## ANALYSIS OF THE FLOW IN A PROPULSION NOZZLE SUBJECTED TO A FLUID INJECTION


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### ABSTRACT

The aero-thermodynamics propulsion systems is one of the fields of fluid mechanics where decisive progress is still needed to improve performance and meet the continued demand to orbit increasingly heavy payloads. It's the chemical propulsion using the thermal energy during combustion of the propellant, which remains the most reliable way to meet the requirements of high demands for thrust, specifically to lift-off. For those of propulsion, the nozzle is the body to convert most effectively heat energy into kinetic energy of the mixture. The divergent portion of a nozzle is the seat of an exhaust gas flow at high enthalpy, where a fraction is transmitted to the wall of the divergent portion, thus altering its lifetime. The long periods of operation and the amplitude of the heat flux set the issues, require cooling technique film for the wall of the divergent portion. For weight constraints, it is a fraction of the flow of fuel supplied to the combustion chamber, which is injected into a section of the diverging form of a gaseous film adjacent to the wall. The injection conditions must be adjusted in order to avoid problems associated with outbreaks of losses and local re-inflammations. This work represents a numerical investigation of the dynamic and thermal of a compressible flow in the nozzle BKE-DLR, representing a laboratory scale model of the Volvo nozzle of the European Vulcain cryogenic engine 2. The Torque of propellants $H_2$ / $O_2$ is injected at 50 bar, in a mixing ratio of 6.2 in a cylindrical combustion chamber, wherein the thermodynamic conditions (pressure, temperature) are taken as reservoirs values for the flow relaxation. The axisymmetric nozzle having a ratio of 57 in its output section is subjected to a $GH_2$ film cooling in a section where the ratio is equal to 32. Energy & Euler's equations are discretized and solved on a non-uniform structured grid, in the sense of finite volume numerical schemes with Roe type for convective terms. A zero-dimensional calculation (0D) allows the use of thermodynamic relations to predict aero-thermochemical variables in each slice of the divergent, especially in the downstream of the injection section. The compressible flow in the absence of cooling is digitally reproduced on the axisymmetric model to predict the level of thrust and the rate of loss by divergence, so that the temperature distribution in the vicinity closes to the wall of the divergent portion. The results are compared with values predicted by thermodynamic calculations. The cooling is then carried out for the two cases, sonic and supersonic for the injection port, wherein the evaluating a cooling performance index defined as a reduced temperature. The distribution of the efficiency index to a power line located downstream of the injection zone, is confronted with the measurements on the test bench (DLR). A parametric analysis is then conducted on the effects of the injection angle relative to the wall and the injected flow rate, on the level of thrust and on the cooling efficiency.



**Keywords:** propulsive Nozzle; fluidic injection; cooling efficiency.

## 1 INTRODUCTION

Rocket engine nozzle is a propelling nozzle used to expand and accelerate the combustion gas produced by burning propellants to supersonic exit velocities. To furnish high performance and thrust, a maximum of the energy which is released inside the combustion chamber due to the reaction of the propellant and the oxidizer has to be converted into kinetic energy.

The burnt gas flowing through the nozzle are of high temperature, which requires a continued cooling of the walls, under reserve to not alter the enthalpy of the flow [1]. The techniques of regenerative cooling consist to circulate a liquid in the tubes surrounding the outer wall of the divergent, are limited to thrusts medium engines because of cycles problems [2]. For the first stage's motors, it is the fluid injection inside the divergent who feels promising, specifically in the experimental stage [3]. This technique not only allows ensure a good level of cooling efficiency, but also helps delay the restricted separation and improve vectoring the thrust [4] .

In the present work, we are interested in the thermal aspect of the H2 gas fluidic injection in the divergent, of a subscale model of an optimized contour nozzle (TOC) comparable to that of Volvo Aero, installed on the cryogenic engine Vulcain 2 [5]. The generating conditions ( $P_{ch}, T_{ch}, M_{ch}$ ) in the nozzle's inlet, are assessed via a thermochemical calculation on the reagent flow in the combustion chamber [6].

A perfect fluid calculation method (Euler) is conducted on the geometric model in the finite volumes method by using the Commercial code 'Ansys-Fluent', [7] will examine the effects of the variation of the injected flow and the injection pressure, on the cooling efficiency factor in the downstream of the fluidic injection zone.

## 2 THERMODYNAMIC CALCULATION

According to the methodology of JANAF [8] , The ideal performances relations consider the mixture of the resulting gas of combustion as a perfect gas constant specific heats and relaxing isentropically and dimensional in parts. Considering a diagrammed propulsive chamber with an open volume on one of its faces with the section $A_{ch}$, and/or operates a combustion with $P_{ch}$ pressure, defined as the initial generating pressure (Figure 1).

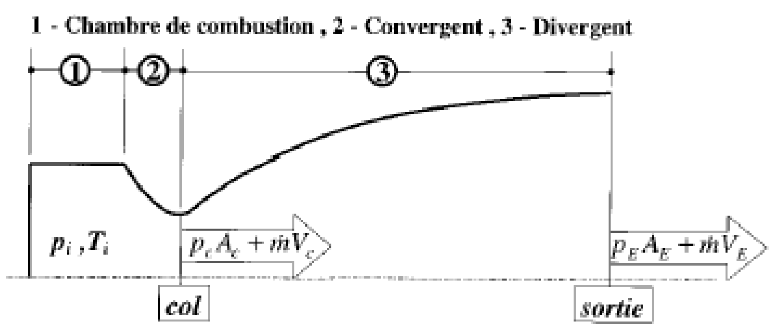


**Figure 1:** Schematic of a propulsive chamber.

If we consider that the nozzle is primed, then, using the Hugoniot relation can express the maximum flow as:

$$\dot{m} = P_{ch} A_t \Gamma(\gamma) / \sqrt{rg.T_{ch}} \quad (1)$$

With: $$\Gamma(\gamma) = \sqrt{\gamma}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \quad (2)$$

Where $rg = Rg / Mw$ is the mass's constant of the mixture (average molecular weight).

The flow characteristics of relaxation can be obtained from the energy & mass conservation laws associated to the equations of the isentropic. When relating the generating conditions to the exit ones, the energy equation is written as follow:

$$CpdT + VdV = 0 \quad (3)$$

An integration of this equation between the generator state ($T_{ch}, P_{ch}$) and the ejection's conditions ($T_e, P_e$) and with the use of the mixture state's equation, allows to express the Mach number at the ejection as:

$$M_e = \sqrt{\frac{2}{\gamma-1}(1 - NPR^{\frac{\gamma-1}{\gamma}})} \quad (4)$$

$NPR = P_e / P_{ch}$ is the expansion ratio at the nozzle outlet (depending on the ejecting section). The thermodynamic conditions ($P, T$) at the inlet of the nozzle are the result of a calculation by means of the code cea of an isentropic and reagent flow in the combustion chamber [9]. Mixture laws are used for the assessment of isentropic coefficient and the average molecular weight of the mixture. The thermodynamic values used in the numerical calculations are as follows:

$M_{ch} = 0{,}26$, $P_{ch} = 50$ bars, $T_{ch} = 3580$ K, $\gamma = 1{,}13$ [6].

## 3 MODEL DESCRIPTION & OPERATING CONDITIONS

The nozzle which we carried our simulation on is the one called BKE-DLR [6] represented in 1/8.3 sub model of the VULCAIN 2 nozzle (Figure 2). This model is used to sunder the phenomenon inherent cooled nozzles, such as the lift offs & the reinflamations.

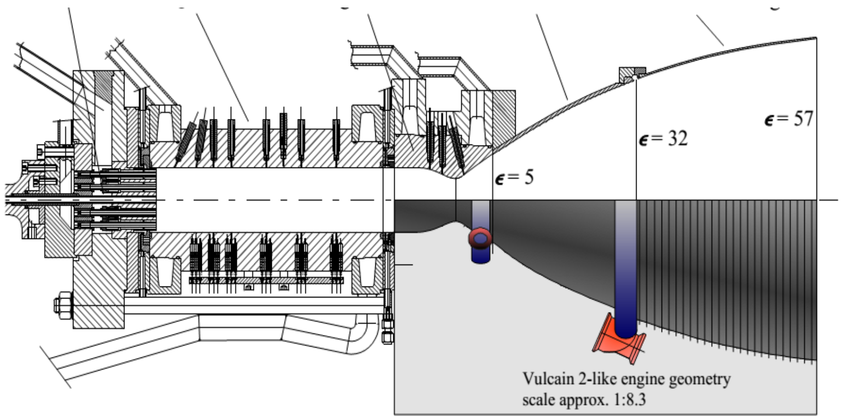


**Figure 2:** Side view of the experimental device BKE [3].

The combustion chamber is powered by H2-O2 with a pressure $P_{ch} = 50$ bars & a ration of injection mixture $mr = 7{,}30$. The section ratios fixed at $\in_e = 57$ for the divergent outlet & at $\in_{ch} = 2{,}29$ for the convergent inlet.

The gaseous hydrogen is injected on the section ration of $\in_{inj} = 32$ .The profile of the divergent (Figure 3) is numerically constructed with a polynomial defines per pieces [6].

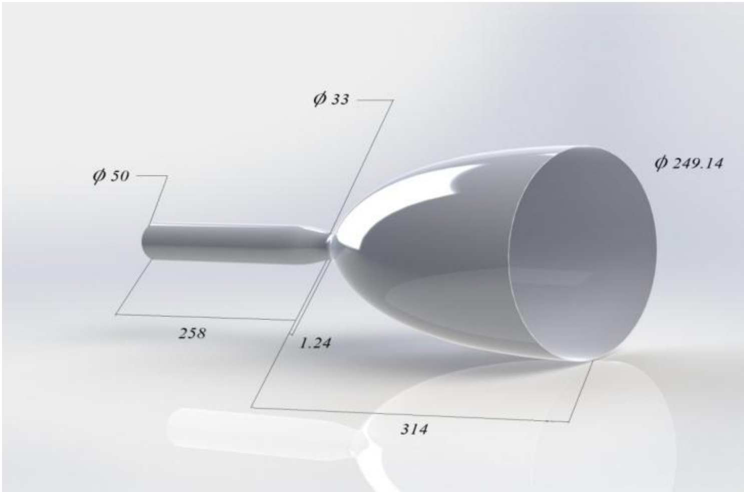


**Figure 3:** Geometric model for the BKE nozzle

## 4 RESULTS AND DISCUSSION

On the geometric model, a non-uniform mesh was used for the calculations in perfect fluid (Figure4), containing 3404 quadrilateral cells.

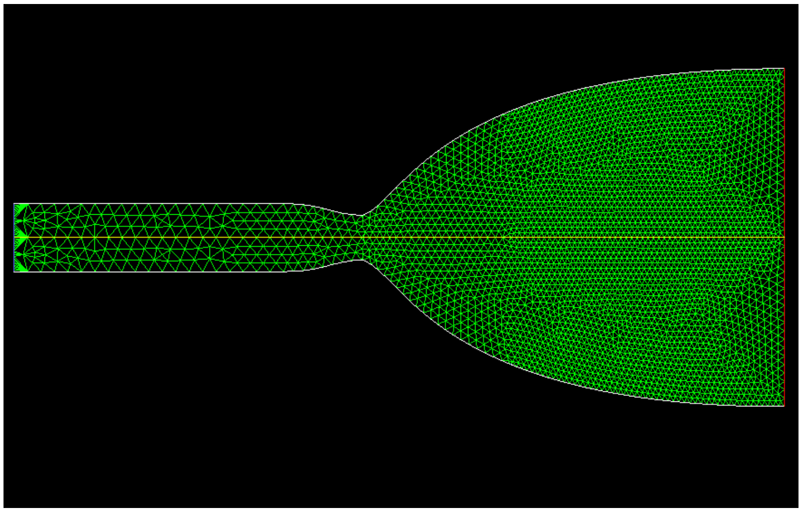

**Figure 4:** Mesh used for Euler's calculations.

The Mach number being a characteristic of the compressible flow in the divergent, its axial value observed insensitivity to the variation of the size of the grid (Figure 5).

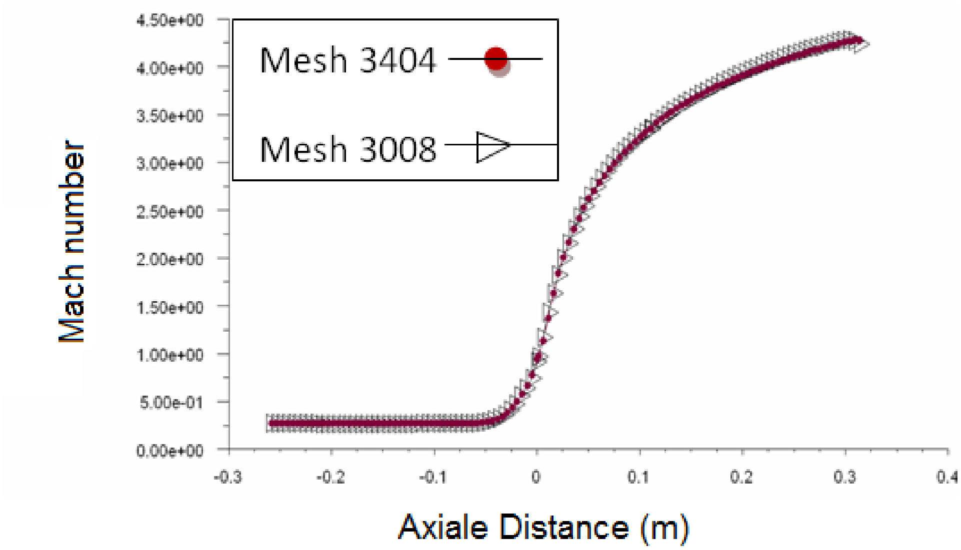


**Figure 5:** Axial Mach number for different meshes.

As a first approach, a simulation is carried out for the case of non-cooled nozzle. This approach not only allows us to "calibrate" the numerical parameters by generating a field of initial solutions for calculations with injection, but we provide aérothermochimiques the conditions at the nozzle's outlet section. The examination of the spatial distribution of the Mach number showed an increase in the axial direction but also in the radial one, due to geometric divergence (Figure 6).

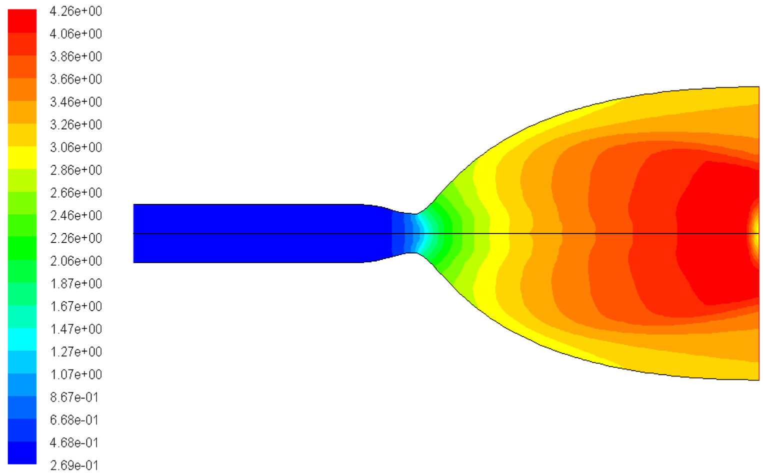


**Figure 6:** Spatial contour of the Mach number (the case without fluid injection).

This divergence is due to the curvature of the profile wall of the TOC, which induces a Mach number on the slightly upper axis (~ 6%) to its thermodynamic value (Figure 7).

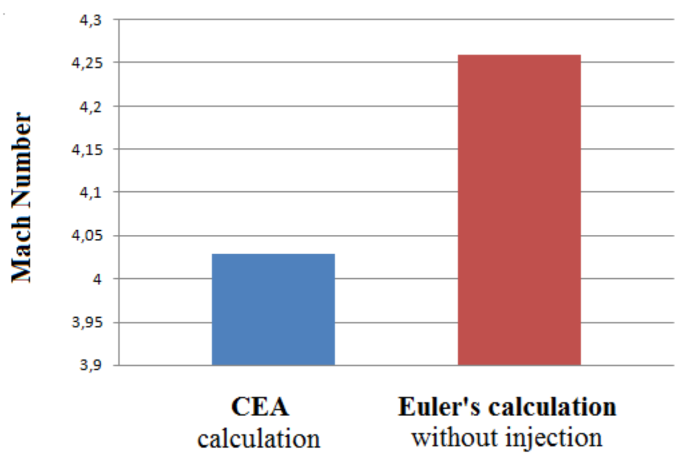


**Figure 7:** Comparison of the Mach number values at the nozzle outlet (case without fluid injection).

For the case with cooling, gaseous hydrogen is injected perpendicularly to the wall of the divergent with an injection pressure of around 0.17 bar and a static temperature of 294 K, which represents a fraction of 4% of the total flow in the nozzle [3].

It is important to locally, examine dynamic atmosphere and heat flow output of the injector. This comes from a dual objective to adapt the conditions of the injector tanks and quantify local cooling effects. [4] For the adopted conditions, the Mach number at the injector's outlet 2.92 is relatively high since it is in the supersonic range (Figure 8).

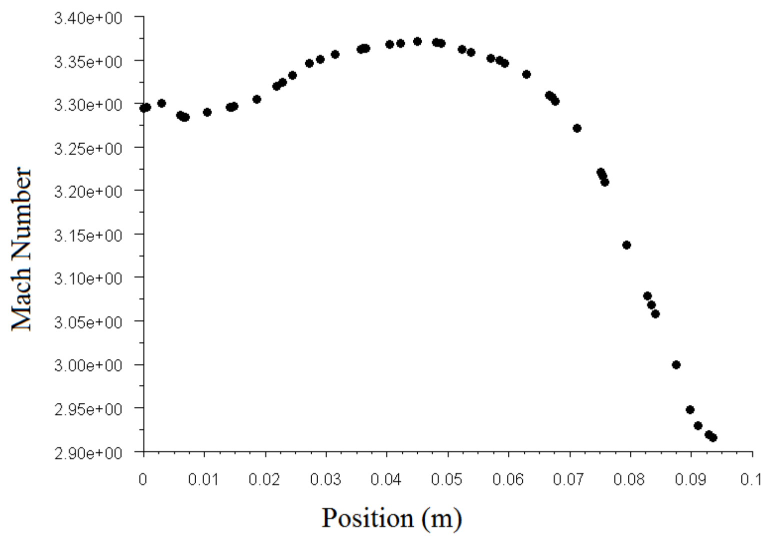


**Figure 8:** Radial distribution of the Mach number on the section $\in_{inj} = 32$ (case with fluid injection).

For thermal aspect, we examines the evolution of the static temperature of the divergent wall, in the downstream of the injection point until the nozzle's outlet. The cooling efficiency is expressed via a dimensionless factor that measures the relative difference between the wall's temperature $T_{div}(x)$, the temperature of the cooling film $T_{Coolant}$ and the total temperature of the burned gas $T_{ch}$, as [4]:

$$\eta_{cooling}(x) = \frac{T_{ch} - T_{div}(x)}{T_{ch} - T_{coolant}} \qquad (5)$$

Figure 9 shows the distribution of the index of cooling efficiency in the downstream extension of the injection zone.

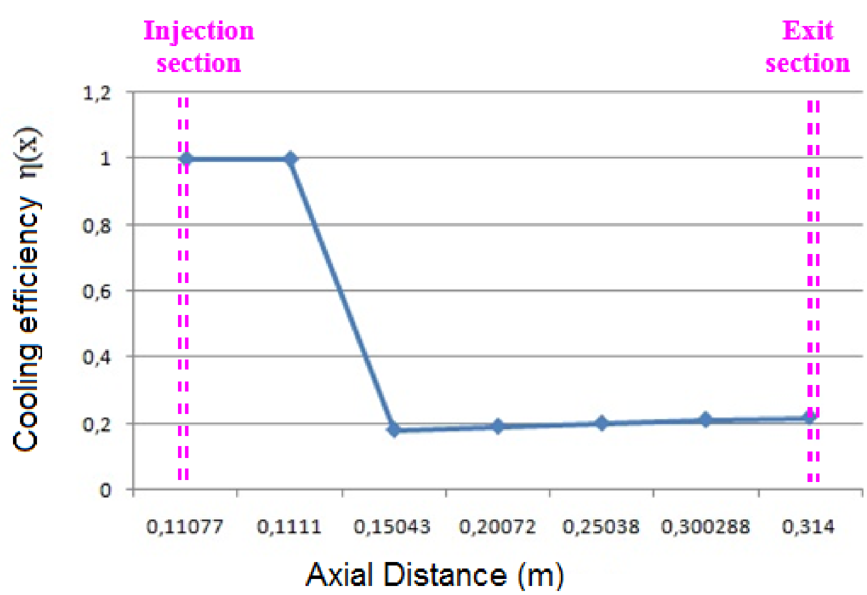


**Figure 9:** Distribution of the cooling efficiency index.

It is noticed over an axial distance of 110 mm (35% of the divergent length) from the injection point, the efficiency index maintains a unit value, which reflects equality between the wall temperature and that of the fluid cooling. The wall temperature starts to be affected by that of the burned gas inducing a sudden drop in efficiency index at 60% in the area limited to 150 mm. The injection conditions does no longer permit to ensure good cooling of the Divergent wall's remaining portion, where there has been efficiencies of about 20%. Although, the thermal effects of the fluidic injection are not very experienced at the ejection section of the nozzle, the Mach number at the outlet was slightly increasing (1.1%) comparing to its value in the uncooled configuration (Figure 10).

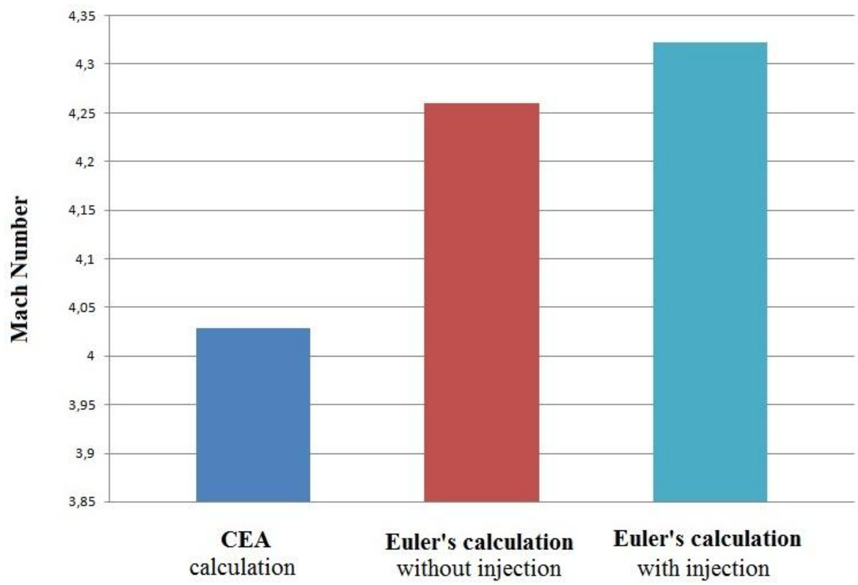


**Figure 10:** The Mach number at the nozzle outlet.

The small portion of the injected flow, allows to contribute to a slight improvement in the ejection thrust level. In order to improve the cooling efficiency without disturbing the overall mixture ratio of the static pressure, it is proposed to decrease the output of the injection orifice. Examination of the curves of (Figure 11), shows that the decrease in pressure has the effect of delaying the heating fluid adjacent to the wall of the divergent.

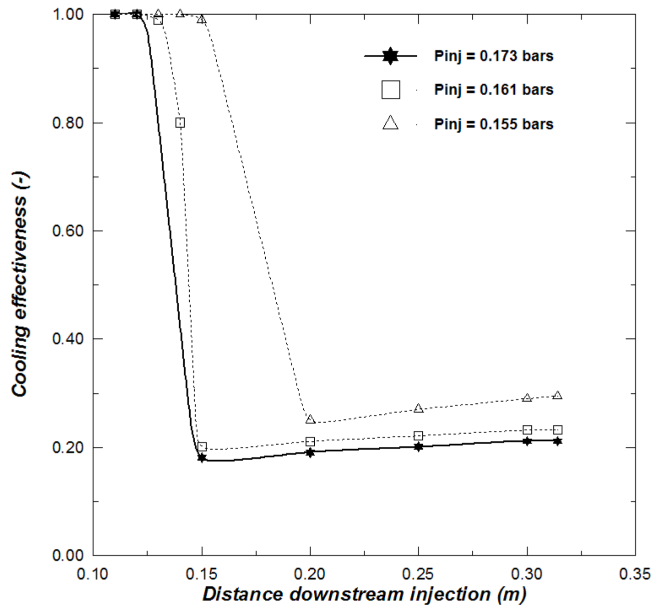


**Figure 11:** The cooling efficiency in the post-injection area.

Indeed, the cooling efficiency maintains a unit value up to distances of 130 mm and 150 mm, to respective pressures of 0.16 bar and 0.15 bar. After this area, the wall temperature increases significantly, causing a decrease in the level of efficiency in 20% - 25%.
A quasi-asymptotic trend is noted on the distribution of the cooling efficiency and, due to the low temperature variation in the near wall of the divergent, as and as we approach the section of ejection.

## 5 CONCLUSION

A numerical simulation was conducted on the thermal environment in a propulsive nozzle model subjected to fluidic injection. The calculations show the flow's importance of the injected fluid and the pressure at the outlet of the injection orifice. The injected flow is limited by several considerations of flammability of the mixture, the small fraction (4%) allows a slight improvement of the Mach number at the ejection, while it preserves a low wall temperature for a distance approaching 30% of the length of the divergent. The diffusion of the fluid temperature in the bottom of the flow is relatively improved with an injection pressure close to 0.15 bars, since cooling efficiencies around 90% are insured 150 mm downstream of injection port.

## NOMENCLATURE

| | |
|---|---|
| $A$ | section's Area |
| $Cp$ | Heat capacity at a constant pressure |
| $M$ | Mach number |
| $\dot{m}$ | Mass flow in the nozzle |
| $mr$ | Mixing ratio of the propellants |
| $Mw$ | Average molecular weight |
| $P$ | Static pressure |

| | |
|---|---|
| $rg$ | Constant mass of the mixture |
| $T$ | Temperature |
| $V$ | Module of the velocity vector |
| **Greek symbols** | |
| $\eta$ | Cooling Efficiency Index |
| $\in$ | Area ratio |
| $\gamma$ | Isentropic ratio |
| $\Gamma$ | Variable Function of $\gamma$ |
| **Indexes** | |
| coolant | Cooling film |
| ch | Combustion chamber |
| div | Divergent nozzle |
| e | Ejection Plan |
| inj | Fluidic injection plane |
| t | Nozzle's collar |
| **Acronyms** | |
| CEA | Chemical Equilibrium and Applications (calculation code) |
| JANAF | Joint Army Navy Air Force (organization) |
| NPR | Expansion ratio |
| TOC | Thrust Optimized Contour |

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