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Numerical Modelling of a Free-Burning Arc in Argon

A Tool for Understanding the Optical Mirage Effect in a TIG Welding Device

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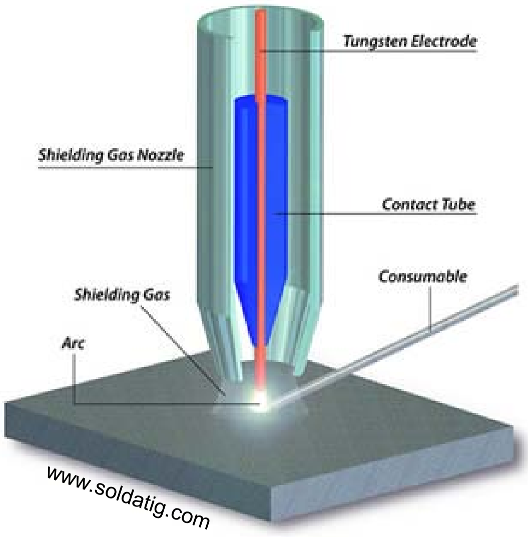
INTRODUCTION – *Electric Arc & TIG Welding Device*

- Electric **arcs** at atmospheric pressure are **thermal plasmas** with:
  - High energy density
  - High **temperature**
  - High **light** emissivity
  - High electric current intensity

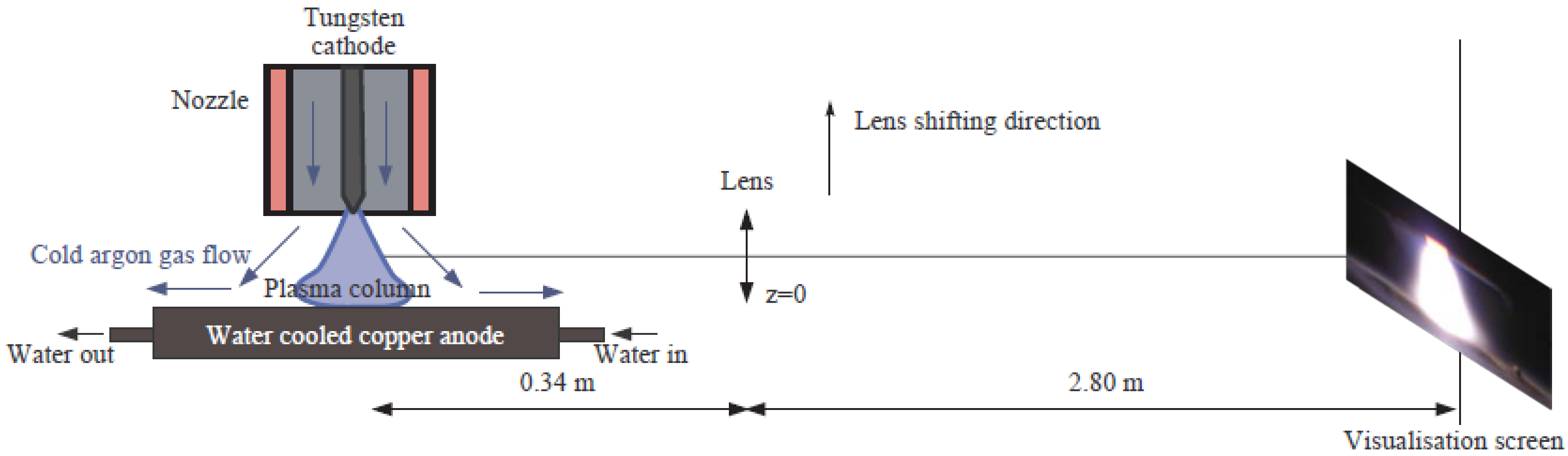
- **Point-to-plane discharge** configuration, “**free-burning arc**”, nearly TIG welding device configuration



- Standard **diagnostic** of electric arcs: **emission spectroscopy**

INTRODUCTION – *Experimental Observation*

- As lens is shifted upward, cathode tip is still visible, whereas the lens optical axis is above the nozzle exit...!



Rays of light, emitted from the cathode tip, are bent when passing through the plasma. **Optical mirage effect...?**

Numerical modelling of the electric arc + ray-tracing...

FREE-BURNING ARC SIMULATION – *General Assumptions*

Axisymmetry	2D (r,z) simulation
Flow	Laminar and steady-state
Inlet and surrounding gases	Argon at atmospheric pressure
Temperature	Local thermodynamic equilibrium
Radiative losses	Net emission coefficient method
Gravity effect	Not taken into account
Electrode erosion, electrode sheath	Not taken into account
Electric current	DC

Laminar Non-Isothermal Flow

Weakly Compressible Navier-Stokes

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} = \nabla \cdot [-p\mathbf{I} + \tau] + F$$

F: $\vec{J} \times \vec{B}$

Explicit coupling

General Heat Transfer

$$\rho C_p\left(\frac{\partial T}{\partial t} + (\mathbf{u} \cdot \nabla)T\right) = -(\nabla \cdot \mathbf{q}) + \tau{:}\mathbf{S} - \frac{T}{\rho}\frac{\partial \rho}{\partial T}\bigg|_p\left(\frac{\partial p}{\partial t} + (\mathbf{u} \cdot \nabla)p\right) + Q$$

Q: $\vec{J} \cdot \vec{E} - U_{rad}$

Meridional Induction and Electric Currents, Potentials

$$-\nabla \cdot d(-\sigma \mathbf{v} \times (\nabla \times \mathbf{A}) + \sigma \nabla V - \mathbf{J}^{e}) = 0$$

$$\nabla \times d(\mu_0^{-1} \nabla \times \mathbf{A} - \mathbf{M}) - d\sigma \mathbf{v} \times (\nabla \times \mathbf{A}) + d\sigma \nabla V = d\mathbf{J}^{e}$$

$\Leftrightarrow$

$$\vec{\nabla} \cdot \sigma \vec{\nabla} V = 0$$

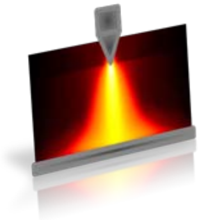
$$\Delta \vec{A} = \mu_0 \vec{J}$$

$\Longrightarrow$

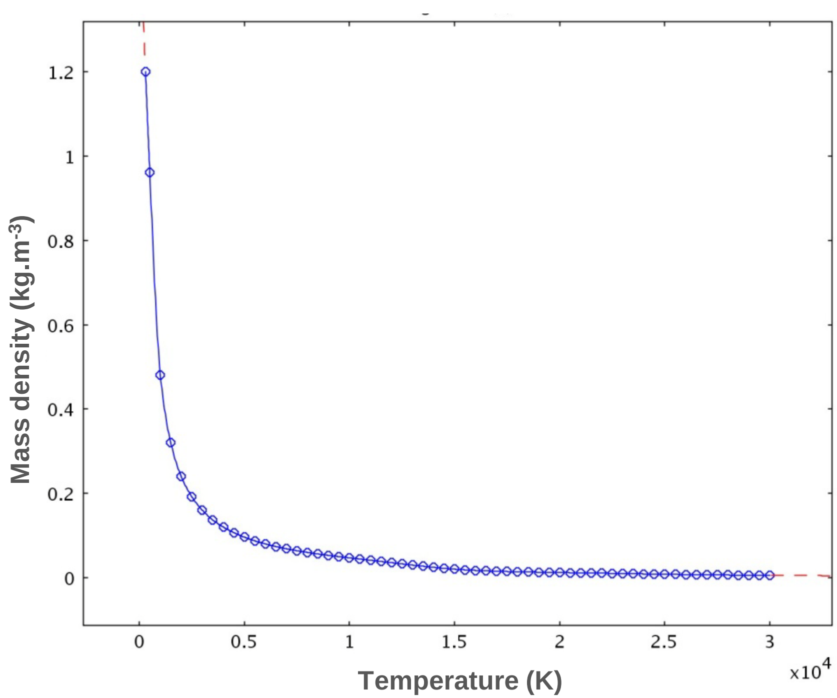
$$\vec{E} = -\vec{\nabla} V$$

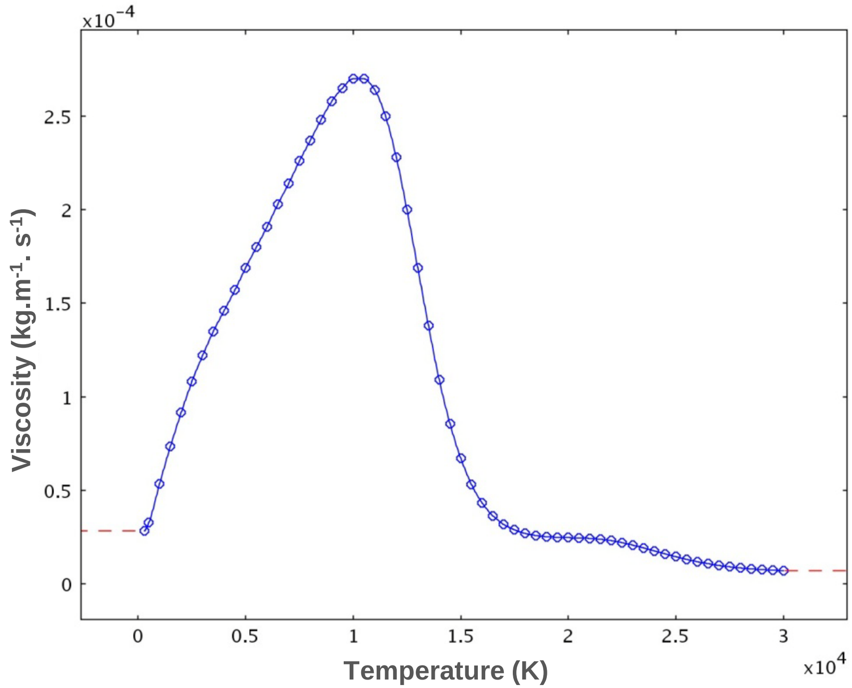
$$\vec{J} = \sigma \vec{\nabla} V$$

$$\vec{B} = \vec{\nabla} \times \vec{A}$$



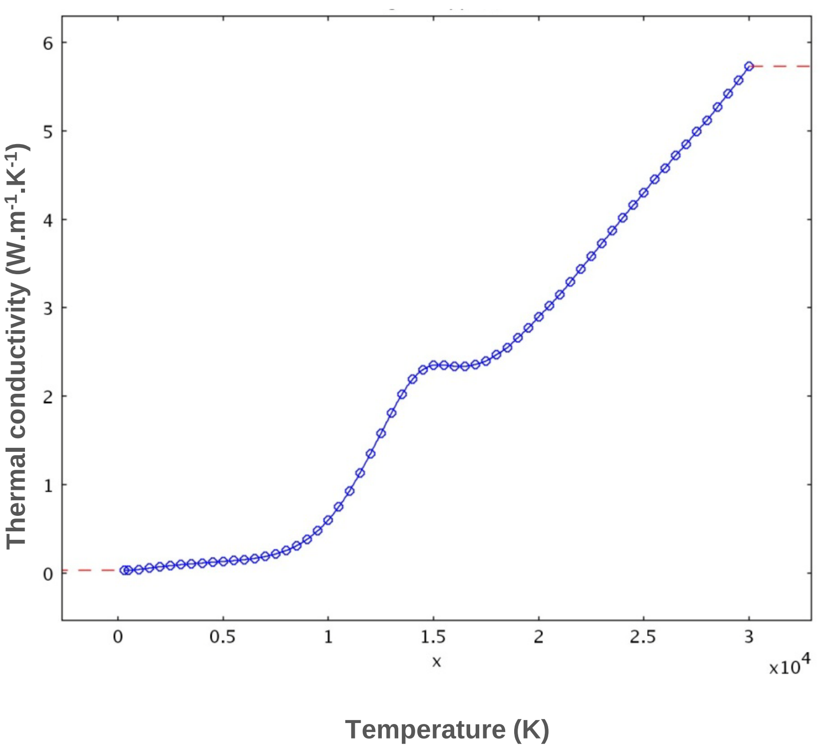
FREE-BURNING ARC SIMULATION – *Input data*

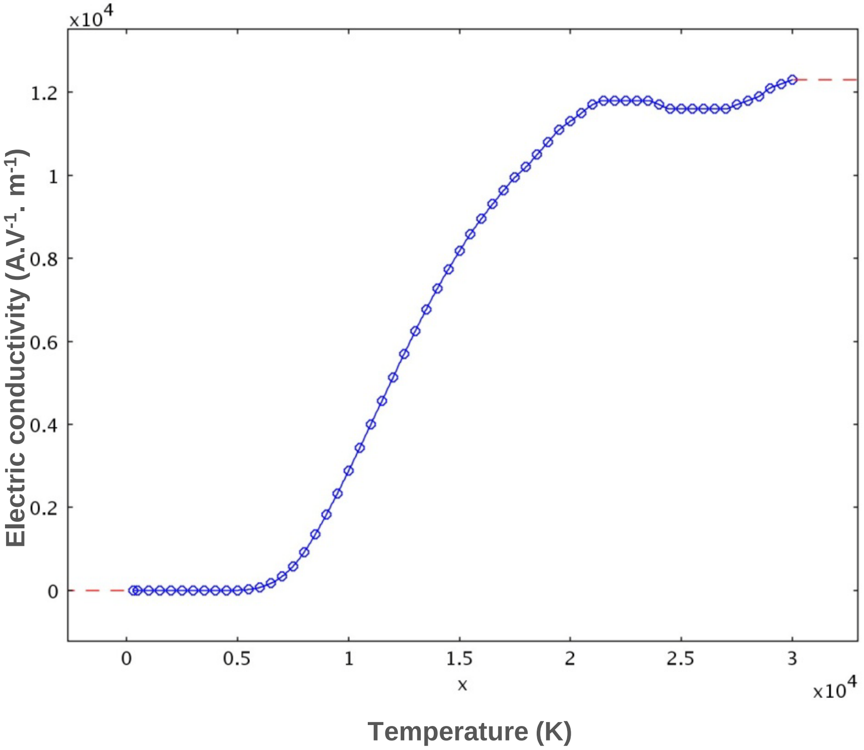




Thermodynamic properties & transport coefficients depend on temperature

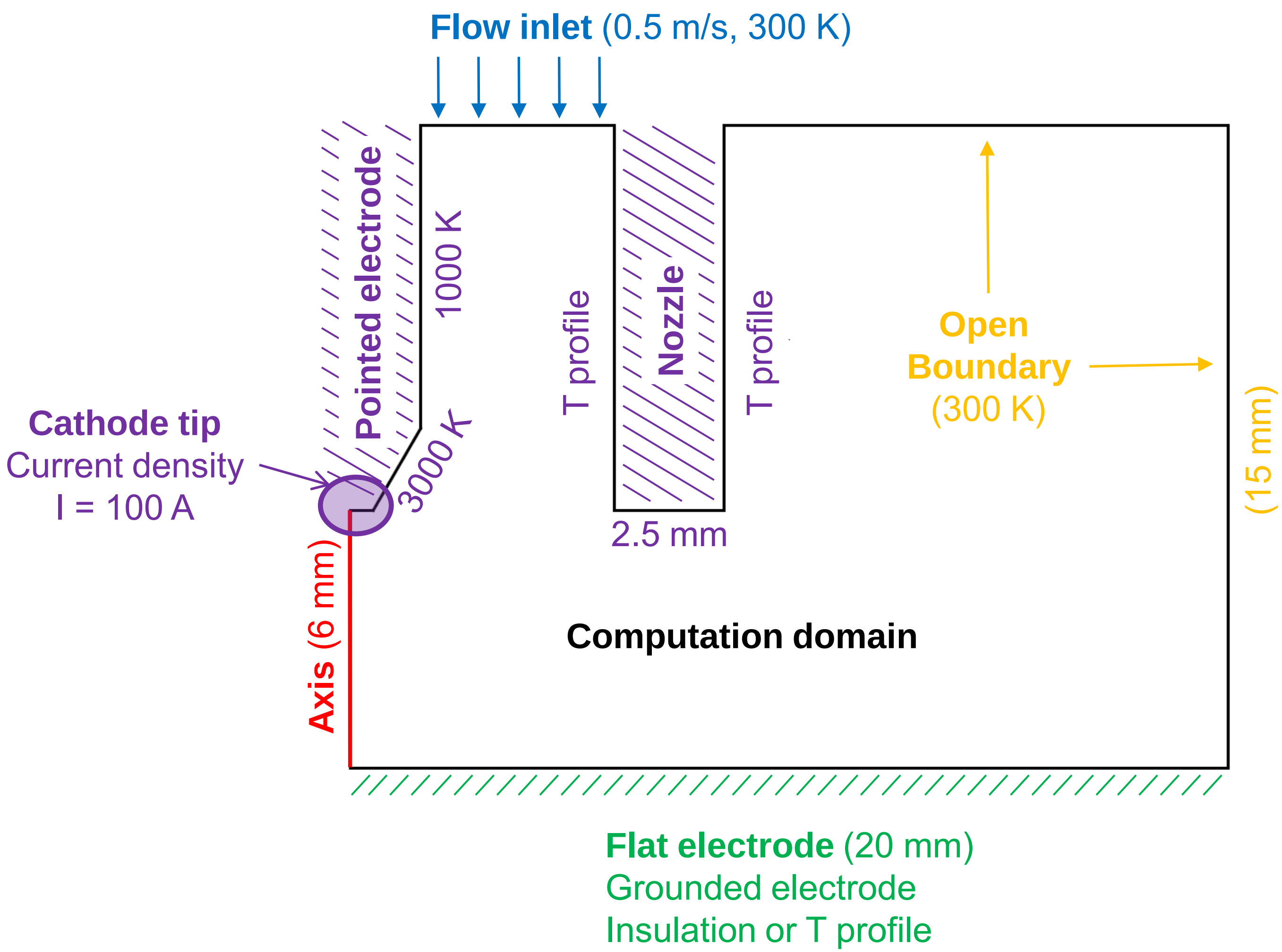
FREE-BURNING ARC SIMULATION – *Input data*





Implicit coupling

FREE-BURNING ARC SIMULATION – *Calculation Domain & Boundary Conditions*



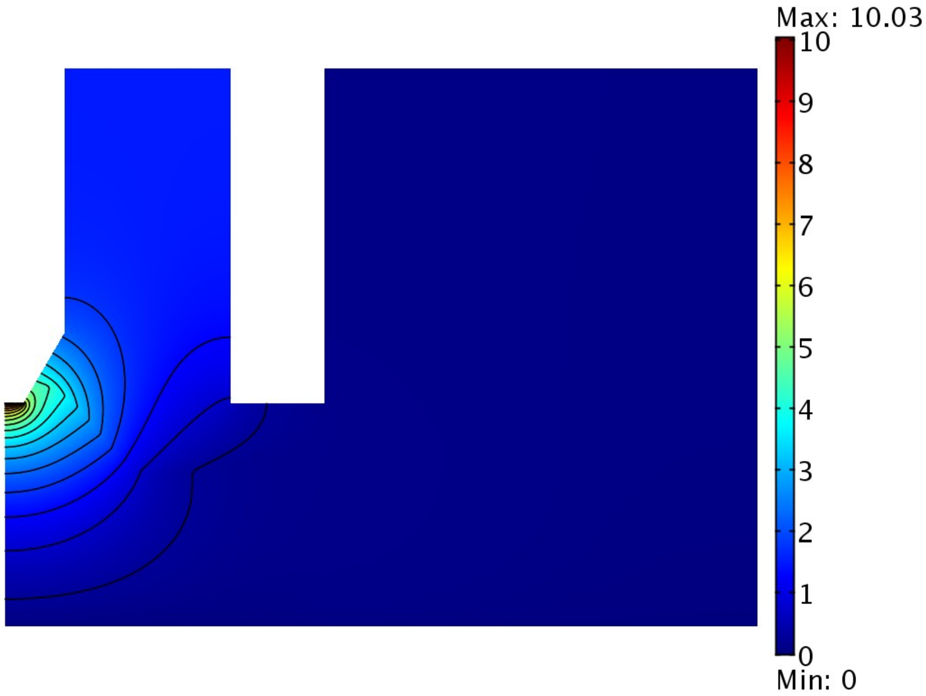
Mesh points
= 67 937

Triangular elements
= 134 655

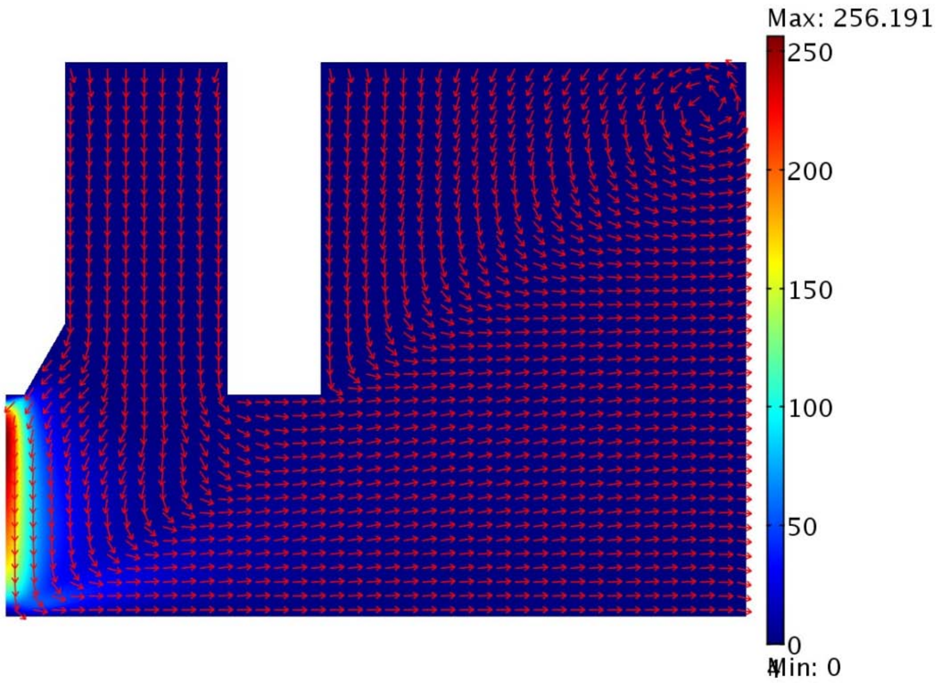
Degrees of freedom
= 2 096 423

Solver
= PARDISO stationary

Electric potential (V)



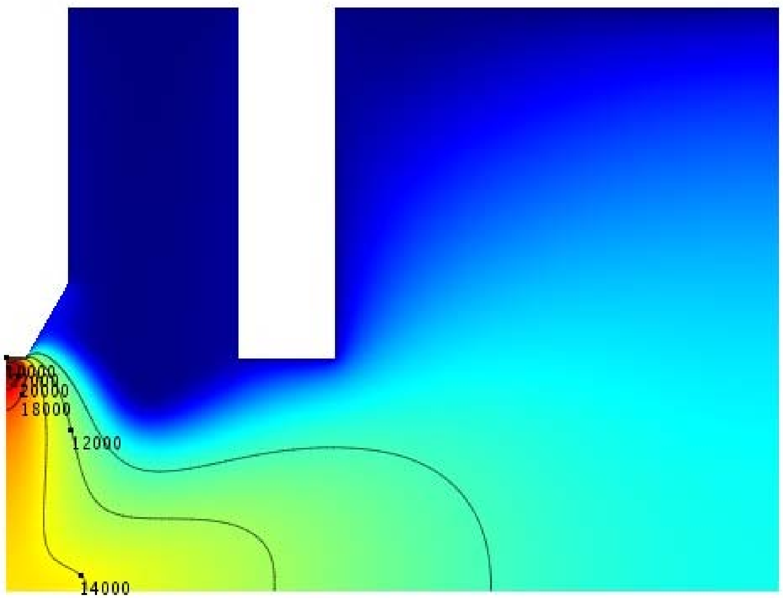
Velocity (m/s)



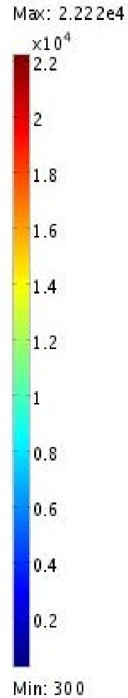
Good agreement with:

- Experimental results
- Previous simulations based on finite volume method

Temperature (K)



Anode boundary condition: **Insulation**



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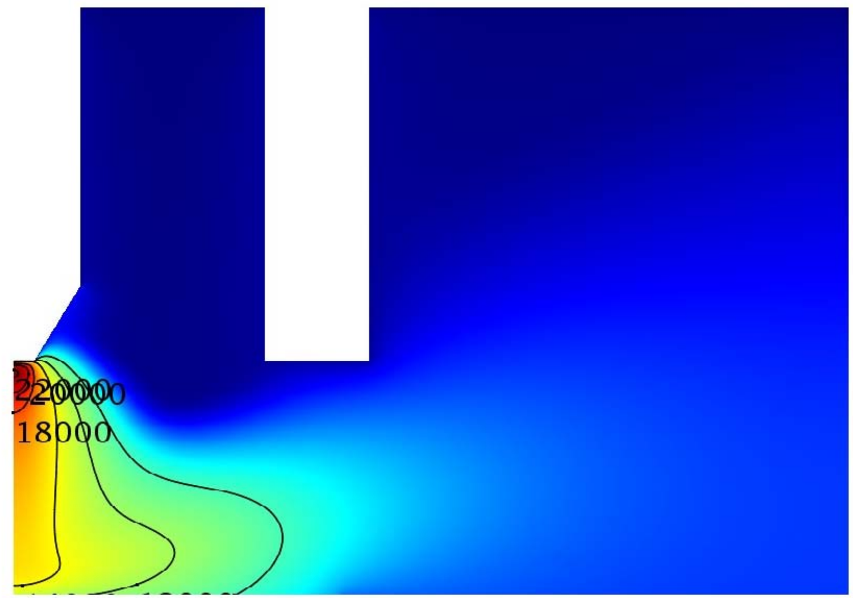
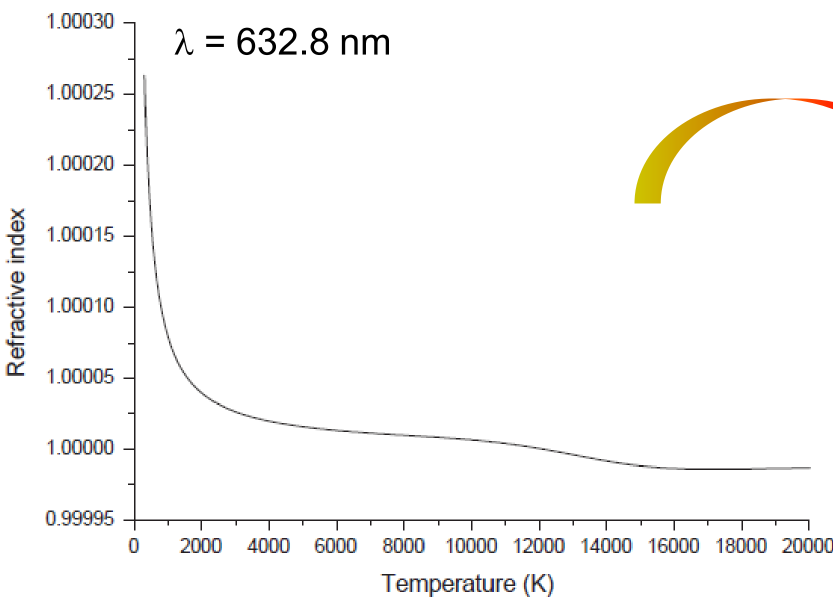


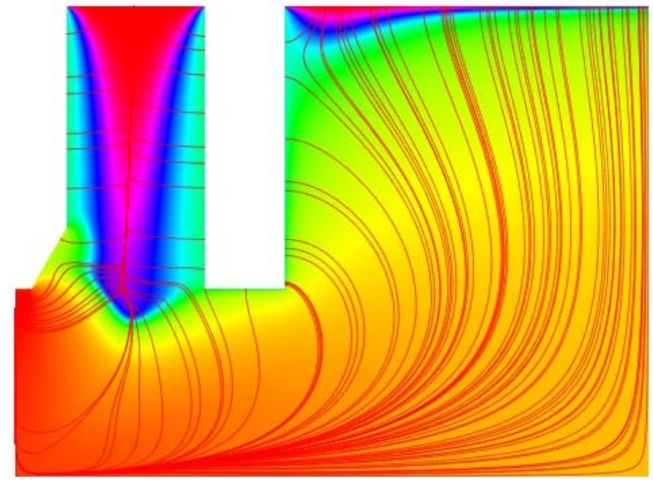
Anode boundary condition: **T profile**

- Only weak influence on temperature field in cathode and nozzle exit regions

FREE-BURNING ARC SIMULATION – *Results*

Refractive index & index gradients (streamlines)





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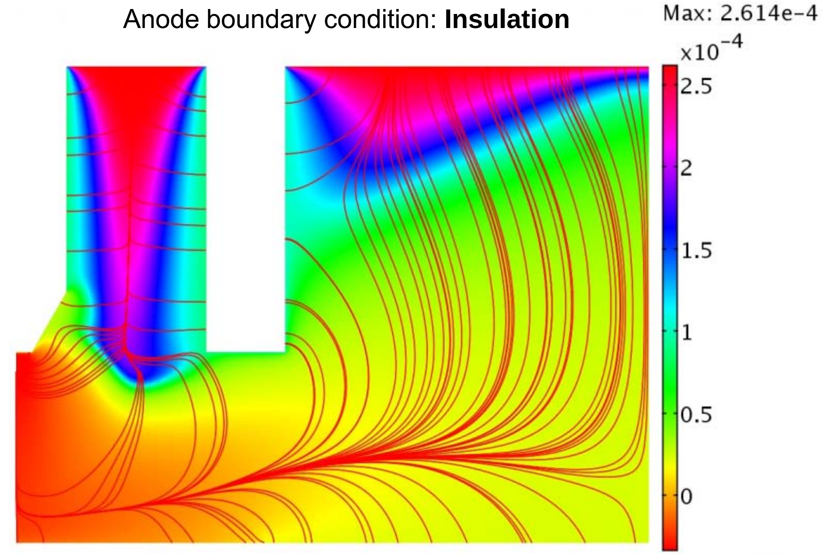


Anode boundary condition: **T profile**

- Validation of refractive index gradients
- Mainly for “low” temperatures
- Nozzle region

Ray-tracing

RAY-TRACING – *Theory*

The ray path in a non homogeneous zone can be calculated with vectorial formulation of Snell-Descartes laws:

$$\frac{d}{ds}\left(n\vec{u}\right)=\vec{\nabla}\left(n\right)$$

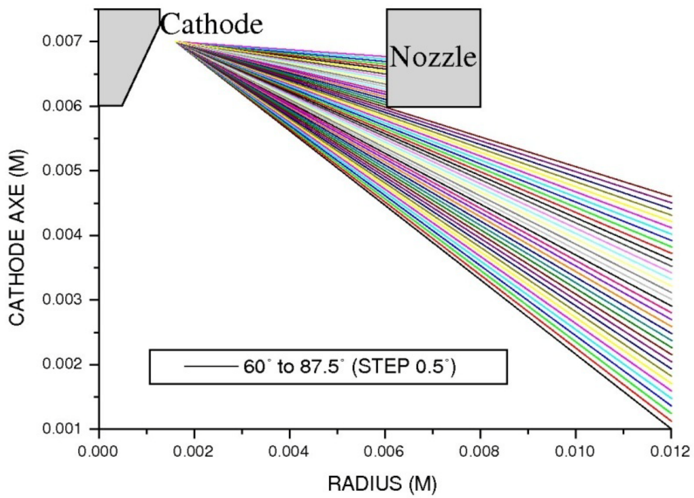
- **ds** is the **curvilinear abscissa**
- $\vec{u}$ the **unit vector tangent at any point in the trajectory** of the light
- **n** the **refractive index**

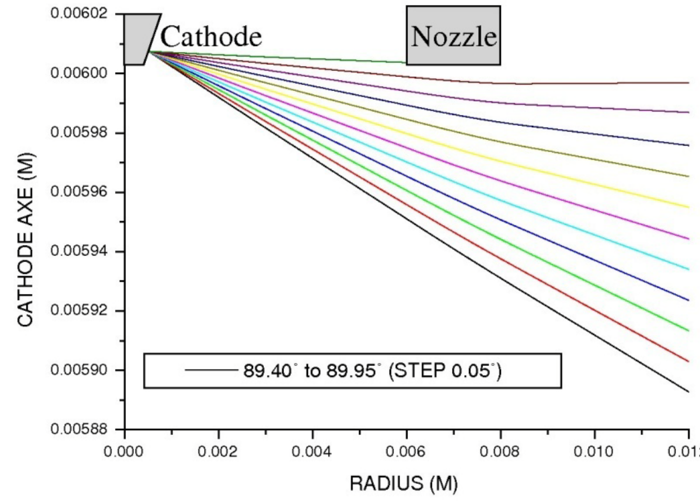
If the ray of **light comes from** a point $\mathbf{M_0(r_0,z_0)}$ with a θ **angle between the cathode axis and the ray propagation direction at** $\mathbf{M_0}$ **point**, we obtained:

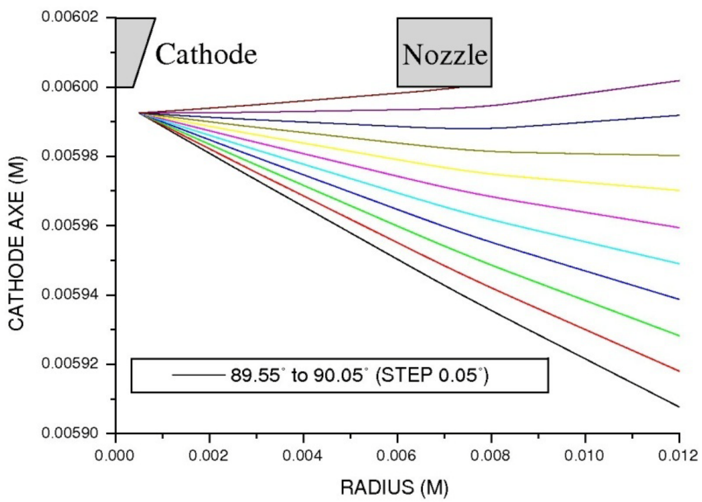
$$\begin{cases} \dfrac{dr_0}{dl} = n_0 \sin\theta \\ \dfrac{dz_0}{dl} = n_0 \cos\theta \end{cases}$$

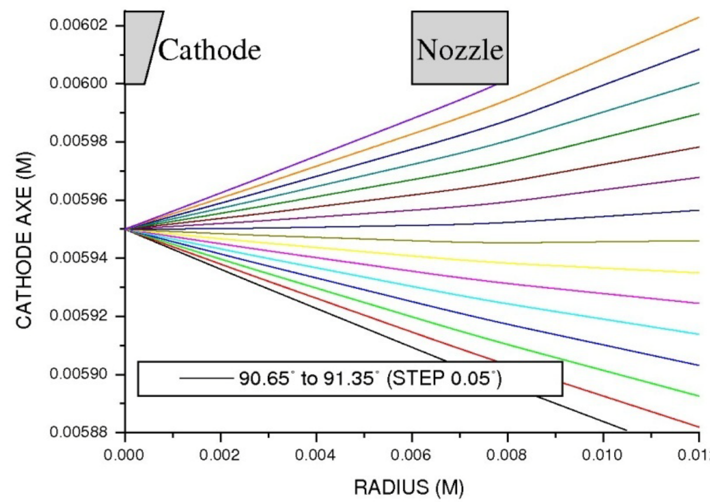
This equation system is solved with Euler method

RAY-TRACING – *Results*









Conclusion

- Demonstration of COMSOL Multiphysics capability to simulate arc discharges
- Still remain difficulties to reach convergence according to boundary condition type (Dirichlet's)
- Success in exporting and post-processing results (for ray-tracing)
- Further works on this subject to improve model and to take into account the electrodes