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Preventing the formation of vortexes in an atmospheric Inductively Coupled Plasma (ICP)

Investigation on Ar and N_2 inductive plasmas at 20 kW and 4 MHz

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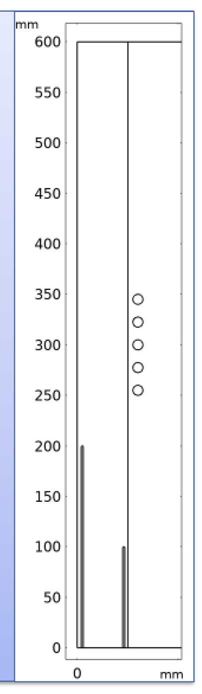
Motivation

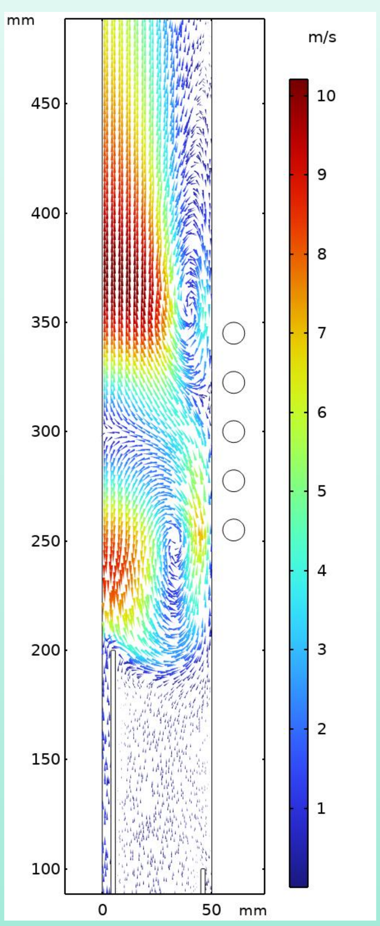
- A good characterization of a high-power ($\leq 1\ MW$) ICP is required to avoid the torch walls burning and to optimize the convection enthalpy at the outlet. A common occurrence in ICPs is the formation of **vortexes**, trapping heat nearby the walls. Alternatively, these vortexes can also prevent injected reactants from reaching the high-temperature region in the plasma core.
- Consequently, we decided to study the influence of the coil/burner geometry, and of the operation parameters, on the vortex formation in the context of an already documented example [4]. This example uses **argon ICP at 20 kW** and typical input **flow rates of 40 L/min**.
- We assumed that this knowledge would be of interest while designing a much higher power torch… however, it turned out that **the gas flow pattern at 1 MW and flow rates of 1400 L/min is drastically different**. The typical toroidal vortexes appearing in the low-power torch do not exist anymore.

Method

- Software: COMSOL Multiphysics®.
- Module: equilibrium discharge, out-of-plane current.
- Laminar flow, heat transfer and magnetic field equations coupled together.
- No kinetic reaction.
- No radiation.
- Low power torch, default case:
  - Coil parameters: 20 kW, 4 MHz and 5 windings.
  - Gas: N_2. Atmospheric pressure.
  - Flow rate: 40 L/min distributed in 3 inlets (2 | 32 | 6)
  - Burner radius: 50 mm.

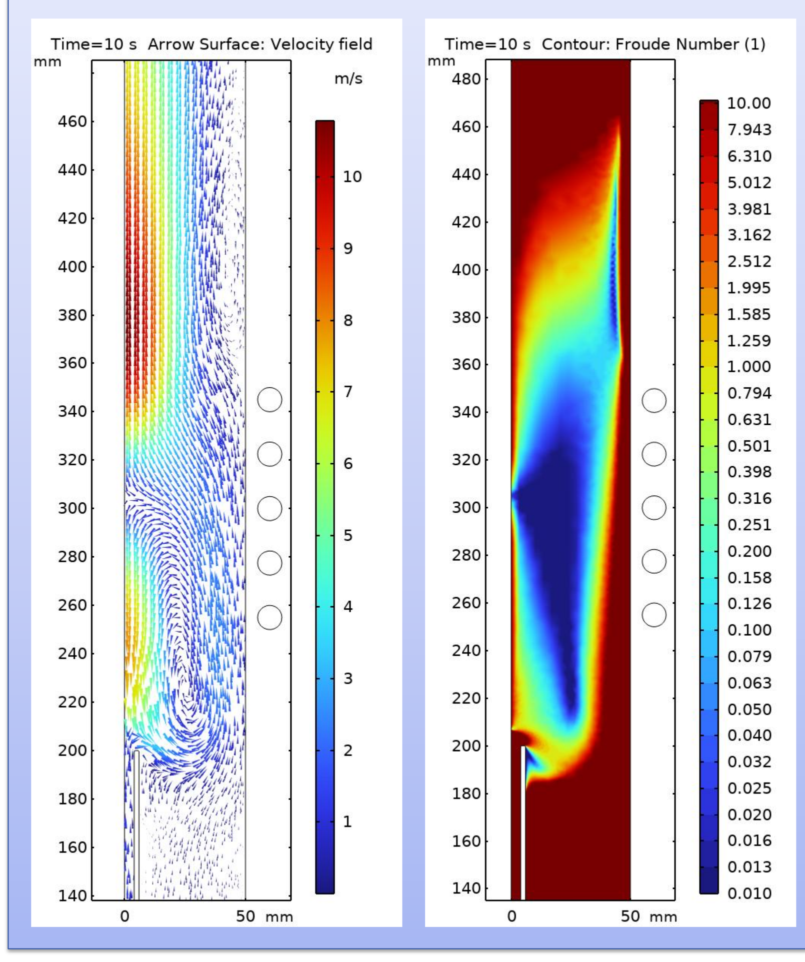


Argon



- Less energy required for ionization.
- At equivalent coil power, plasma is hotter and closer to the burner walls.
- Velocity distribution differs.
- Vortex located downstream is more pronounced.

Default case



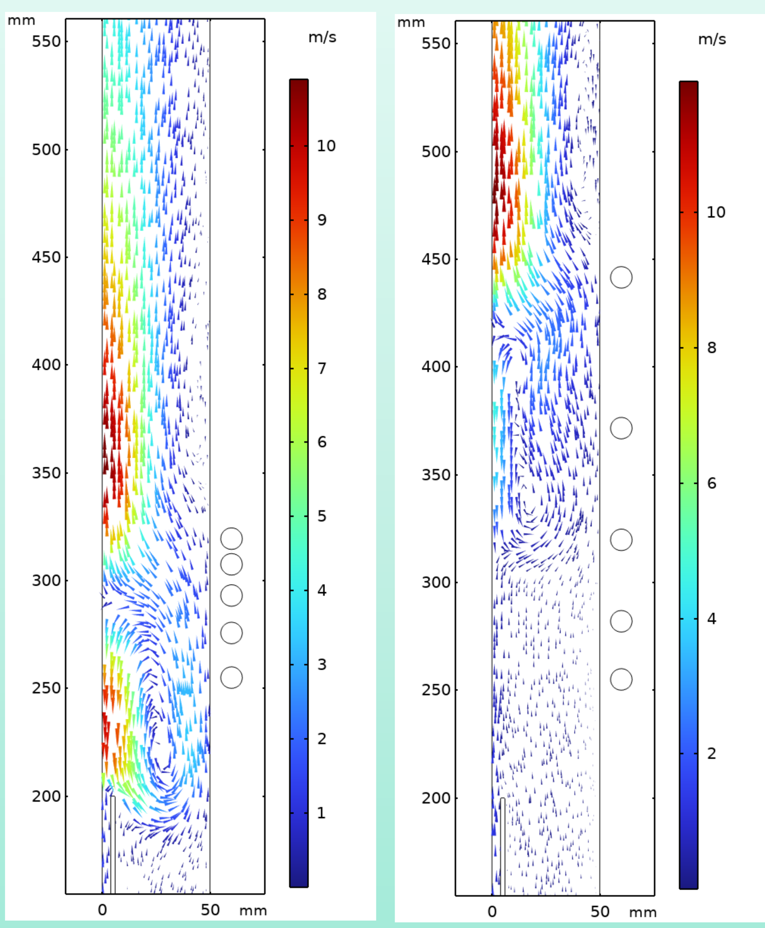
Froude number
Ratio of the gas inertia force over the Lorentz force.

$$Fr = \frac{\rho v^2/R}{\sigma\left|\Re\left(\vec{E_0}\times\vec{B_0}\right)\right|}$$

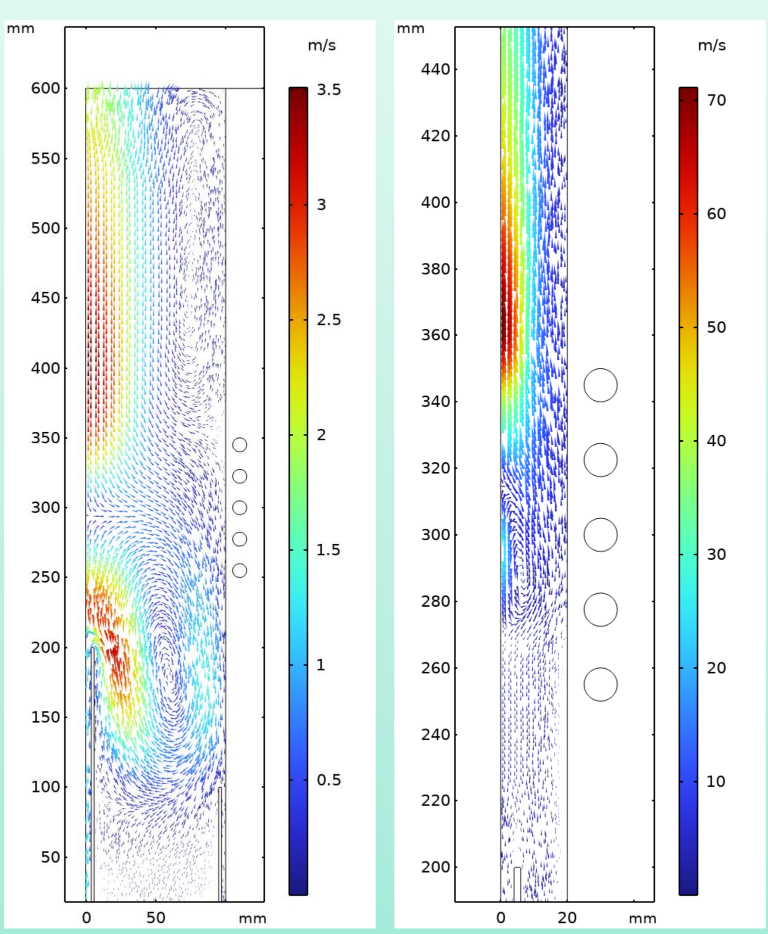
It is cited as an important criteria in [4], assuming the vortex are due to Lorentz force. Consequently, one must increase the Froude number to lessen vortexes.

Coil elongation: $\times\,0.92$ vs $\times\,1.2$

- Velocity and temperature magnitudes are similar in both cases.
- Shrinking coil space does not have much influence on the velocity distribution. It requires a better voltage isolation though.
- Elongating the coil has an interesting effect: the fraction of plasma going upstream (due to thermal expansion) is reduced. However, twice as much coil current is required to obtain the same coil power.

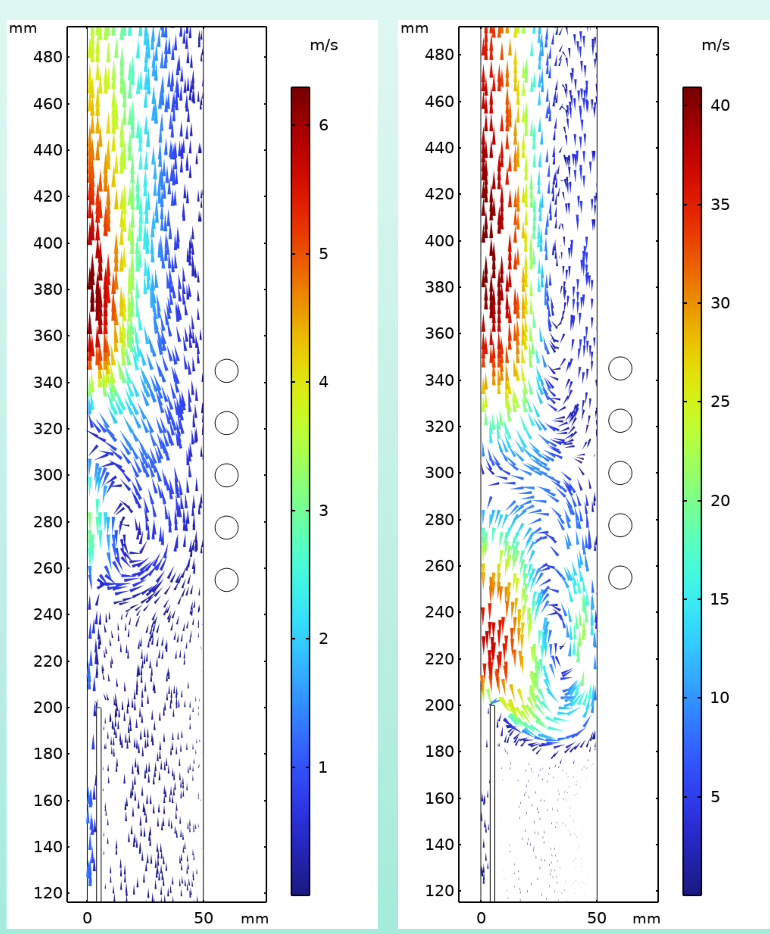


Burner radius: 100 mm vs 20 mm



- As constant pressure, the Froude number dependency on the burner radius is: $Fr \sim R^{-3}$
- The vortex are drastically weakened with the smaller radius.
- However, ignition and operation of the torch is easier with larger radiuses.

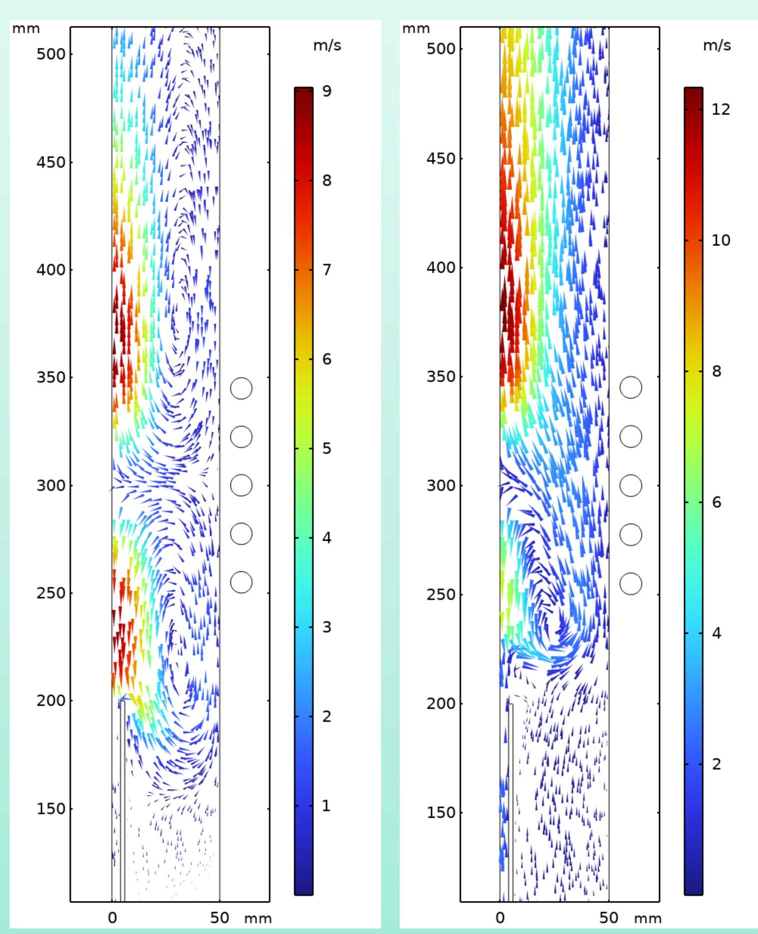
Coil power: 10 kW vs 100 kW



- Lower powers lead to weaker vortexes. On the other hand, the plasma is not stable below 10 kW.
- Higher power is usually the goal for heating purposes. It also implies stronger Lorentz forces and a more important plasma expansion upstream.

Flow rate: 10 L/min vs 80 L/min

- Lower flow rates mean lower gas inertia force. The thermal expansion becomes more isotropic, with strengthened recirculation vortexes.
- Higher flow rates reduce the 1st vortex, and the 2nd is not present anymore. However, the plasma is less stable, and more gas flows out without interacting with the plasma itself.



Conclusion

- Our simulations reproduced the results and observations from [4] properly.
- At low power, it is possible to optimize the geometry and the operation parameters to lessen the formation of vortexes.

But…

- New focus on **1 MW torch with high flow rates** raises different problems: the 2nd vortex downstream does not exist anymore, while the plasma expansion upstream is strong enough to reach the inlet and burn the walls.
- Gas inertia from the inlets is not sufficient: the plasma flows upstream at $\geq 600\ m.s^{-1}$ and $14000\ K$.
- Currently **investigating nozzle geometries** to solve this issue.

References

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[2] Bernardi, D. *et al.* Numerical simulation for the characterization of operating conditions of RF-RF hybrid plasma torches. *Eur. Phys. J. D* **28**, 399–422 (2004).
[3] Sangeeta B. Punjabi *et al.* The effect of various coil parameters on ICP torch simulation. J. Phys.: Conf. Ser. **208** 012048 (2010).
[4] Voronov, M. *et al.* Force-based analysis of vortexes in atmospheric pressure ICPs. *Plasma Sources Sci. Technol.* **27** 125005 (2018).