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Numerical simulation of a RF – RF hybrid plasma torch with argon at atmospheric pressure

Evaluation of minimum sustaining current (MSI) in dual frequency (ICP) torch

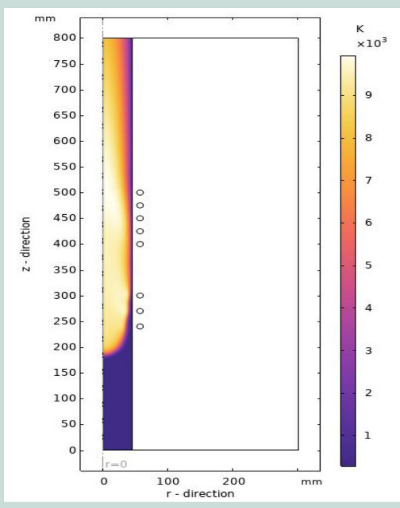
Biruk Alemu, Loann Terraz and Rainer Kling

Overview

- Inductively coupled plasma (ICP) at atmospheric pressure is an alternative to the classic gas-based combustion in the context of industrial heating applications
- Working with high-frequency electronics is feasible for higher plasma power coupling, but not at a desirable cost
- We investigate a hybrid approach, in which the high frequency (HF) coil ignites the plasma at a relatively low power, while the medium frequency (MF) coil supplies the remaining power in a cost-effective manner
- We present how the MSI of the MF coil changes as we vary the distance between the coils and the amount of power supplied to the HF coil

Implementation and Simplification

- Pure Argon gas at 1 atmosphere
- Local thermodynamics equilibrium (LTE) plasma assumed
- No kinetic reaction implemented
- Electrically neutral plasma
- 2D–axisymmetric simulation
- Radiation is not considered for the heat transfer
- The burner wall is modeled as a fixed temperature boundary condition at $293.15\ K$

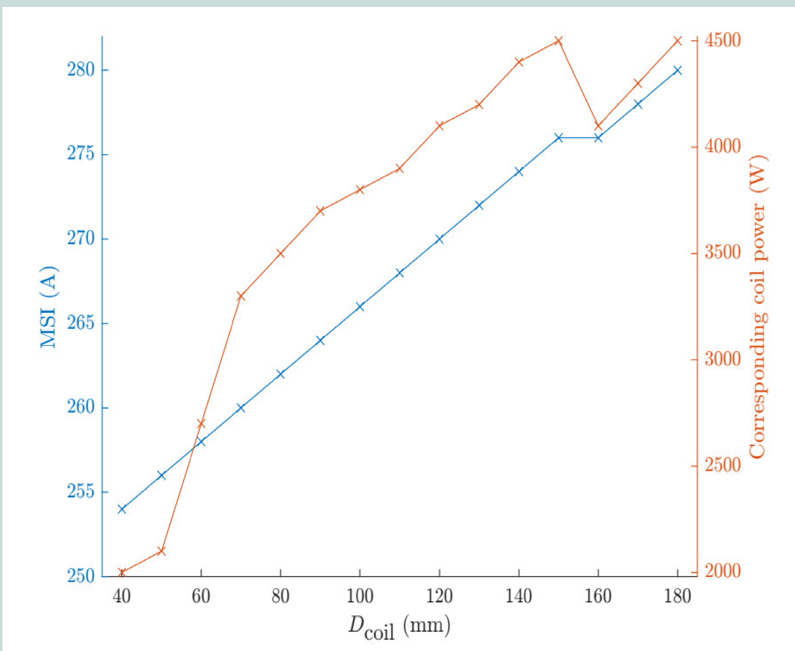


Temperature profile of 2D axisymmetric model of the dual frequency torch

Simulation results

Default values

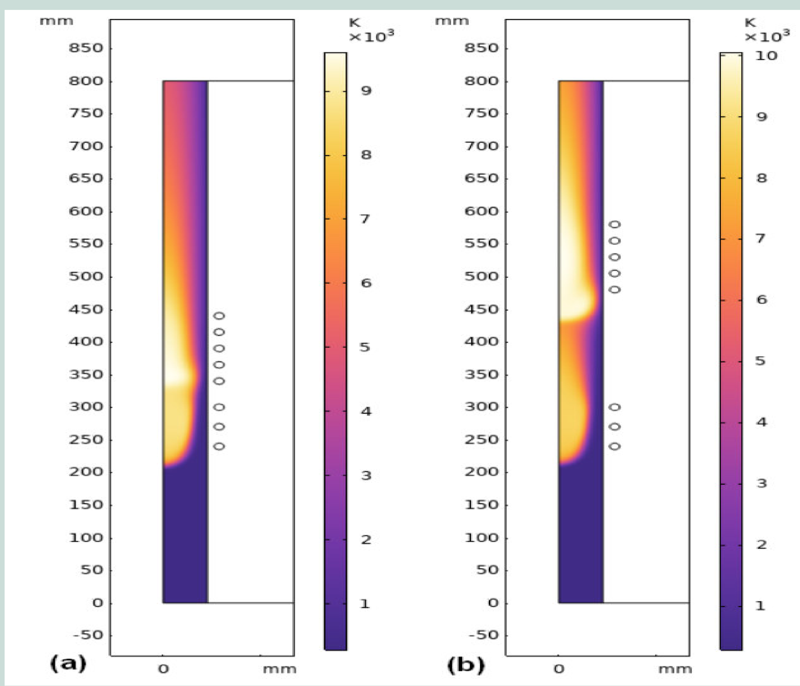
Variable	Values	Description
f_{HF}	13.56 MHz	HF coil frequency
P_{HF}	3 kW	HF coil excitation power
f_{MF}	200 kHz	MF coil frequency
I_{MF}	5000 A	MF coil excitation current
D_{coil}	100 mm	Distance between the two coils
Q_{inlet}	100 L/min	Argon flow at the inlet
α_{swirl}	0°	Swirl angle of the gas inflow



MSI of the MF coil for different coil distance with $P_{HF} = 3\ kW$

Varying the distance between the coils

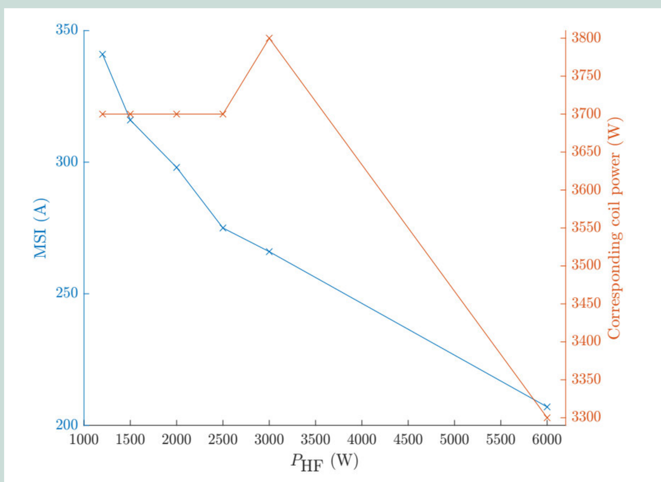
- MSI values for MF coil at varied distance between $40\ mm$ and $180\ mm$
- $3\ kW$ power excitation used for HF coil
- The MSI increases almost linearly with the coil distance, the shorter the distance, the hotter the gas at the entrance of the MF coil



2D temperature plot when MSI is reached
a) $D_{coil} = 40\ mm$ b) $D_{coil} = 180\ mm$

Varying the power of HF coil

- The coil distance fixed at $100\ mm$
- The MSI increases from $266\ A$ at $P_{HF} = 3\ kW$ to $341\ A$ at $P_{HF} = 1.2\ kW$
- It is more reasonable to choose the HF power around $2.5\ kW$ or $3\ kW$ rather than around $1.2\ kW$



MSI of the MF coil for different power excitation of the HF coil

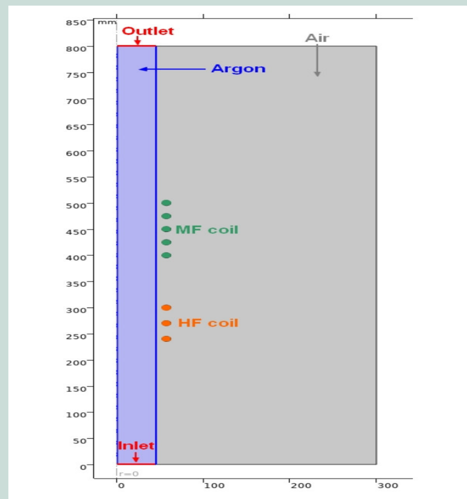
Conclusion

- Igniting and sustaining an inductive plasma at a low/medium frequency may be impossible at atmospheric pressure. On the other hand, coupling a lot of power with high-frequency electronics is expensive. The hybrid torch concept presented here is an attempt to solve this issue
- We quantified the minimum sustaining current for stable plasma operation while varying the distance between the coils and the power from the HF support. The advantage of this design is lost if the coil distance increases too much (plasmas completely separated)
- Having a quasi-constant impendance means the design can be modified without further complications form the engineering point of view

Geometry

Integration of High frequency (HF) and Medium frequency (MF) coils

- Diameter of the tube $D_{burner} = 90\ mm$
- Length of the tube $L_{burner} = 800\ mm$
- Number of HF windings $N_{HF} = 3$
- Length of the HF coil $L_{HF} = 70\ mm$
- Number of MF windings $N_{MF} = 5$
- Radius of copper coil $R_{coil} = 5\ mm$
- Length of the MF coil $L_{MF} = 110\ mm$



2D axisymmetric model of the plasma torch

Equations

The equilibrium discharge model from COMSOL Multiphysics couples the following interfaces

- Magnetic fields
- Heat transfer in fluids
- Laminar flow

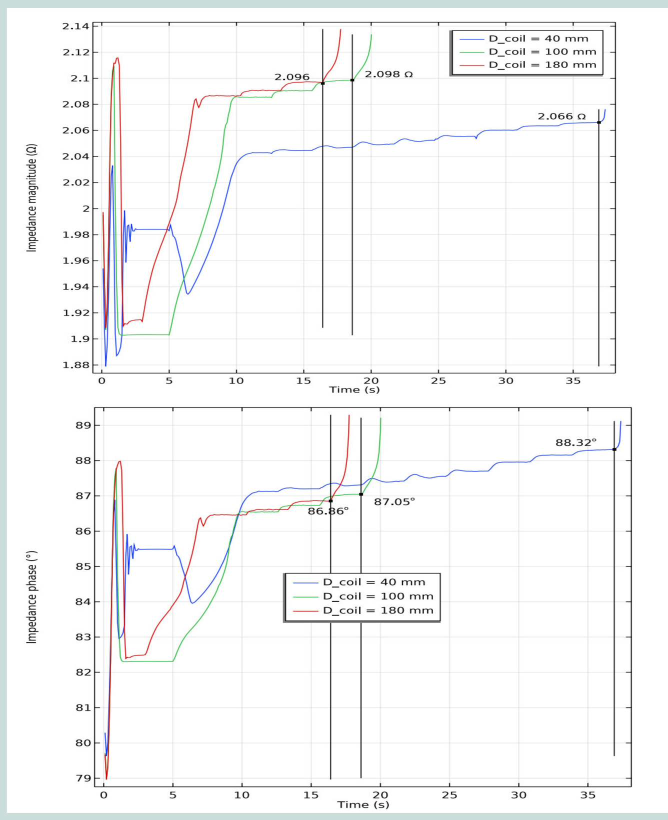
$$\nabla \times H = J$$
$$B = \nabla \times A$$
$$J = \sigma E + j\omega D + \sigma u \times B + J_e$$
$$E = -j\omega A$$

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u.\nabla T + \nabla.q = Q + Q_p + Q_{vp}$$
$$q = -\kappa \nabla T$$
$$\rho \frac{\partial u}{\partial t} + \rho (u.\nabla) u = \nabla.[-pI + K] + F$$
$$\frac{\partial \rho}{\partial t} + \nabla.(\rho u) = 0$$

Additional quantities of interest

Impedance of the MF coil

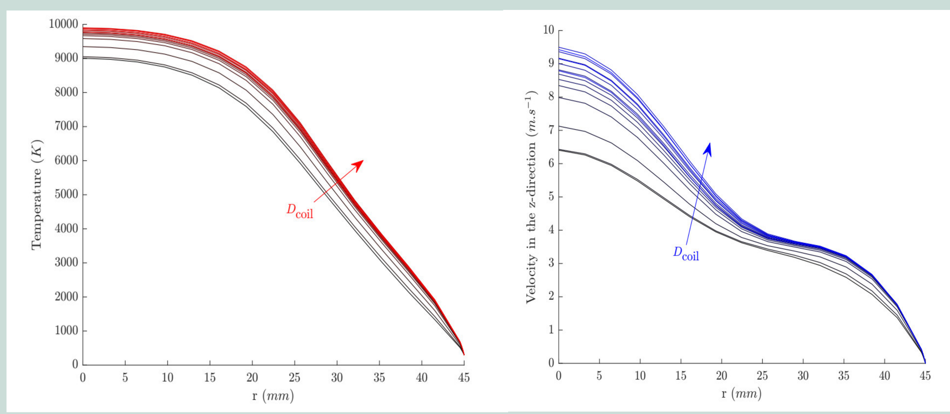
- Maximum and minimum impedance magnitude of $2.121\ \Omega$ (at $P_{HF} = 1.2\ kW$) and $2.066\ \Omega$ (at $D_{coil} = 180\ mm$) are respectively achieved
- Maximum and minimum impedance phase of $88.32°$ (at $D_{coil} = 40\ mm$) and $86.86°$ (at $D_{coil} = 180\ mm$ are also respectively obtained



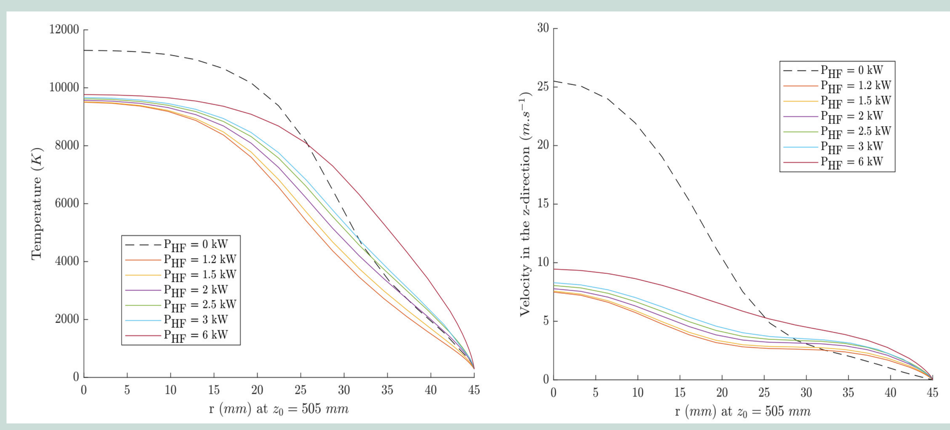
The phase and magnitude of the complex impedance of the MF coil is calculated at the MSI value

Temperature and velocity profiles

- Temperature and velocity profiles along radial direction at the end of MF coil (z_0) are investigated when 1) at variable D_{coil} 2) at different P_{HF} level
- Both temperature and velocity increase as D_{coil} and P_{HF} increases



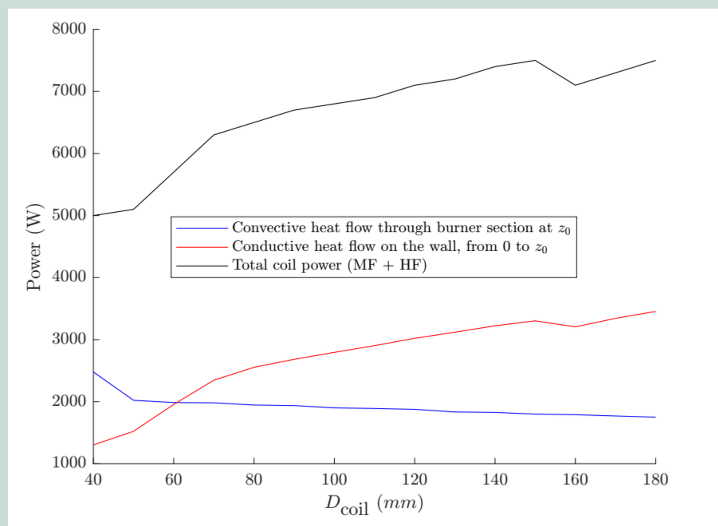
Temperature and velocity profile in radial direction at varied coil distance



Temperature and velocity profile at different high frequency power level

Conductive and convective heat flows at the end of the MF coil

- P_{HF} is fixed at $3\ kW$
- The convective heat flux integrated over a disk of radius R_{burner}, located at z_0
- The conductive heat flux integrated over the burner wall on a cylindrical surface of length z_0



Convective heat flow over the burner section at z_0 and conductive heat flow over the burner wall up to z_0

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Biruk Alemu
+49 721 608 47064
biruk.alemu@kit.edu

Karlsruhe Institute of Technology (KIT)
Light Technology Institute (LTI)
Engesserstr. 13 Bldg.30.34
76131 Karlsruhe, Germany