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Numerical model of restrikes in DC gliding arc discharges

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Plasma-assisted combustion (PAC) is a promising technology that could lead to a breakthrough in propulsion systems. Many plasmas can be used for such applications. Among them, DC electric arcs are interesting because they can produce large volumes of thermal plasmas with controlled energy deposition. When such discharges are applied in a gas flow, convection entrains the head of the arc downstream while its feet remain attached to the electrodes, thus increasing the length of the arc over time. However, this growth is limited by a restrike phenomenon, which starts from streamers appearing in high electric field regions and shortcircuiting the long, stretched electric arc. From a numerical point of view, DC arcs can be efficiently simulated with a resistive magneto-hydrodynamics (MHD) model, with numerical requirements in terms of spatial and temporal discretization that are compatible with classic CFD and combustion simulations. However, arc restrikes rely on the propagation of streamer discharges that are highly non-neutral phenomena, whereas classical MHD assumes neutrality. To tackle this problem, we propose in this paper a model of restrike that can be used in an MHD approach. The model is based on the current knowledge about the physics of streamer discharges. After the description of the core ideas of the model, we perform a parametric study of the input parameters to examine the influence in the discharge dynamics.

I. Introduction

Adding a plasma in a reactive flow is a promising way to enhance combustion stability and ignition for propulsion applications. Different kinds of plasmas can be used [1], such as repetitive nanosecond discharges [2], DC filamentary gliding arcs [3, 4], or microwave discharges [5]. These discharges have the ability to enhance combustion and ignition, but the underlying discharge effects may differ. Contrary to other plasma technologies, due to their ability to stretch over large distances, DC electric arcs make it possible to generate large volumes of high-temperature thermal plasmas of the order 5000-10000 K. Moreover, by tuning the current intensity level, the maximum voltage, and the geometry of the electrodes, it is possible to efficiently control the total energy deposited by the discharge, which is one of the key parameters to reliably trigger combustion. In flowing gas streams, the DC arc discharge exhibits a restrike mechanism, caused by fast propagative cold discharges called “streamers” [6, 7]. The conditions for streamers formation can appear when the flow stretches the arc, because the electric field between the electrodes and the arc branches increases with the arc length. When the electric field reaches the breakdown field, a streamer can bridge the gap separating the two arcs branches; then, it may ignite and propagate at velocities around 10^6 m/s until it reaches the electrode or the arc channel, providing a shortcut to the electric current. Then, the temperature of the streamer

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channel may increase due to Joule heating, leading to the formation of a new arc channel while the old current path cools down and disappears in the absence of a sufficient amount of current. This restrike phenomenon directly influences the maximum spatial extension of the DC arc and then the volume fraction of the reactive flow that may interact with the hot plasma channel and experience ignition. Modeling this complex phenomenon is crucial because it determines the overall efficiency of DC-arc plasma-assisted combustion technology.

From a numerical perspective, the simulation of arc discharges in flows is an active research field. Notably, some of the difficulties met in thermal plasma-assisted combustion codes are the need for proper plasma-assisted combustion chemistry models, arc-electrodes interaction models, turbulence models valid in the arc region. More generally, numerical methods must be adapted to address the peculiarities of arc discharges in CFD codes. A widely used approach to model thermal equilibrium plasmas is the resistive magneto-hydrodynamics approach (MHD) [10,13]. This approach has the advantage of being computationally fast because it allows spatial and temporal discretizations compatible with classical CFD and reactive flow simulations in combustion chambers. However, MHD assumes the quasi-neutrality of the plasma, which is incompatible with the physics of streamer formation. For that reason, and because streamers may play an essential role in the restrike phenomenon, a macro-model of arc restrike is needed to retrieve the dynamics of the arc observed in experiments [8, 9].

A few models of restrike have been developed in the past, especially in the plasma torch community [10-12] and the lightning protection community [14]. These models can effectively reproduce the reattachment of the arc to the electrode. However, the existing models are based on geometrical assumptions imposing electrical breakdown when the arc is close enough to the electrode. This lack of generality makes them incompatible with other geometries, and they cannot model the arc-to-arc restrikes observed in experiments, which may occur in many different locations. This study proposes a model based on streamer physics, which does not rely on any geometrical assumptions. The proposed model is therefore quite general and intended for any configuration or application where restrike phenomena occur.

The first part of this article is a reminder of the resistive MHD approach and the numerical method implemented in this study to couple the physics of electric arcs with a CFD solver. The second part is dedicated to describing the restrike model and its effects on an arc discharge. Then, in the third part, a sensitivity analysis is conducted on the model's input parameters for the well-documented gliding-arc configuration of Ref. [9].

II. Numerical strategy

Solving the interaction between an electric arc and a flow remains today a complex numerical task. The main difficulty when solving the resistive MHD equations is related to the different nature of the equations that must be solved for fluid dynamics and electromagnetism. Reactive flow physics requires solving the compressible Navier-Stokes equations, which are hyperbolic for the eulerian part and parabolic for diffusion processes. On the other hand, the electromagnetic fields must be computed to deduce the magnetic forces and the Joule effect. In most cases, the electrostatic equation is replaced with several elliptic Poisson-type equations to be solved. Here, two different and dedicated codes are coupled to address these difficulties: CEDRE and Taranis.

The Navier-Stokes equation is solved using CEDRE [15], a CFD code mainly developed at ONERA for energetic and aerodynamic applications. CEDRE can receive local source terms from an external program by using the CUIPI library [15]. This ability to exchange source terms is exploited in this study to include all the plasma-related source terms in Cedre, namely the Joule effect, Laplace force, and electric-field-dependent species production rates. These source terms are computed with the second code, Taranis that can solve the electromagnetic fields and plasma properties. The coupling between Cedre and Taranis is summarized in figure 1. The combination of the two codes allows the simulation of resistive MHD plasma in a compressible flow. For more details about the coupling strategy for the plasma simulations with Cedre, please refer to Rassou [16].

The coupling between Cedre and Taranis allows many different levels of approximation for the plasma simulation and the computation of the fields. In this study, owing to the timescales of interest and the current intensity level, several assumptions have been made as a first step:

- We consider the plasma as an air-fluid in local thermodynamic equilibrium (LTE);
- Fluid properties are tabulated from the relations of Angola's work [21] and depend only on temperature and pressure;
- Boundary layers around the electrodes are not taken into account;
- Radiative transfer and magnetic forces are assumed to be negligible due to the low current intensity level;
- The electric field is computed within the electrostatic and quasi-neutral approximation:

$$\nabla \cdot (\sigma \nabla V) = 0$$

Further work will be needed to precisely assess the impact of these assumptions, but they seem reasonable for the low current DC electric arcs of interest in this study.

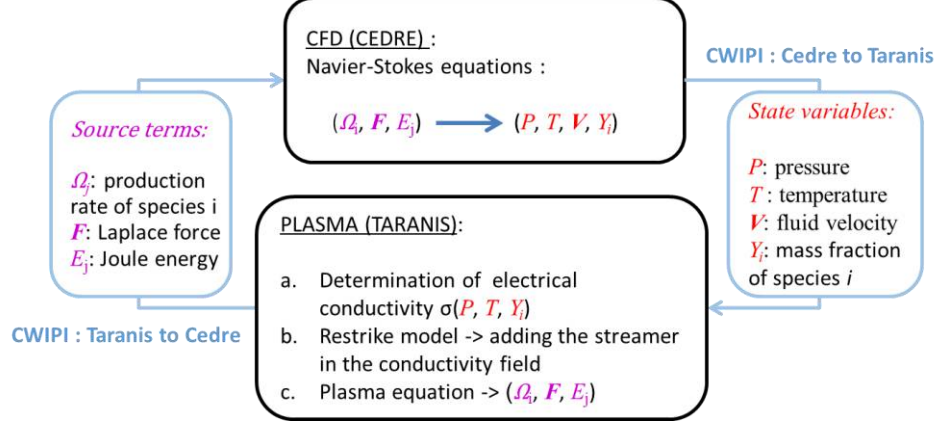


Fig. 1: Coupling strategy at each time step between CEDRE and TARANIS for solving MHD plasmas

III. Restrike model

Restrike cannot be simulated in typical CFD applications. Indeed, a streamer is a nanosecond scale phenomenon that requires a time step of 10^{-12} s in a multi-fluid drift-diffusion approach [17]. This tiny time step is related to the velocity of streamers (10^6 m/s) and the need to compute the field for every dielectric relaxation time, which is the characteristic time for the evolution of space charges. Such an approach accurately describes the streamer but fails when the streamer-to-arc transition occurs because the increase of the electron density induces a fast decrease of the dielectric relaxation time, leading to a prohibitive computational cost [18]. In the specific case of an electrical arc, quasi-neutrality is very reasonable due to the high electron density; in this case, the Debye length, which is the typical size of space charges, is much smaller than the radius of the arc. The quasi-neutral MHD description presented previously is then well adapted for this discharge regime, and the dielectric relaxation time is no longer taken into account, but streamer discharges cannot be simulated.

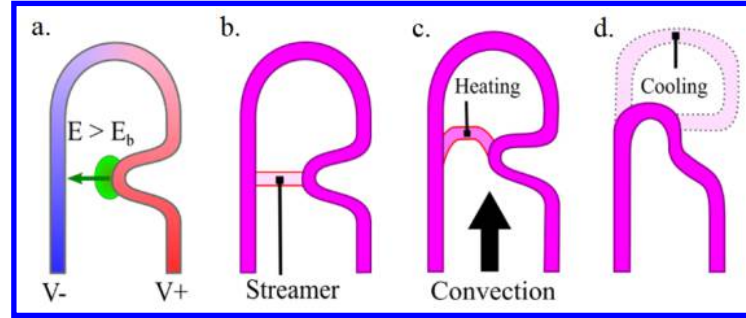


Fig. 2: restrike dynamics, (a) local high electric field, (b) streamer channel after propagation, (c) heating of the channel to arc transition, (d) cooling of the pre-existing arc channel.

The restrike model presented in this study intends to simulate with a reasonable approximation the streamer onset and propagation phases before the arc transition. Streamers are a big topic in the cold plasma community; the review by Nijdam [19] provides typical values for streamer properties that have been considered in this study for the

derivation of the restrike model. Figure 2 presents the key steps during a restrike phenomenon. At first, in Fig.2a, an electric field exists in the gap separating the branches due to the voltage difference between the two arc branches. The electric field is amplified in some places due to the proximity of the branches and local curvature (green area in Fig.2a). The electric field may exceed there the breakdown field, which may initiate a streamer discharge. The streamer bridges the gap from one arc branch to the other at 1 mm/ns [19], leaving a conductive plasma channel in its trail, as shown in Fig.2b. As the current flows through the channel, the plasma heats up, and an electro-thermal instability may occur when temperature increases, leading to increased conductivity. Then more current flows in the channel, leading to an even higher temperature increase and so on. The result is a transition from the cold-plasma streamer regime to the thermal plasma electric arc regime in Fig.2c. The new arc channel now shortcuts the pre-existing one, as it is a path of less resistance for the current. The current redistribution from the old channel to the new one decreases the Joule effect in the former. Then, the old channel cools down due to thermal diffusion, radiative transfer, and convection, and it finally disappears, as shown in Fig.2d.

The difficult part of the restrike dynamics in CFD corresponds to the streamer initiation and the streamer propagation (transition from Fig.2a to Fig.2b), whereas an MHD solver can handle the evolution of an established streamer channel (from Fig.2b). The model we are developing here targets that difficult part by searching potential streamer initiation places, evaluating its trajectory, and adding a representative streamer channel. To do that:

1. For streamer initiation, we assume that the streamer is initiated in a cell at the moment when the reduced field E/N is locally more important than the breakdown-reduced field, corresponding to 125 Td in air. If this condition is met in multiple cells, we choose the cell with the maximum reduced field as the streamer starting point.
2. We assume that the streamer follows the electric field lines during its propagation. This assumption is consistent with the experimental and numerical evidence that streamers preferably propagate along field lines. It is particularly true for short gaps, but branching phenomena may occur for longer gaps, leading to a more statistical distribution of the streamers around the field lines. In the presented results, the gaps are small enough to assume that branching is unlikely, and it does not seem to occur in observations. To compute the streamer propagation, we simply compute the electric-field line. The terminal condition of the propagation corresponds to a high-conductivity cell, which is physically a cell from an electrode or the arc discharge. The value of the conductivity threshold is defined as an input parameter.
3. When the trajectory of the streamer is found, we add to the electrical conductivity field the conductivity of the streamer channel. This channel is a succession of defined conductivity cylinders that follow the computed field line. The conductivity and radius of the cylinders are input parameters. The streamer is maintained, and the flow field convects it through multiple iterations until its temperature is hot enough or during a maximum duration corresponding to a third input parameter.

The different input parameters of the model are summarized in table 1.

Phase of the streamer evolution	Input parameters
<i>Streamer initiation</i>	<i>Breakdown reduced field</i>
<i>Streamer propagation</i>	<i>Conductivity threshold</i>
<i>Streamer-arc transition</i>	<i>Channel conductivity</i>
	<i>Channel radius</i>
	<i>The time limit for the arc transition (Decay time)</i>

Table 1: Input parameters of restrike model

In practice, the conductivity threshold and channel conductivity are set to the same value. This value is the typical conductivity of the streamer channel in atmospheric pressure air, corresponding to 1 S/m [20]. The channel radius also corresponds to the typically observed radii in air for a centimeter-long streamer, 300 μm [19]. The time limit for the arc transition corresponds to the lifetime of a streamer channel in air in the absence of an arc transition. This lifetime is complex to address since it depends on plasma chemistry: attachment, recombination, fast heating mechanisms, vibrational relaxation, amount of current and electric field in the channel, and the interaction with the flow. To set this value in the presented simulations of gliding arcs, we have estimated the maximum lifetime of streamer channels to

be around 100 μs based on fast camera video of gliding arcs from Zhu's work [9] produced in similar experimental conditions.

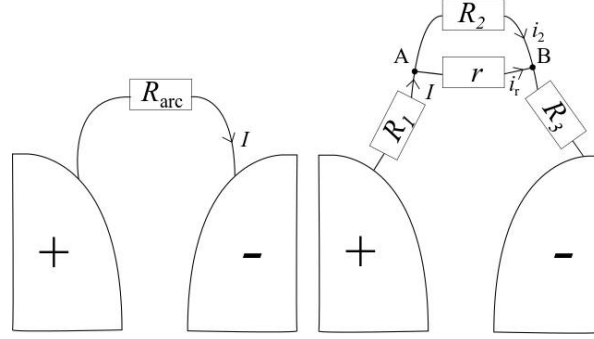


Fig. 3: simplified electric scheme of an electric arc and an electric arc with a streamer

Streamer breakdown in a gliding arc discharge can be viewed with a circuit representation of the plasma (Fig.3). In this representation, the letter R represents the resistance of the arc, and the subscripts indicate different segments of the arc and the resistance of the streamer channel is r . For an arc discharge, the resistance of the plasma decreases non-linearly as the temperature increases. The power supply may also have crucial importance on the restrike dynamics since it may control the maximum energy deposition. In the following analysis, the generator is considered to be an ideal current source of intensity I . When no streamer channel is present, the arc resistance is:

$$R_{arc} = R_1 + R_2 + R_3$$

When the streamer has bridged the gap, it acts as a resistor in parallel with part of the arc. This part corresponds to the branch of resistance R_2 . The new resistance of the arc becomes:

$$R_{restrike} = R_1 + \frac{R_2 \cdot r}{R_2 + r} + R_3.$$

A first observation is $R_{arc} > R_{restrike}$; according to Ohm's law, if the current I is constant, the voltage difference between the electrodes drops after a breakdown. This voltage reduction induces a proportional decrease of the electric field in the gap, which means that a second restrike is less likely to happen when one streamer channel has connected the two arc branches. Current is split into the new streamer channel of resistance r and the old arc channel of resistance R_2 according to the following relations:

$$i_r = \frac{R_2}{R_2 + r} I$$

$$i_2 = \frac{r}{R_2 + r} I$$

The streamer channel is heated by the current i_r via Joule effect, $P_{Joule,r} = r i_r^2$, whereas the decrease of the current i_2 in R_2 leads to a decreasing Joule effect that may become smaller than the cooling rate of the arc. As the temperature T rises in the streamer channel, r decreases. The resistance r is linearly dependent on the streamer channel length, so two cases are possible:

- For a short streamer channel, r will eventually become smaller than R_2 . At that point, the channel will continue to heat until its conductivity matches the arc discharge, and the R_2 -branch of the arc will disappear as the current i_2 decreases to zero.
- For a long streamer channel, r may always be higher than R_2 and the streamer will never transit to an arc discharge during its lifetime. It will decay due to electron attachment and recombination.

The occurrence of one of these two scenarios directly depends on the current density field computed by the electrostatic solver and is a result of the global MHD model. Then, some of the many streamer discharges predicted by the restrike model may not transit to an arc and fail to shortcut the discharge. This kind of aborted discharge is observed experimentally.

IV. Parametric study of restrike model's input parameters Restrike model

A. Simulation setup

Our model has been tested on 2D simulations of gliding arcs, as the literature provides many experiments on the topic, which leave plentiful data to compare with our simulation. Regarding this work, critics can be made toward the 2D constraints of the discharge and the LTE assumption, as shown in that gliding arcs tend to exhibit out-of-equilibrium behavior. However, with sufficiently high current, the LTE approximation is quite accurate. This work aims not to reproduce accurately gliding discharges but to exhibit the different behavior of the restrike model and study its influence. We present in this section a parametric study of the input parameters used in the model.

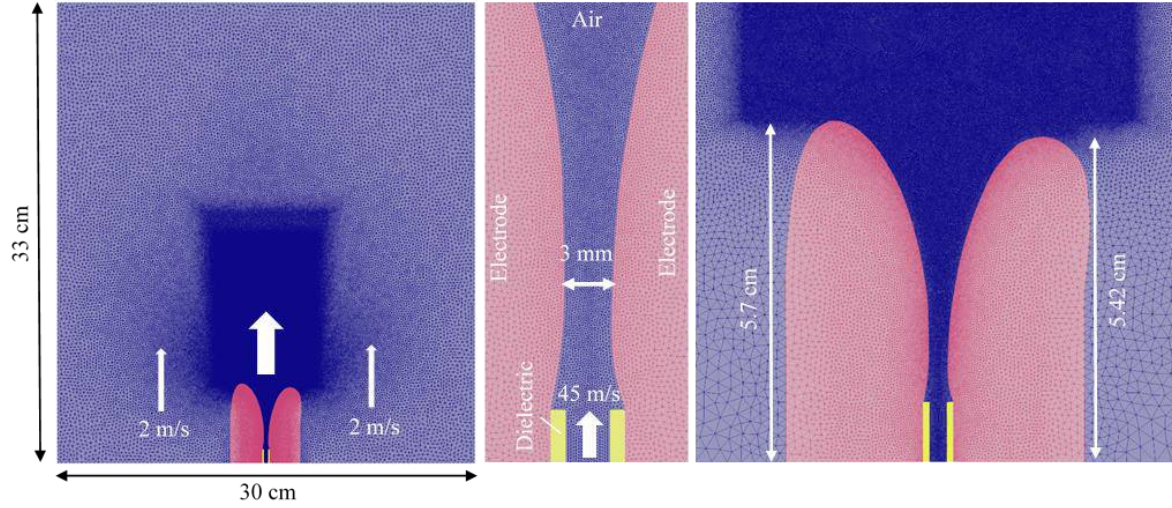


Fig. 4: Simulation setup. Left: full view of the mesh and geometry. Middle: Interelectrode gap and electrodes. Right: Close-up view of the electrodes. The mesh size in the refined region is 150 μm.

The simulation domain is represented in figure 4. It is a 2D box of 30 cm x 33 cm, containing two asymmetric electrodes at the bottom of the simulation domain, 57 and 54.2 mm in length. The gap separating the electrodes is 3 mm. The shape of the electrodes reproduces the original electrodes used in Zhu's experiments [9] to compare our results with the discharges they studied. We inject a flow rate of 17.5 SLM of air between the electrodes, leading to a flow of 45 m/s at the end of the dielectric pipe represented in yellow in figure 4. A crossflow of 2 m/s is added on both sides of the domain to help the flow computation. Concerning the electric parameters, the potential of the shorter electrodes is set at 0 V at the boundary condition, while the largest electrode has its potential computed at each iteration to ensure a constant current of 300 mA from one electrode to the other. Aside from the electrodes, the other boundaries of the simulation domain are Neumann conditions on the voltage.

Simulations	Breakdown field	Discharge radius	Conductivity channel	Decay time
Reference case 0	125 Td	300 μm	1 S/m	0.1 ms
Case 1	50 Td	300 μm	1 S/m	0.1 ms
Case 2	200 Td	300 μm	1 S/m	0.1 ms
Case 3	125 Td	150 μm	1 S/m	0.1 ms
Case 4	125 Td	600 μm	1 S/m	0.1 ms
Case 5	125 Td	300 μm	0.2 S/m	0.1 ms
Case 6	125 Td	300 μm	10 S/m	0.1 ms

Table 2: input parameters for the different simulations cases.

The different simulations performed in this study are summarized in Table 2. The base simulation has parameters corresponding to the standard value measured or computed in streamer studies of the literature. Simulations 1 and 2 show the impact of the breakdown field in the model. Simulations 3,4,5 and 6 show the effects of variations of the discharge radius and the conductivity of the channel. The decay time of the streamer is not studied in this paper.

B. Reference simulation case (case 0)

The base simulation gives results that should be the closest to the experiments, as the parameters of the restrike model are chosen to correspond to experimental measurements or computed properties of streamers in air. On figure 5, we show a sequence of images of a restrike event. At 15.80 ms, the arc head reaches 120 mm, and both feet are at 40 mm. In the timeframe between 15.80 ms and 15.92 ms, the model detects a possible streamer at $Y=50$ mm and applies a conductive channel along its trajectory. At 15.92 ms, the streamer channel has already reached a temperature of 2700 K. If the streamer channel would be at LTE, its conductivity should be $2.8 \cdot 10^{-3}$ S/m, which is far below the conductivity of a streamer, so the model keeps the conductivity in the channel at 1 S/m during the streamer transition. At 16.08 ms, the streamer has heated up to 5500 K and has a conductivity of 50 S/m; it is now an arc channel of the same conductivity as the old arc channel at 15.80 ms. However, it has a lower resistance because the new path it offers for the electrical current is much shorter than the bypassed channel arc; all the current passes through the new arc channel. Consequently, during the following millisecond, the old channel cools down due to the loss of the Joule effect, as it can be seen at 16.76 ms. With the base parameters, we retrieve the scenario we describe in Fig.2.

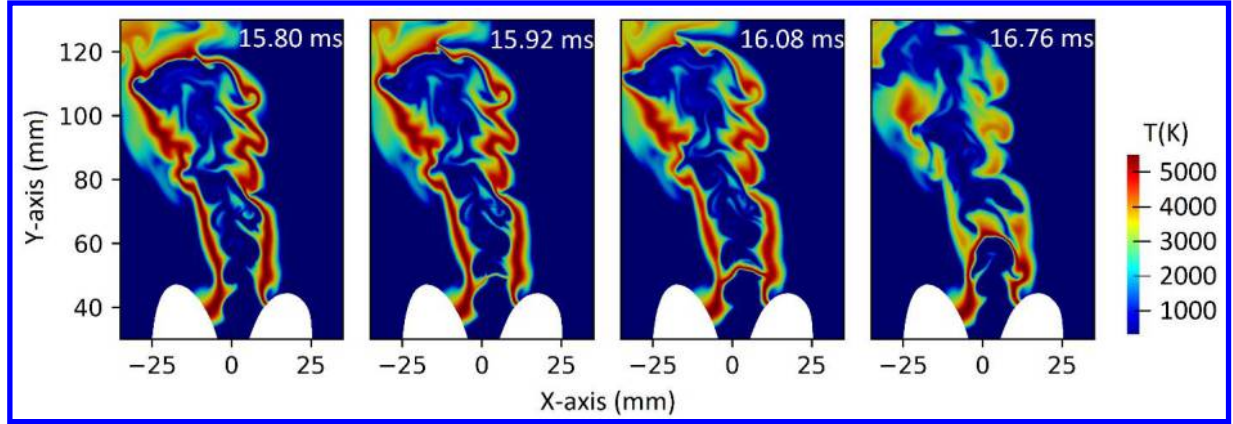


Fig. 5: Sequence showing the restrike dynamics observed in base simulation.

Fig. 8 shows an image of the average current density values for different streamer radii, integrated over 40 ms. The radius set in the base simulation is $300 \mu\text{m}$. That image can be compared with what could display a 25 fps camera. When considering the experimental reference for the simulation [9], we retrieve qualitatively similar discharge structures and spatial extension when the model is activated.

C. Influence of the breakdown field (cases 0, 1, 2)

Now, we present the effects of different values of the breakdown field with simulations 1 and 2, where the field is set to 50 Td and 200 Td. First, at 50 Td, much more breakdowns occur because the condition is more favorable. However, most of the streamers that the model trigger do not lead to a restrike. On figure 6, we present a sequence of a failed restrike. In image Fig.6a, a streamer is detected then its channel is set along the corresponding field line. Over the following iterations, the channel is convected by the flow. However, the resistance of the streamer channel is much higher than the arc resistance, so the current in the streamer channel remains at a low level, and no arc transition is made over the 0.4 ms timeframe. At 0.4 ms (Fig.6d), the algorithm detects a new maximal reduced electric field elsewhere, and a new streamer is initiated there. This test shows that if the condition is not met for an arc transition, then the streamer channel does not evolve to a new arc channel.

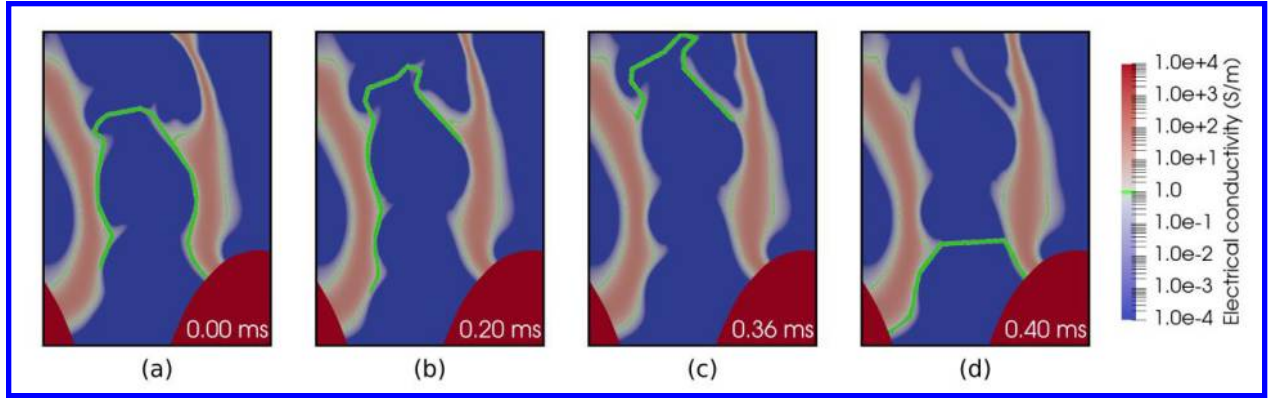


Fig. 6: Conductivity field gliding arc in the reference case of table 2. (a)-(c): A streamer channel between the two branches of the arc is present, but it does not produce a restrike. (d) A new channel is added in the place of the maximum field.

This test case shows that if the conditions are not met for an arc transition, then the streamer channel does not evolve to an arc channel. This result would not be observed if the streamer channel was directly modeled as a power source term instead of a conductive source term, as a power source term does not allow any feedback of the arc channel. Finally, for that reason, when the breakdown field is set lower, it does not drastically reduce the size of the arc discharge since, in that case, many streamers do not lead to a restrike. Considering the case of 200 Td on Fig.7, the arc grows larger than the default case (Fig.8). That is because a higher breakdown field implies that the electric field must reach a higher value, which can only be achieved if the arc branches are longer.

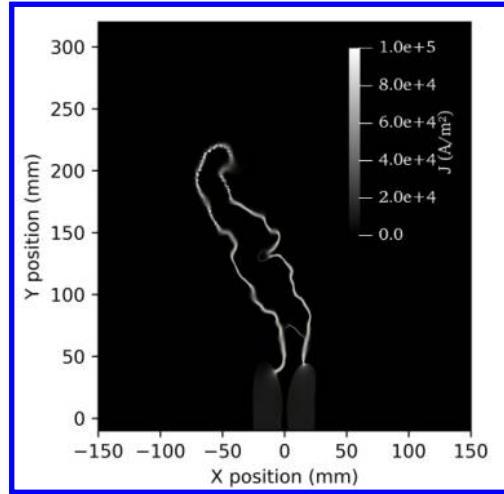


Fig. 7: Current density field in a gliding arc with a breakdown field of 200 Td. The time corresponds to the maximum spatial extension of the arc just before the restrike due to a streamer in the bottom part.

D. Influence of the streamer radius (cases 0, 3, 4)

Cases 3 and 4 were computed to see the influence of the radius of the streamers on the restrike dynamics. Three radii are considered: 150, 300, and 600 μm , corresponding to the range of values obtained for streamers in the literature depending on the gas pressure or chemical composition. The resistance r of a streamer of length L , radius R , and conductivity σ , is:

$$r = \frac{L}{\sigma \cdot \pi \cdot R^2}$$

During a restrike event, when the radius R increases, r decreases, more current may flow in the channel, and the shortcut and cooling of the arc occur faster. However, it appears in the simulations that an increase in the radius R does not lead to a significant increase of the current density J in the streamer channel. Because the volumic Joule effect in the channel is $P_J = \sigma^{-1} J^2$, the channel heating time does change consequently. In Fig.9, the channel radius does not seem to have a substantial impact during the first 15 ms; then, the discharge dynamics exhibit significant differences with the reference case. The radius does not seem to significantly influence the structure of the discharge up to 40 ms. Figure 8 shows that the volume swept by the arc is similar for all radii. Thus, it appears finally that the arc dynamics are not very sensitive to the streamer radius.

E. Influence of the conductivity (cases 0, 5, 6)

This part emphasizes the influence of the conductivity of the streamer channel deposited along field lines. The values that have been considered are 0.2 S/m for case 5, 1 S/m for the reference case, and 10 S/m for case 6 (see Table 2). We observe an important impact on the discharge (Fig.9), especially when the conductivity is lowered at 0.2 S/m. Contrary to the streamer radius, this parameter seems to have a significant effect on the volumic Joule effect in the channel, as P_J is inversely proportional to the conductivity. We can observe very different dynamics during the first restrike, and for case 5 with $\sigma = 0.2$ S/m, the arc extension is much larger than in the two other cases. In addition to this strong influence of the conductivity, it is also the input parameter with the most important uncertainty, as it depends on the complex streamer chemistry in the channel. As it is still a highly discussed topic in the community, further improvements of the restrike model may be dedicated to a simple chemical model able to compute a more accurate conductivity value.

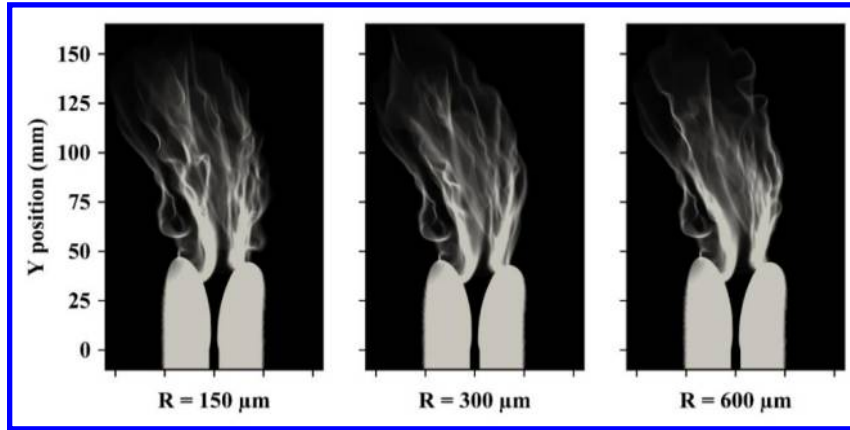


Fig. 8: Current density in the gliding arc for different streamer radii R . The current density fields are averaged over 40 ms to compare with the time-integrated experimental images of Zhu.

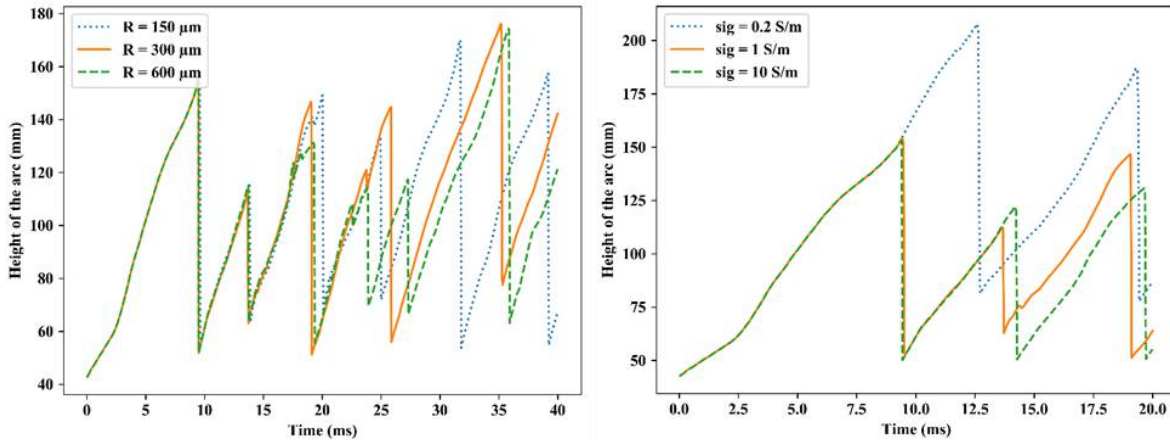


Fig. 9: Position the arc's head as a function of time for different streamer's radii (left) and channel conductivities (right).

V. Conclusion

This paper presents a numerical model for the restrike phenomenon in MHD simulations of arc. The input parameters are the breakdown field, the streamer radius, and the streamer channel conductivity. A parametric study has been conducted to check the influence of these parameters on the restrike dynamics. The main results of this study are:

- The model produces convincing gliding arc dynamics, even under LTE and 2D approximations;
- The breakdown reduced field has an important impact, as a low field will trigger many streamers but with few restrikes, and high field will trigger streamers only when the arc dimension is important enough;
- The streamer radius does not appear as a critical parameter for the restrike dynamics;
- The electrical conductivity has a significant impact on the arc dynamics as it strongly influences the Joule effect and the heating rate of the fluid.

Acknowledgments

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