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# A quasi neutral approach to simulate plasma-assisted combustion in supersonic flow.

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## Abstract

The primary objective of this study is to establish a numerical strategy for simulating a supersonic combustion chamber where plasma is utilized to ignite combustion. Following a description of the methodology based on the quasi-neutrality hypothesis for simulating the plasma, simulations are conducted in non-reactive and reactive conditions. Qualitative comparisons are made with an experiment for non-reactive case. A second simulation aims to predict outcomes for future experimental investigations.

## 1. Introduction

The development of vehicles flying at Mach 5 requires the design of combustion chambers that can provide sufficient thrust. One of the most promising technologies is the scramjet (supersonic combustion ramjet). In these chambers, the flow remains supersonic, and the residence time is extremely short. Utilizing systems to hold combustion is essential. Typically, passive [1], these systems mainly consist of pylons or cavities, with parallel usage of both being a common approach.

More recently, active systems have begun to emerge, leveraging technologies such as microwaves, laser applicators, or plasma. The latter, known as Plasma-Assisted Combustion (PAC), is the focus of this study. PAC can be based on either extremely short repetitive discharges, often referred to as nanosecond repetitive discharges (NRP), or continuous electrical arcs [2]. The advantage of the former lies in their ability to deliver high instantaneous power and facilitate the creation of radicals beneficial for combustion. In contrast, the latter allows for higher average powers.

To simulate the interaction between plasma and combustion, a numerical tool capable of modeling the mechanical, thermal, and energetic effects of plasma on flow is necessary. This requires the characterization of the plasma model to be used. For rapid discharges, the electric field is crucial, necessitating a local modeling of charge distribution. This type of resolution relies on solving Poisson's equation and demands highly refined spatial and temporal discretization. Arcs are predominantly simulated using the quasi-neutrality hypothesis, which enables the solution of a current equation requiring less stringent discretization. This study will focus on the means of simulating electrical arcs in reactive supersonic flows.

## 2. Numerical approach

### 2.1. Navier Stokes approach

Various combustion chamber simulations necessitate adequate prediction of flow dynamics. To achieve this, it is crucial to employ a reactive and compressible fluid mechanics code. For our calculations, we utilize the Cedre code developed at ONERA, which has been validated across multiple reactive cases [3].

The power deposited by the plasma will be substantial. Consequently, reliable thermodynamics up to at least 10,000 K is essential. In our approach, the use of interpolation polynomials enables the computation of thermal capacity.

### 2.2. Electrical approach

With the fluid part previously resolved, we now need to calculate the impact of the plasma on it and the transport of the latter. The first hypothesis made is to assume quasi-neutrality of the medium by imposing that each cell has an equal amount of positive and negative charge. A second hypothesis is added, considering that electrical phenomena are instantaneous compared to fluid phenomena. Under these two hypotheses, it is possible to solve a current equation.

To solve this equation, it is necessary to know the electrical conductivity of each cell. An additional hypothesis is required to evaluate this magnitude, assuming that thermodynamic equilibrium is reached (at least for the charged species responsible for electrical conductivity). In this way, for air, it is possible to evaluate conductivity as a function of temperature and pressure using Capitelli's tables [4].

The equation to be solved being stationary, it is not influenced by the time step. Therefore, it will be possible to use the same time step as for the fluid resolution. The spatial step is more complex to determine with this type of modeling. The simulated electrical arc must be described using several cells in this diameter. The characteristic dimension retained in combustion chamber conditions is on the order of 100 microns. To perform these operations, we use TARANIS, a finite volume solver developed at ONERA.

### 2.3. Coupling resolution

The two codes used to solve the equations have been described. Since the equations are not independent, a coupling mechanism must be implemented. A strong coupling approach, solving both fluid and electrical equations in a single step, is potentially feasible but raises issues with coupled sub-variables. Instead, a weak coupling based on the CWIPI library has been established. Figure 1 illustrates the functioning of this coupling.

- Fluid Equation Resolution: The first step involves solving the fluid equations. The resulting pressure, temperature, and velocity fields are transmitted to the electrical solver.
- Electrical Solver Input: The pressure and temperature fields are used to calculate the electrical conductivity of the voxels. Once the current is computed, the velocity field is employed to evaluate the Laplace forces and Joule effect.
- Coupling Output: Through the coupling, a force and volumetric power can be transmitted. These terms are treated as source terms in a new resolution of the fluid equations.
- Iterative Domain Evolution: Iteratively, the domain can evolve, with plasma effects accounted.

For this type of coupling to be conservative, the meshes used in both solvers must be identical. Without this characteristic, a slight modification of the plasma energy is observed. Consequently, the region where the plasma is present is often the most refined, leading to a reduction in the time step for flow resolution.

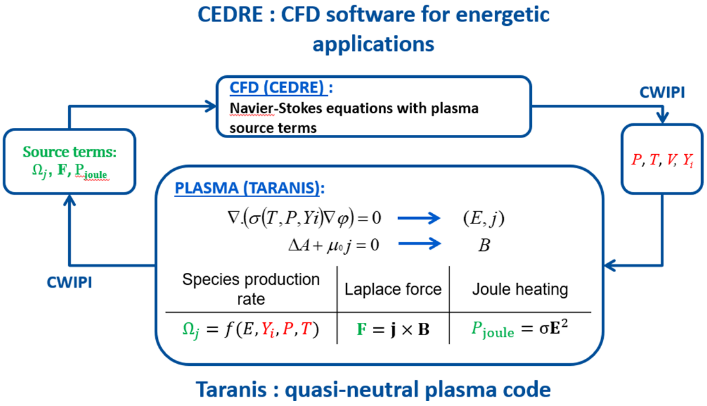


**Figure 1 : numerical schematic used**

### 2.4. Restrike model

The proposed modelling approach is limited to describing the behavior within the arc when it can be considered as a thermal plasma. With this approach, the convective extension of the arc is well accounted. However, a crucial phenomenon missing from the modelling is the possibility of arc breakdown or cutting.

Arc breakdown occurs when the local electric field is sufficiently high to initiate a streamer (non-equilibrium discharge). If this streamer connects to a conductive region, the resulting current can heat up this new pathway. Upon sufficient heating, it can transition and become an arc. This new path will reduce the size of the original arc. This physical evolution is illustrated in Figure 2.

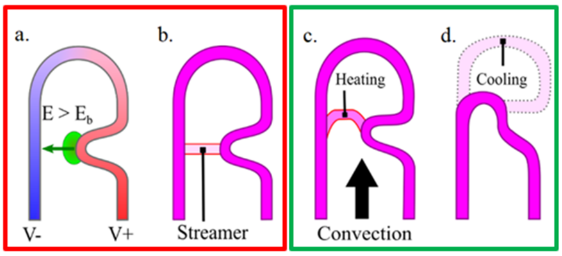


**Figure 2 : restrike phenomena**

A macro-model, as described by Bourlet et al., has been integrated into the simulations. This model involves initiating a channel from the region with an electric field exceeding the breakdown field in the medium. The channel is initialized with a constant conductivity, allowing for current new path. If it transitions to an arc before the channel's decay, the arc structure is modified, resulting in a reduction of its size. Without this modelling approach, there are no constraints on the discharge size, leading to uncontrolled growth until it either exits the domain or is reduced in size by turbulent effects.
The proposed numerical approach has the merit of being relatively simple, significantly reducing the physical description of the plasma. This simplification enables a more straightforward and efficient simulation of arc dynamics.

## 3. LAPCAT experiments

### 3.1. Rig configuration

LAPCAT is a facility enabling supersonic combustion experiments. The setup consists of a burner system, a feeding nozzle, a combustion chamber, and an exhaust system for burned gases. The burner system heats the incoming air using hydrogen combustion, achieving temperatures between 300 K and

1700 K. The used nozzle is a 2D nozzle providing a Mach 2 flow. The setup has a total length of 1 meter with a very slight expansion to compensate for combustion and prevent thermal blocking.

Generally, hydrogen injection for supersonic combustion occurs 200 mm after the nozzle's throat. The wall-injected fuel mixes with preheated air. When the initial temperature is sufficient (approximately 1500 K experimentally), the ignition delay time is short enough for combustion to occur within the chamber. This facility has also been used to test a plasma applicator. Different series of experiments enabled the imaging of plasma with and without crossflow.

The strategy followed in the remainder of this article is to initially validate the modeling approach described before using the experimental plasma applicator in a non-reactive scenario. Subsequently, a numerical prediction will be made on a different geometry in anticipation of future reactive experiments.

### 3.2. Numerical simulations

For numerical simulations, both geometries are based on the downstream section of the burners, nozzle, and supersonic part of the duct. In Figure 3, the low-speed inlet (red) corresponds to the burner exit. Depending on the simulation, the temperature is either 1700 K or 1400 K. The blue walls will be meshed using a boundary layer mesh type. A temperature of 700 K is typically used to replicate wall conditions during experiments (simulate the zirconia effect). A supersonic outlet (green) is utilized.
The plasma applicator is positioned at 0.2 m for both simulations: First Case - Coaxial, air-fed at 300 K, Second Case - Hydrogen-fed, enabling combustion within the duct.

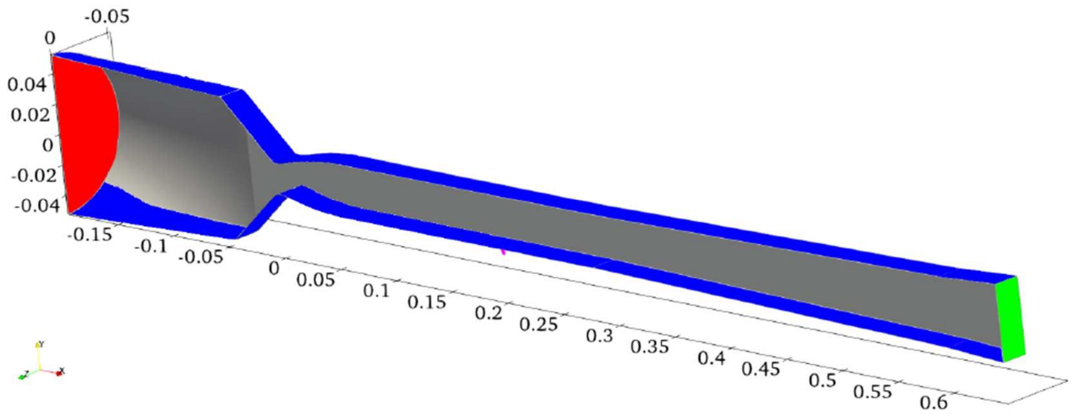


**Figure 3 : LAPCAT geometry**

For the electrical resolution, the boundary conditions are as follows. The applicator electrode delivers a constant current. The blue wall is considered a conductive wall remaining at electrical ground potential. The current will be transmitted between these two surfaces via the electrical arc to be simulated.
Despite differing compositions between the two simulations (presence of hydrogen), the electrical conductivity remains based on d'Angola's interpolations. When the arc interacts with hydrogen, it will slightly alter the energy deposition (conductivity modification) but won't change the arc shape. In consequence, these simulations require future improvements.

## 4. Plasma with air injection

### 4.1. Injector and conditions

For the non-reactive case, the applicator is of a coaxial type [5]. The anode is connected to a direct current (DC) generator, with a maximum current of 5A, although most experiments are conducted at 3A. The cathode is grounded. The insulation between the two electrodes is relocated inside the injector, ensuring the insulating material is not exposed to high temperatures and enhancing system robustness. Air is injected between the cathode and anode. A voltage of approximately 3kV (maximum of 5kV) is applied to initiate the first arc. Figure 4 illustrates the mesh used for simulation, with refinement in the region where the arc propagates.

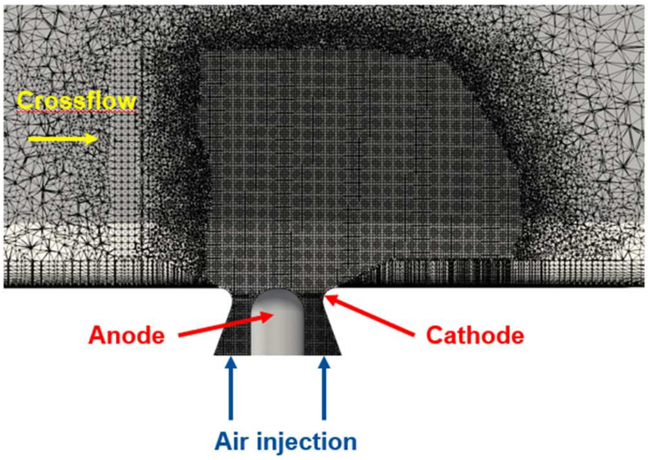


**Figure 4 : mesh used for non-reactive case**

Without crossflow, the arc is vertical, measuring between 1 to 2 cm in length that is higher than refined area. The configuration of interest for simulation involves the presence of crossflow. A barrel shock will be visible at the air injection point and reduce arc penetration in the rig. Consequently, the arc will be located on the downstream side of the injector and assume a curved shape, conforming to the flow.

### 4.2. Arc with restrike

Simulations with air injection and crossflow enable the identification of a curved arc compatible with the flow structure. Figure 5 presents the temperature field. The first observation is that the temperature exceeds 5000 K within the arc, consistent with spectroscopic measurements on arcs. The color scale also reveals the presence of a barrel shock (warmer zone upstream of the injection). The arc positions itself between the central electrode and the downstream flow, in an area where mixing is relatively significant, potentially suitable for initiating combustion in the chamber upon fuel injection.
The last visible point on this image is the re-strike initiating in the middle of the arc. Similarly to the experiment, the phenomenon occurs between the two legs of the arc. This particularity is due to the higher pressure at the injection level, which reduces the electric field, leading to a reduced breakdown voltage

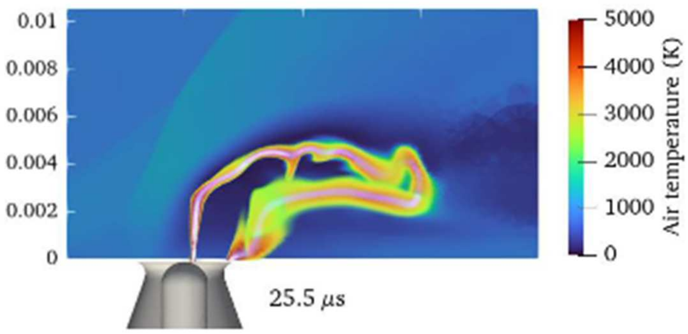


**Figure 5 : temperature field with arc reconnection.**

### 4.3. Comparison experiment simulation

Figure 6 presents the arc obtained from experiments on the left and a simulated arc on the right, both captured with flash photography or realistic visualization. On the left, the difference in brightness between the lower and upper parts of the arc is due to extinction during sensor integration (acquisition frequency on the order of 100 kHz). The obtained dimensions are similar between experiments and simulations, however, a small difference in shape exists between the two. The simulation produces arcs that are slightly longer and less inclined. The length is likely due to the flashing model not being perfectly adjusted. The shape difference is probably due to the use of a RANS turbulence model, which alters the mixing between the very hot zone and the rest of the medium.

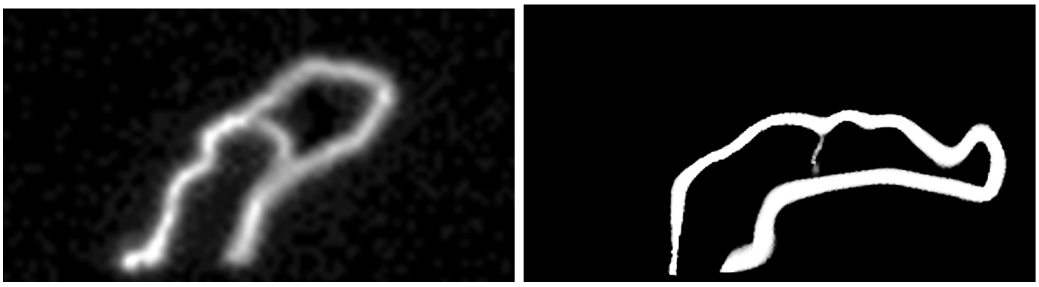

**Figure 6 : left : experimental photography of the arc, right : realistic visualization of the simulation.**

Nevertheless, these initial simulations demonstrate the ability of the developed tool to simulate electrical arcs in supersonic flows. At the end of this first part, the tool is validated for non-reactive flows.

## 5. Plasma with combustion

### 5.1. Injector and conditions

The objective of the developed tool is to simulate plasma-combustion interaction, which necessitates a reactive flow scenario. The model and codes are compatible with this type of simulation. However, the coaxial injector used previously complicates simulations due to the significant velocity increase when switching to hydrogen. To decouple numerical difficulties from the transition to reactive simulations, a more literature-described configuration is adopted, featuring an arc farther from the fuel injection point.

The retained geometry for this study segment is developed by S. Leonov and named PIM [6]. As shown in Figure 7, the injector consists of an electrode at the injection point and a ceramic insulator surrounding it (matte color). The return to mass is achieved through the wall itself (metallic color).

This plasma injection system is positioned similarly to the previous one in the LAPCAT rig. However, the obtained arc geometry differs, with the arc located within the mixing layer between fuel and air. The Figure 7 visualizes the arc before and after re-strike. The maximum size of the simulated arc is approximately twice the insulator size, which is consistent with experimental observations described in the literature.

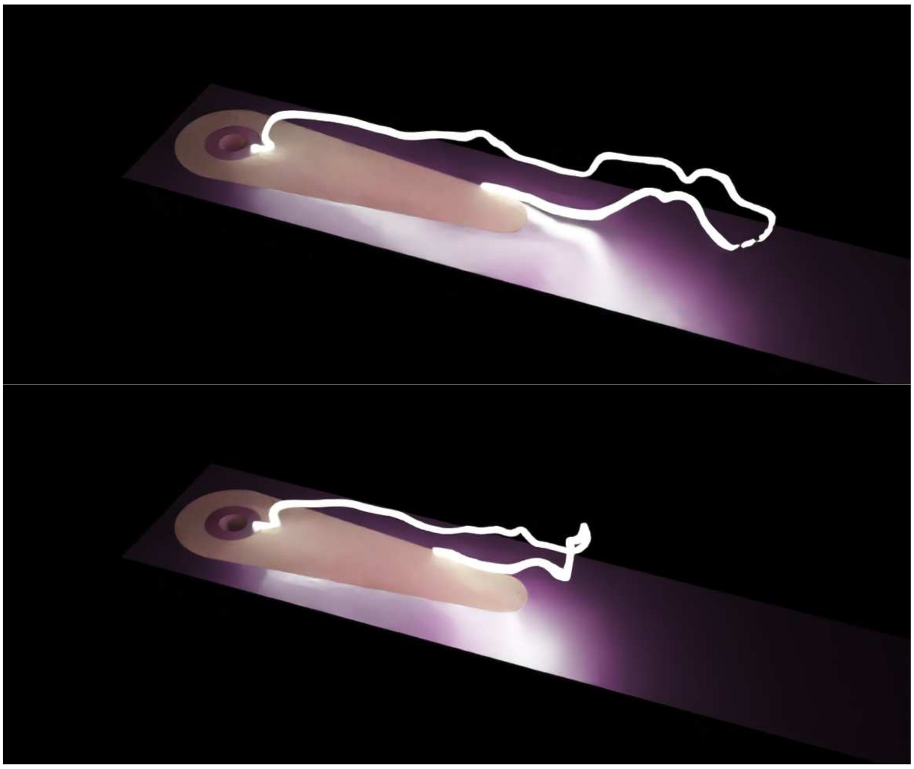

**Figure 7 : simulated arc before and after restrike with PIM geometry.**

### 5.2. Interaction plasma combustion

To estimate the plasma-combustion interaction, the rig operating conditions used are unfavorable for combustion, meaning the generated temperature is insufficient to trigger self-ignition. After stabilizing the simulation without plasma, the plasma is activated.

Figure 8 presents the integral of heat release over the fluid volume during the simulation. Before plasma activation, the heat release is effectively zero, confirming non-ignition. Activating the 5 A arc ignites combustion within 0.1 ms. As long as the plasma remains on, combustion is sustained. Upon plasma extinction, combustion ceases. Thus, the plasma has both an ignition and stabilization effect on combustion under these conditions.

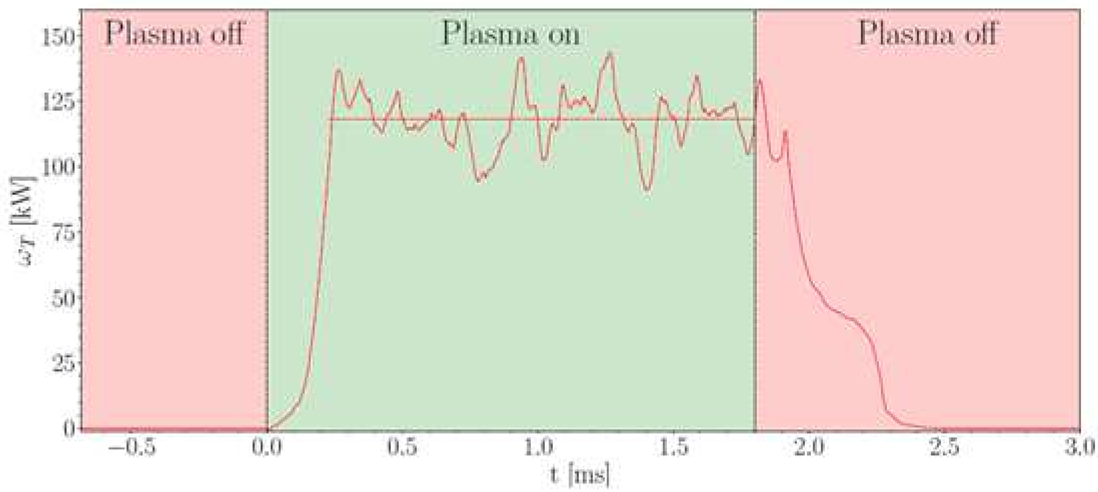


**Figure 8 : heat release integration on fluid domain.**

### 5.3. Combustion shape

At a more local scale, it is possible to visualize the volumetric heat release. Figure 9 shows the arc at the injection level in violet and the heat release. An initial phase of heat release occurs near the arc, heating an initial volume of gas. This heated gas then mixes with fresh gas, modifying the auto-ignition time. Combustion develops a few centimeters further downstream.
The arc thus has the effect of shortening the overall auto-ignition time and facilitating ignition. However, maintaining electrical power consumption is necessary to sustain combustion.

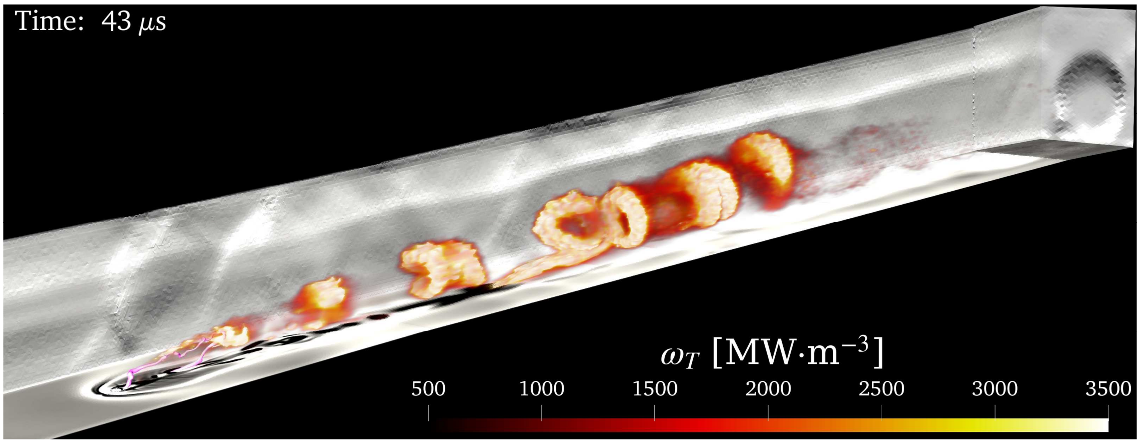


**Figure 9 : volumetric heat release**

## 6. Conclusion

The implemented numerical strategy enables the simulation of plasma-combustion interaction, accounting for the dynamics of the electrical arc. The quasi-neutrality hypothesis-based resolution demonstrates interesting efficiency while qualitatively reproducing the experimentally observed results. This strategy is also compatible with reactive flows and allows for the computation of plasma-assisted combustion in supersonic conditions.

## References


- Journal article

1. CHOUBEY, Gautam, PATEL, Om, SOLANKI, Malhar, *et al.* Influence of cavity floor injection strategy on mixing improvement study of a splitter plate-assisted supersonic combustor. *Engineering Analysis with Boundary Elements*, 2023, vol. 155, p. 995-1012.
2. Leonov, S. B., Elliott, S., Carter, C., Houpt, A., Lax, P., & Ombrello, T. (2021). Modes of plasma-stabilized combustion in cavity-based M= 2 configuration. Experimental Thermal and Fluid Science, 124, 110355.
3. PELLETIER, Guillaume, FERRIER, Marc, VINCENT-RANDONNIER, Axel, *et al.* Wall roughness effects on combustion development in confined supersonic flow. *Journal of Propulsion and Power*, 2021, vol. 37, no 1, p. 151-166.
4. CAPITELLI, Mario, CELIBERTO, Roberto, COLONNA, Gianpiero, *et al. Fundamental aspects of plasma chemical physics*. Springer New York, 2016
5. Vincent-Randonnier, A., Mallart-Martinez, N., & Labaune, J. (2024). Design of a plasma-assisted injector: Principle, characterization and application to supersonic combustion of hydrogen. *International Journal of Hydrogen Energy*, *88*, 1410-1421
6. Leonov, S. B. (2018). Electrically driven supersonic combustion. *Energies*, *11*(7), 1733.