Effect of Magnetic Field, Geometry and Mixtures Ratios on Plasma Production in a Cascaded Arc

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Introduction

• **Magnum-psi Project:** (MAgnetised plasma Generator and NUmerical Modelling for Plasma Surface Interaction studies)

• **Aim of Magnum-psi project:**
  - Study of plasmas expected in the divertor region of future Tokamak:- ITER
    - particle flux density $\sim 10^{22}-10^{24}$ m$^{-2}$s$^{-1}$
    - electron and ion temperature $\sim 1$ eV
    - magnetic field $\sim 5$ T
  - Study of industrial applications of plasmas like deposition, etching and generation of (reactive) particles etc.

• **Plasma Source:** Cascaded Arc

• **Tool:** PLASIMO (PLAsma SImulation MOdel).
Pilot-psi experimental set-up

- Gas flow
- Cascaded arc plasma source
- Vacuum vessel
- Plasma jet
- Target
- Pumps

Dimensions:
- Length: 100 cm
- Height: 40 cm
**Plasma Source Geometry**

**Straight arc channel:**
4 mm diameter, 32 mm length

- **Inlet (West Boundary)**
- **Channel Wall (North Boundary)**
- **Symmetry axis (South Boundary)**
- **Outlet (East Boundary)**

**Computational Grid:** 16 radial × 64 axial points

- Ar, H₂, Ar+H₂
- Cathode
- Anode
- Plasma & Neutrals
Mathematical Model

With the use of a 2-D hydrodynamical model, plasma processes in the arc are simulated. The governing equations in the model are:

\[ \nabla \cdot (n_h \vec{u}) - \nabla \cdot (D_h \nabla n_h) = S_h \]

\( D_h \) and \( \vec{u} \) are the diffusion coefficient of species \( h \) and the plasma bulk velocity respectively, while \( S_h \) denotes the net production of species \( h \) due to the collisional-radiative processes.

Total Continuity equations:

\[ \nabla \cdot (\rho \vec{u}) = 0 \]
Momentum balance: \( \vec{v} \cdot (\rho_i \vec{u}, \vec{u}) = -\left( \nabla p \right)_i + \left( \nabla \cdot \tau \right)_i \)

where \( i \) denotes the axial or radial component and \( \tau \) viscous stress tensor.

Energy balance (heavy particles): \( \nabla \cdot \left( \rho_h \varepsilon_h \vec{u} \right) + p_h \nabla \cdot \vec{u} + \nabla \cdot \vec{q}_h = \tau_h : \nabla \vec{u} + Q_h \)

where \( \varepsilon_h \) is the internal energy per unit mass of the heavy particle. The heat flux is \( \vec{q}_h = -\kappa \vec{\nabla}T \) and \( Q_h \) denotes the energy gain or loss through elastic/inelastic reactions.

Energy balance (electrons): \( \nabla \cdot \left( \rho_e \varepsilon_e \vec{u} \right) + p_e \nabla \cdot \vec{u} + \nabla \cdot \vec{q}_e = Q_{Ohm} + Q_e \)
$Q_{Ohm}$ is the energy gain through Ohmic heating.

$$Q_{Ohm} = \sigma E^2$$

Equation of state: $p = \sum_\alpha n_\alpha k_B T_\alpha$

The (axial) electric field is computed from the electric conductivity integrated over the cross section of the channel as:

$$I = E \int_0^a 2\pi r \sigma(r) dr$$
<table>
<thead>
<tr>
<th>Q.</th>
<th>Inlet</th>
<th>Outlet</th>
<th>Axis</th>
<th>Channel wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p )</td>
<td>( \frac{\partial p}{\partial z} = C )</td>
<td>( \frac{\partial p}{\partial z} = C )</td>
<td>( \frac{\partial p}{\partial r} = 0 )</td>
<td>( \frac{\partial p}{\partial r} = 0 )</td>
</tr>
<tr>
<td>( u_z )</td>
<td>( u_z = u_{in}^{\text{max}} \left[ 1 - \left( \frac{r}{R_{in}} \right)^2 \right] )</td>
<td>( u_z = u_{out}^{\text{max}} \left[ 1 - \left( \frac{r}{R_{out}} \right)^5 \right] )</td>
<td>( \frac{\partial u_z}{\partial r} = 0 )</td>
<td>( u_z = 0 )</td>
</tr>
<tr>
<td>( u_r )</td>
<td>( u_r = 0 )</td>
<td>( \frac{\partial u_r}{\partial z} = 0 )</td>
<td>( u_r = 0 )</td>
<td>( u_r = 0 )</td>
</tr>
</tbody>
</table>
| \( T_{e,h} \) | \( T_h = 500K \)  
\( T_e = 6000K \) | \( \frac{\partial T_{e,h}}{\partial z} = 0 \) | \( \frac{\partial T_{e,h}}{\partial r} = 0 \) | \( T_h = 500K \)  
\( T_e = 6000K \) |
For forward reactions (which are temperature dependent), Arrhenius like fit is used

\[ k = c(T)^\beta \exp\left(\frac{-E}{T}\right) \]

Where \( c \) is the rate constant, \( T \) is the electron or heavy particle temp in eV, \( E \) is the reaction energy in eV and \( \beta \) is the power of Temp. For the backward reactions, rates are computed using detailed balancing.

**Ionization by electron impact:** \( Ar + e \leftrightarrow Ar^+ + 2e \)

**Molecular ionisation:** \( H_2 + e \leftrightarrow H_2^+ + 2e \)

**Dissociative recombination:** \( H_2^+ + e \rightarrow H + H^+ + e \) 
\( \rightarrow H + H \)

**Dissociation by electron impact:** \( H_2^+ + e \rightarrow H + H^+ + e \)
Electron assisted dissociation: \[ H_2 + e \leftrightarrow H + H + e \]

Heavy particle assisted dissociation: \[ H_2 + M \leftrightarrow H + H + M \]

Ionization by electron impact: \[ H + e \leftrightarrow H^+ + 2e \]

Vibrational excitation: \[ H_2^{v=0} + e \leftrightarrow H_2^{v=4,8} + e \]

Charge Transfer: \[ H_2^{v=4,8} + H^+ \rightarrow H_2^+ + H \]

Dissociative recombination: \[ H_2^+ + H_2 \rightarrow H_3^+ + H \]
\[ H_3^+ + e \rightarrow H_2^+ + H \]

Dissociative attachment: \[ H_2^{v=8} + e \rightarrow H^- + H \]

Recombination: \[ H^- + H^+ \rightarrow H^{**} + H \]
\[ H^- + H_2^+ \rightarrow H^{**} + H_2 \]
Associative Charge Exchange:

\[ Ar^+ + H_2 \rightarrow ArH^+ + H \]

Dissociative recombination:

\[ ArH^+ + e \rightarrow H^+ + Ar \]
Reactions at the channel walls

\[
H + \text{wall} \rightarrow \frac{1}{2} \text{H}_2^{v=4,8}
\]

\[
\text{H}_2^{v=4,8} + \text{wall} \rightarrow \text{H}_2
\]

\[
\text{H}_2^+ + \text{wall} \rightarrow \text{H}_2
\]

\[
\text{H}_3^+ + \text{wall} \rightarrow \text{H}_2 + \text{H}
\]

\[
\text{Ar}^+ + \text{wall} \rightarrow \text{Ar}
\]

\[
\text{ArH}^+ + \text{wall} \rightarrow \text{Ar} + \text{H}
\]

The wall reaction coefficient for association process of H depends on the wall temperature, the wall material, and the surface conditions of the wall. Consequently, in the literature different values of H wall reaction can be found, ranging from \(10^{-3}\) approximately to 1. However in our study a reaction probability of 0.05 is used as it verify experimental results of cascaded arc. For all the other reactions with the wall a probability of 1 is used supposing that all ionic species are neutralized at the wall,
Effect of magnetic field on $\text{H}^+$ Yield

The thermal conductivity of electrons in the presence of ions and neutrals:

$$\kappa_e = \frac{2.4 \ k_B^2 n_e T_e}{(1.0 + (\nu_{ei}/\sqrt{2}\nu_{e0})) \ m_e\nu_{e0}}$$

Modified thermal conductivity due to the presence of magnetic field:

$$\kappa_e(B_{\text{ext}}) = \frac{1}{\left(1 + \left(\frac{\omega_{ce}}{\nu_{e0} + \nu_{ei}}\right)^2\right)} \kappa_e(0)$$
The ambipolar diffusion coefficient:

With ion and electron mobilities

In the presence of a magnetic field, the electron transport coefficients are strongly reduced, and, in the limit where the ion transport is dominant, the ambipolar diffusion coefficient becomes

\[ D_a = D_i \left(1 + \frac{T_e}{T_i}\right) \left(1 + \frac{\mu_i}{\mu_e} \left(1 + \left(\frac{\omega_{ce}}{v_{e0} + v_{ei}}\right)^2\right)\right) \]
Computed results of H+ yield versus magnetic field for the hydrogen arc at the outlet
<table>
<thead>
<tr>
<th>Current (A)</th>
<th>R (mm)</th>
<th>L (mm)</th>
<th>H^+ yield (s^{-1})</th>
<th>H^+ (eV ion^{-1})</th>
<th>Ionization (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>2</td>
<td>30</td>
<td>1.385 × 10^{20}</td>
<td>320</td>
<td>5.4</td>
</tr>
<tr>
<td>60</td>
<td>2</td>
<td>32</td>
<td>1.391 × 10^{20}</td>
<td>343</td>
<td>5.4</td>
</tr>
<tr>
<td>60</td>
<td>2</td>
<td>40</td>
<td>1.442 × 10^{20}</td>
<td>427</td>
<td>5.6</td>
</tr>
<tr>
<td>410</td>
<td>5</td>
<td>30</td>
<td>1.394 × 10^{21}</td>
<td>199</td>
<td>38</td>
</tr>
<tr>
<td>410</td>
<td>5</td>
<td>32</td>
<td>1.463 × 10^{21}</td>
<td>201</td>
<td>37.6</td>
</tr>
<tr>
<td>410</td>
<td>5</td>
<td>70</td>
<td>2.148 × 10^{21}</td>
<td>294</td>
<td>18.4</td>
</tr>
</tbody>
</table>
Comparison of axial pressure along the arc with experimental values for different mixtures ratios.
Plot of fluxes for $A=$pure Ar3.0 SLM, mixtures, $B=$Ar2.91 SLM+H$_2$0.09 SLM, $C=$Ar2.88 SLM+H$_2$0.12 SLM, $D=$Ar2.75 SLM+H$_2$0.25 SLM, $E=$Ar2.5 SLM+H$_2$0.5 SLM, $F=$Ar2.0 SLM+H$_2$1.0 SLM, $G=$Ar1.5 SLM+H$_2$1.5 SLM, and $H=$pure H$_2$3.0 SLM with and without ACX and DR.
H\(^+\) density profile for the Ar2.5 SLM+H\(_2\)0.5 SLM mixture
Density profiles for the case of Ar2.88 SLM+H20.12 SLM mixture

**Ar^+**

**H^+**
The $\text{H}^+ / \text{Ar}^+$ concentration ratio for a 3% admixture of $\text{H}_2$ was found to be 1:4 in the experiments at 20 mm from the exit of arc. In our simulations we have found a ratio 1:2 at the exit of arc for the 2.91/0.09 SLM mixture (approximately 3% $\text{H}_2$). Going to a mixture of 2.88/0.12 SLM 4% of $\text{H}_2$, we can see that there is shift of density in the arc, now the dominant ion is $\text{H}^+$. In the same experiment it was reported that the $\text{Ar}^+$ ion density drops to an undetectable level with the inclusion of more than 4% $\text{H}_2$. 
Plots of the ion densities of H+ and Ar+ inside the arc for the mixture of Ar2.88 SLM+H20.12 SLM.
Energy required per ion for different mixture ratios

$A=$ pure Ar 3.0 SLM, mixtures, $B=$ Ar 2.91 SLM + H$_2$ 0.09 SLM, $C=$ Ar 2.88 SLM + H$_2$ 0.12 SLM, $D=$ Ar 2.75 SLM + H$_2$ 0.25 SLM, $E=$ Ar 2.5 SLM + H$_2$ 0.5 SLM, $F=$ Ar 2.0 SLM + H$_2$ 1.0 SLM, $G=$ Ar 1.5 SLM + H$_2$ 1.5 SLM, and $H=$ pure H$_2$ 3.0 SLM
Velocity profiles for the case of pure Ar, H2, and 50% mixture of Ar+H2

Simulation results are in good agreement with the experimental findings.

Inclusion of the magnetic field significantly increases the ion yield.

In the hydrogen arc, lengthening the arc will not increase the ionization degree; however, widening the arc will increase the ionization degree.

Associative charge exchange reaction followed by dissociative recombination reaction plays a very important role in the dissociation of H₂ molecules and higher ionization of H⁺ at the same time reducing the Ar⁺ density in the arc.

Higher H⁺ ion flux can be achieved by adding small fraction of hydrogen into argon arc.
Thank you very much for your attention