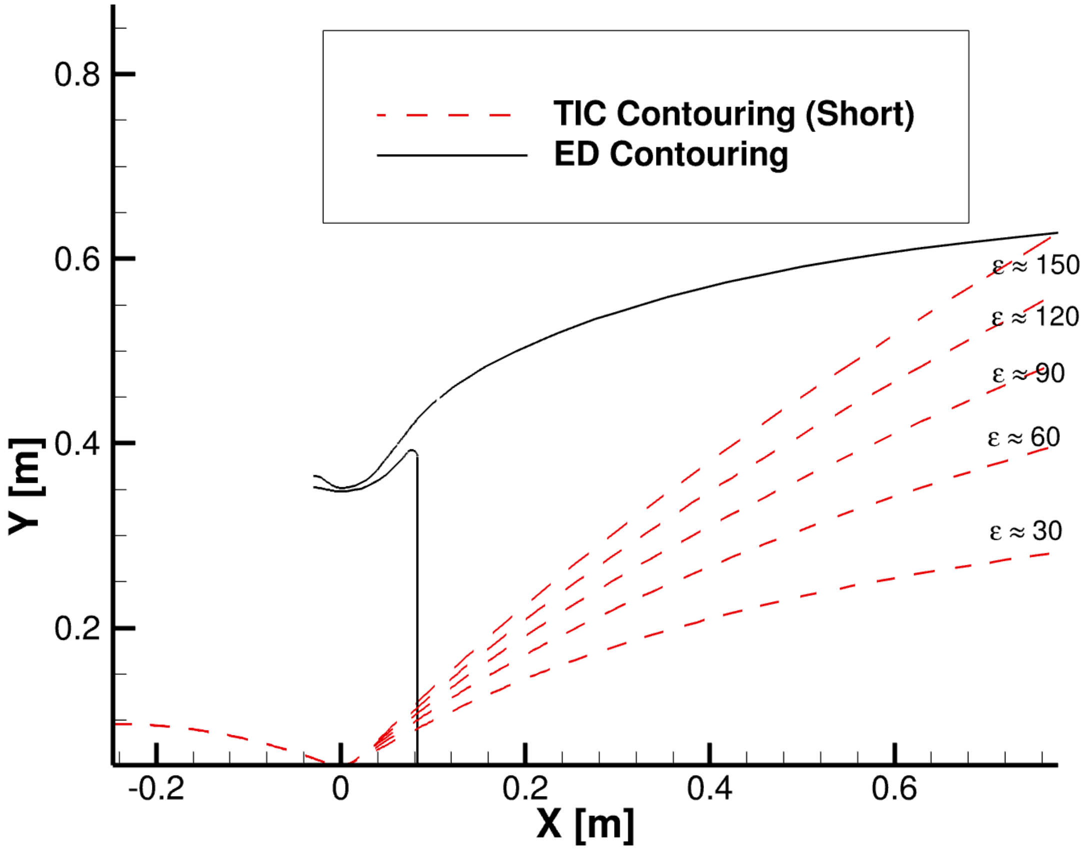

Figure 9. Variation of the expansion ratio for the short TIC nozzle

Table 3 summarizes the axial thrust F_x of the truncated ED nozzle compared to the different TIC nozzles with varying expansion ratios. It can be seen that the maximal axial thrust for the TIC nozzle is around 90.06 kN and will be reached at an expansion ratio of $\varepsilon \approx 60$. On the one hand, for expansion ratios smaller than that the axial thrust of the TIC nozzle will decrease again due too low exit Mach numbers. On the other hand, if expansion ratios greater than $\varepsilon \approx 60$ are applied the axial thrust will also decrease due to high divergence losses. The TIC configuration with an expansion ratio of $\varepsilon = 60$ will be more efficient than the ED nozzle.

Table 3. Comparison of the axial thrust of the truncated ED nozzle (58% of total length) and the different TIC nozzle configurations

Shorter Nozzles	F_x [kN]
ED	89.49
TIC ($\varepsilon \approx 150$)	86.06
TIC ($\varepsilon = 120$)	87.72
TIC ($\varepsilon = 90$)	89.09
TIC ($\varepsilon = 60$)	90.06
TIC ($\varepsilon = 30$)	89.09

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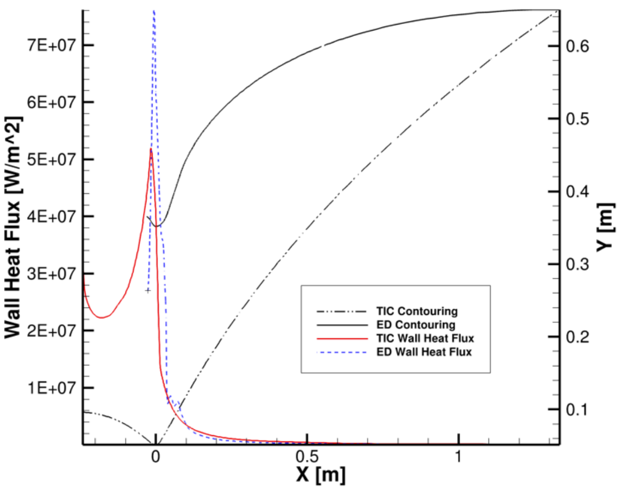
3. Conclusion and Outlook

In this paper it has been shown how an ED nozzle can be designed for upper stage applications with the Angelino method. By applying this contouring method an ED nozzle was calculated according to the specific reference engine LM10-Mira (10t thrust class) for the same exit radius R_e, throat area A_t, chamber pressure p_c and propellant set up. Then, for this full-length ED nozzle, a comparable TIC has been designed for the same parameters. For both nozzles viscous and turbulent numerical simulations have been conducted in order to compare the nozzle performance. As a result of the simulations, it was found out that the performance of the full-length ED nozzle is inferior to the TIC due to higher friction losses. If the ED nozzle is truncated at several positions and for each of those truncated ED nozzles a TIC nozzle is designed for the same length and exit radius then the ED nozzle gets more performant if the truncation is at $\approx 75\%$ or more of its full length. The reason are higher divergence losses of the TIC nozzle. If the expansion ratio of the TIC is again optimized between the lowest possible divergence loss and the highest possible exit Mach number in order to obtain the best possible TIC nozzle for this length then the TIC is more performant again.

However, in future this preliminary parametric analysis has to be extended in order to find also the best possible performing ED configuration for this length. At the end, it should then be found out whether the Angelino contouring method giving an approximation of the Ideal contour is suitable for ED nozzles.

Also, there are further open points as for example the real purpose of the base of the ED nozzle. From the full-length ED nozzle (see Table 1) a base thrust contribution of $F_{Base} \approx 14N$ has been calculated. This value is so small compared to the total axial thrust that it could be neglected. This leads to the assumption that the task of the base is only to increase the exit radius of the nozzle and to enable high expansion ratios for even small nozzle lengths. As a result, the assumption arises that the advantage of the ED nozzle over the TIC will only become really apparent for large expansion ratios. Therefore, for further parametric analysis it could be useful to design an ED nozzle for bigger radial dimensions.

Finally, there are the heat fluxes of the ED nozzles that are due to small throat gaps particularly high. In Figure 10 it can be seen that the heat fluxes along the internal and external wall of the ED nozzle are around 25-30% higher compared to the TIC nozzle. This leads to the assumption that always a compromise between performance and wall heat fluxes has to be made for the ED nozzle so that high performing nozzles always require very good cooling strategies.



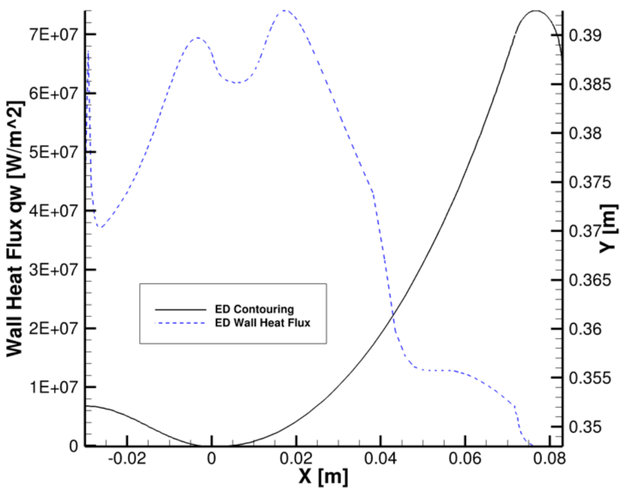


Figure 10. Wall Heat Flux for the full-length TIC nozzle as well as the ED nozzle (left – external wall, right – internal wall)

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