CHALMERS HÖGSKOLAN VÄST

Plasma Arc Welding Simulation with OpenFOAM

MARGARITA SASS-TISOVSKAYA

Supervisor : Isabelle Choquet,
Co-supervisor : Håkan Nilsson*
Examiner : Lars Davidson*

Dept. of Engineering Science
Högskolan Väst

***Dept. of Applied Mechanics,**
Chalmers University of Technology

Licentiate : 17 December 2009

IN PARTNERSHIP WITH THE Knowledge Foundation

ESAB SVETSNING & SKÄRNING Sverige

Volvo Construction Equipment

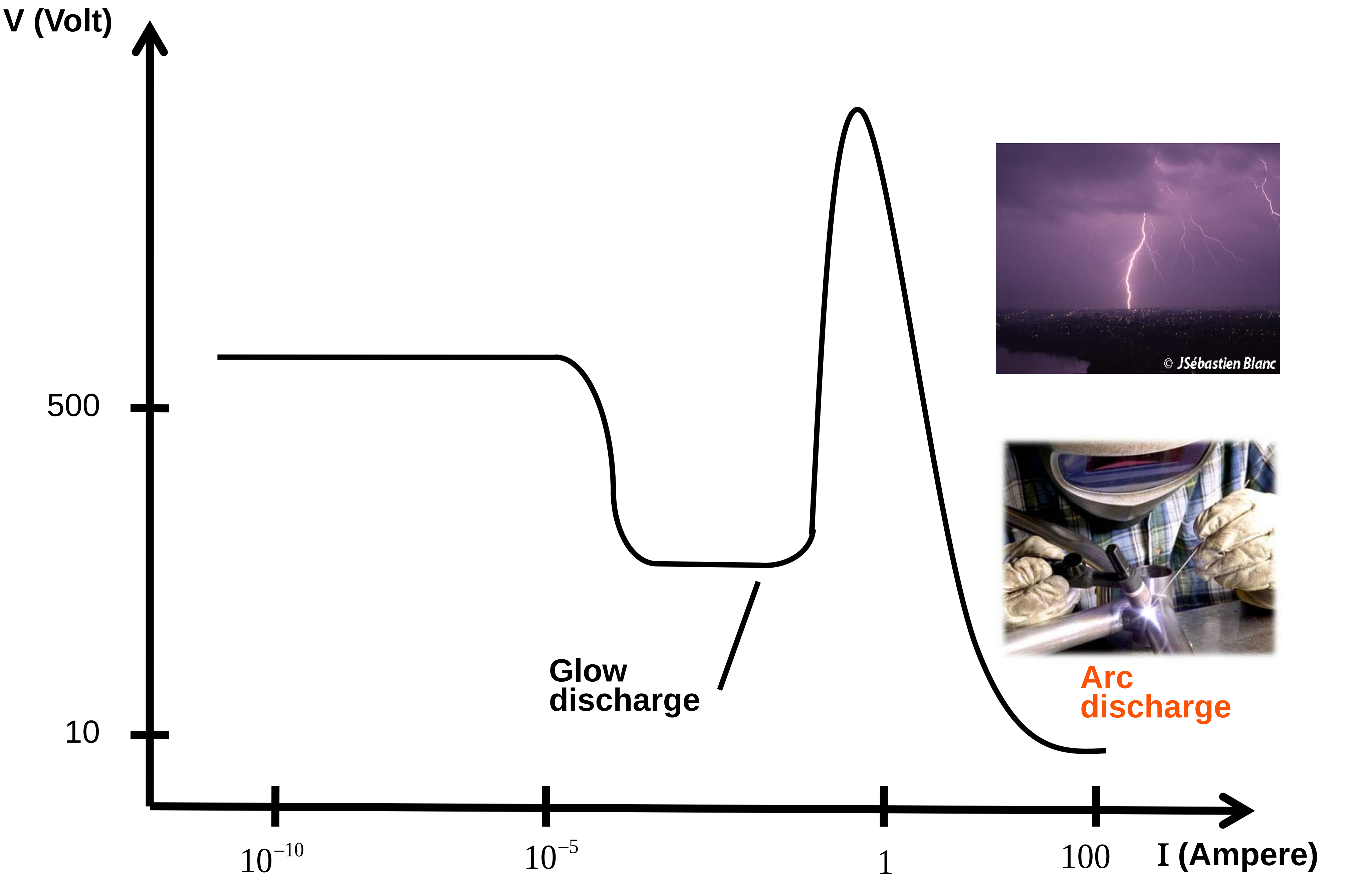
SSAB

MIGATRONIC

Outline:

- Introduction and motivation
- Problem description and main assumptions
- Mathematical model
- Implementation
- Results and discussions
- Summary and future work

Introduction:



Motivation: tandem arc welding

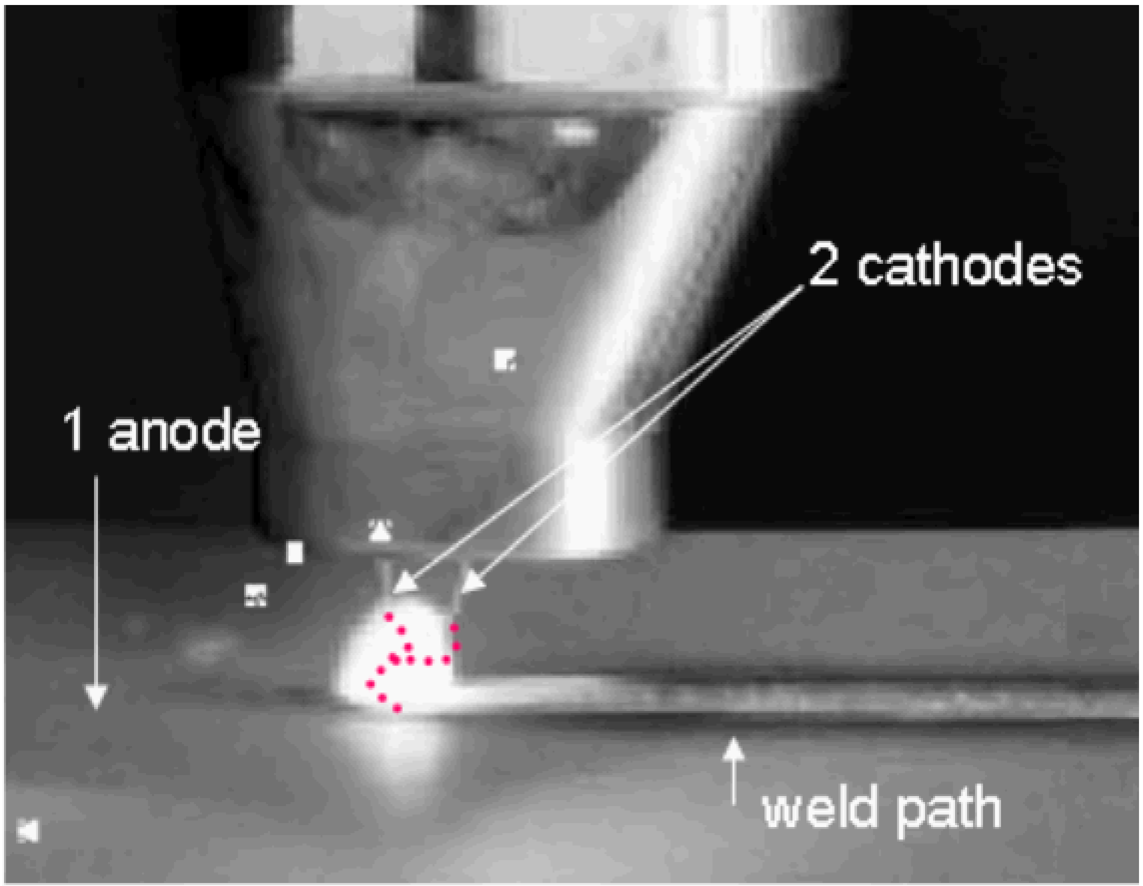


Figure : Tandem arc welding in operation (ESAB)

- Two heat sources
- High deposition efficiency
- Stability issue

- Extreme operating conditions

- Difficult experimental investigation
- Need for numerical simulations

Aim of this study:

- Develop a 3D simulation tool valid within the frame of tandem arcs.

Methodology used:

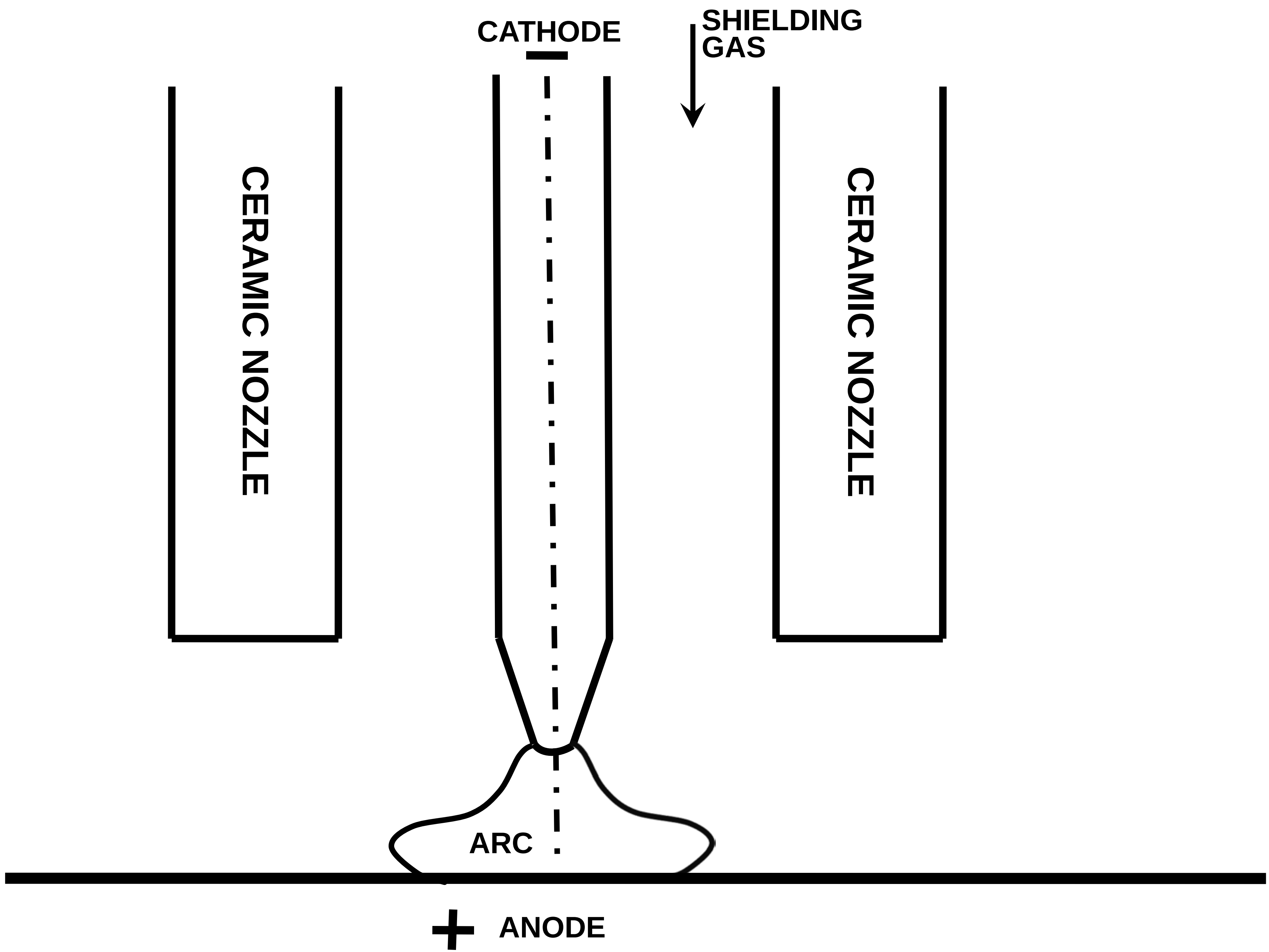
- Implementation in the open-source CFD software OpenFOAM
- Well documented welding arc test case:

  single arc Tungsten Inert Gas (TIG) welding

Outline:

- Introduction and motivation
- **Problem description and main assumptions**
- Mathematical model
- Implementation
- Results and discussions
- Summary and future work

Problem description: Tungsten Inert Gas welding



Problem description: arc plasma flow

- Newtonian fluid, laminar and incompressible
- Thermally expansible fluid
- Local thermodynamic equilibrium (LTE) , $Te=Th$.
- Negligible heat dissipation due to viscous effects
- Optically thin media, i.e. no radiative absorption

- Local electrical neutrality
- Steady electromagnetic phenomena
- Negligible magnetic convection compared to the magnetic diffusion

Outline:

- Introduction and motivation
- Problem description and main assumptions
- **Mathematical model**
- Implementation
- Results and discussions
- Summary and future work

Governing equations: thermal fluid

Continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho\, U) = 0$$

Where $\rho = \rho(T)$ is the density and U is the velocity.

Momentum equations

$$\frac{\partial}{\partial t}(\rho U) + \nabla \cdot (\rho U U) - \nabla \cdot \underbrace{\left[\mu \left(\nabla U + \nabla U^{T} \right) - \frac{2}{3} \mu (\nabla \cdot U) I \right]}_{\text{Viscous friction for Newtonian fluid}} = -\nabla p + \underbrace{j \times B}_{\text{Lorenz Force}}$$

where $\mu = \mu(T)$ is the effective viscosity

Enthalpy equation

$$\frac{\partial}{\partial t}(\rho h) + \rho U\, \nabla \cdot h - \nabla \cdot (\alpha \nabla h) = U \cdot \nabla p + \underbrace{j \cdot E}_{\text{Joule heating}} - \underbrace{S_r}_{\text{Radiation loss}} + \underbrace{S_e}_{\text{Transport of electron enthalpy}}$$

Governing equations: electromagnetism

- **Electric potential equation**

$$\nabla \cdot \left(\sigma \nabla \varphi\right) = 0$$

φ is the electric potential, $\sigma = \sigma(T)$ is the electric conductivity

- **Magnetic potential equation**

$$\nabla^2 A = \sigma \mu_0 \nabla \varphi$$

where μ_0 is permeability of vacuum, A the magnetic potential vector

Governing equations

The magnetic field B can be derived in 2 ways:

✓ *1st : for general 3D case*

$$B = \nabla \times A$$

where A magnetic potential vector

✓ *2nd : only for axisymmetric case*

$$\frac{\partial B_\Theta}{\partial r} = -\mu_0 j_x$$

where a cylindrical coordinate system (r, Θ, x) is used

No need to solve the magnetic potential equation

Outline:

- Introduction and motivation
- Problem description and main assumptions
- Mathematical model
- **Implementation**
- Results and discussions
- Summary and future work

buoyantSimpleFoam solver

The *buoyantSimpleFoam* solver is a standard, steady-state solver for buoyant, turbulent flow of compressible fluids used for ventilation and heat transfer.

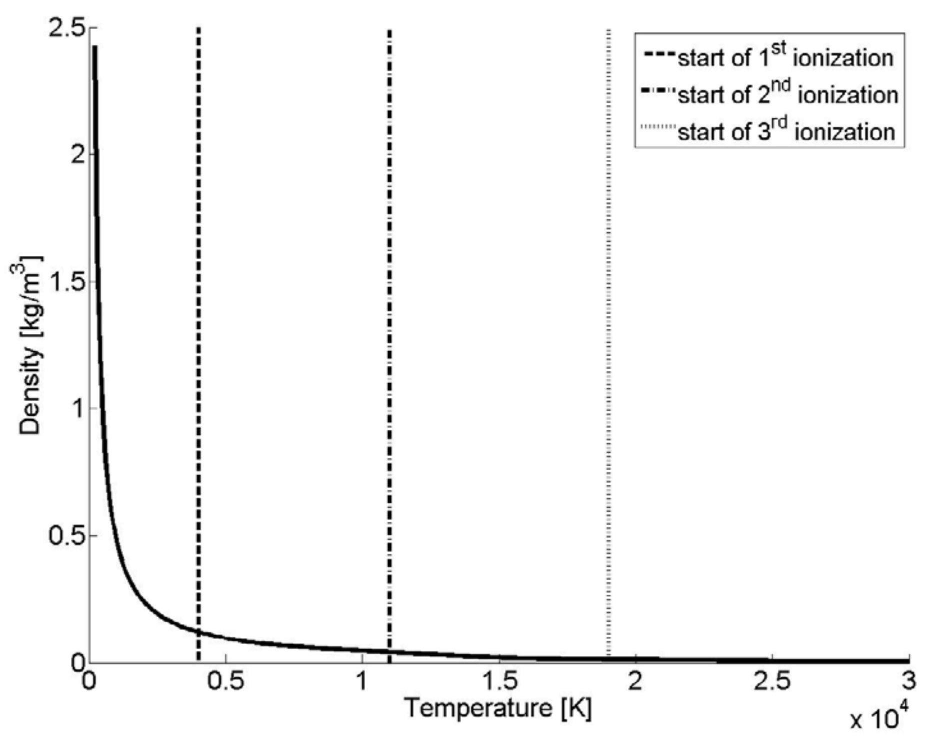
arcFoam solver

The simulation tool developed for arc welding problem

Governing equations

- **Continuity equation:**

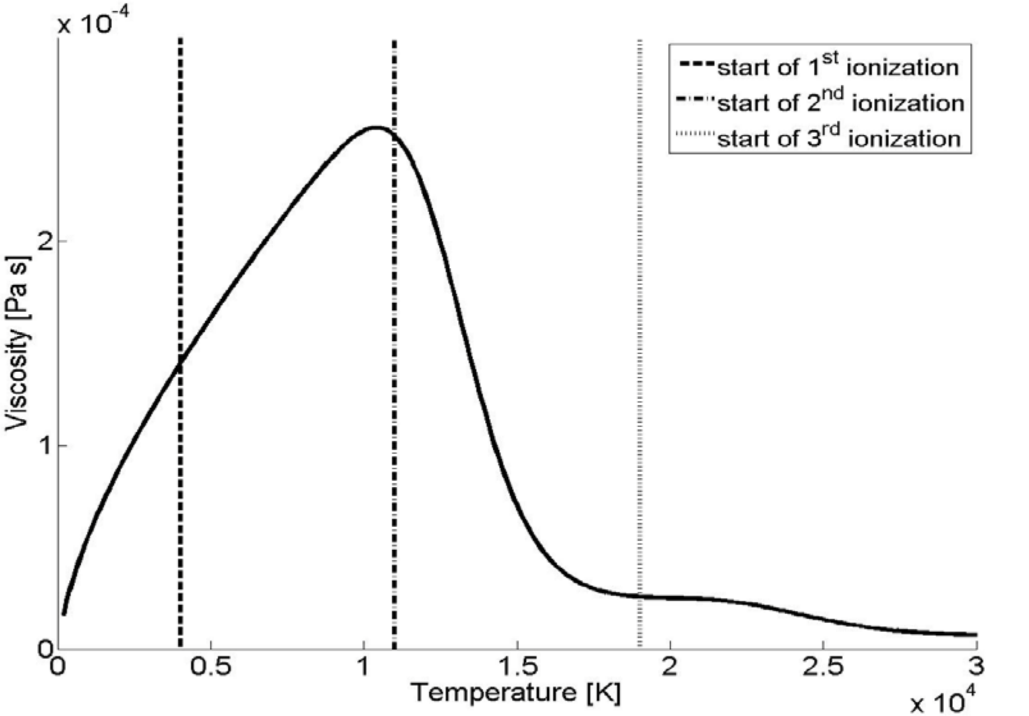
buoyantSimpleFOAM solver	*arcFOAM solver*
$$\nabla \cdot (\rho U) = 0$$	$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho\, U) = 0$$
where $\rho = \frac{p}{RT}$	where $\rho = \rho(T)$



Governing equations

➢ **Momentum equations :**

buoyantSimpleFOAM solver	*arcFOAM solver*
$\nabla\cdot(\rho UU)-\nabla\cdot\left[\mu\left(\nabla U+\nabla U^{T}\right)-\frac{2}{3}\mu(\nabla\cdot U)I\right]=-\nabla p$	$\frac{\partial}{\partial t}(\rho U)+\nabla\cdot(\rho UU)-\nabla\cdot\left[\mu\left(\nabla U+\nabla U^{T}\right)-\frac{2}{3}\mu(\nabla\cdot U)I\right]=-\nabla p+j\times B$



Governing equations

- **Enthalpy equation:**

buoyantSimpleFOAM solver

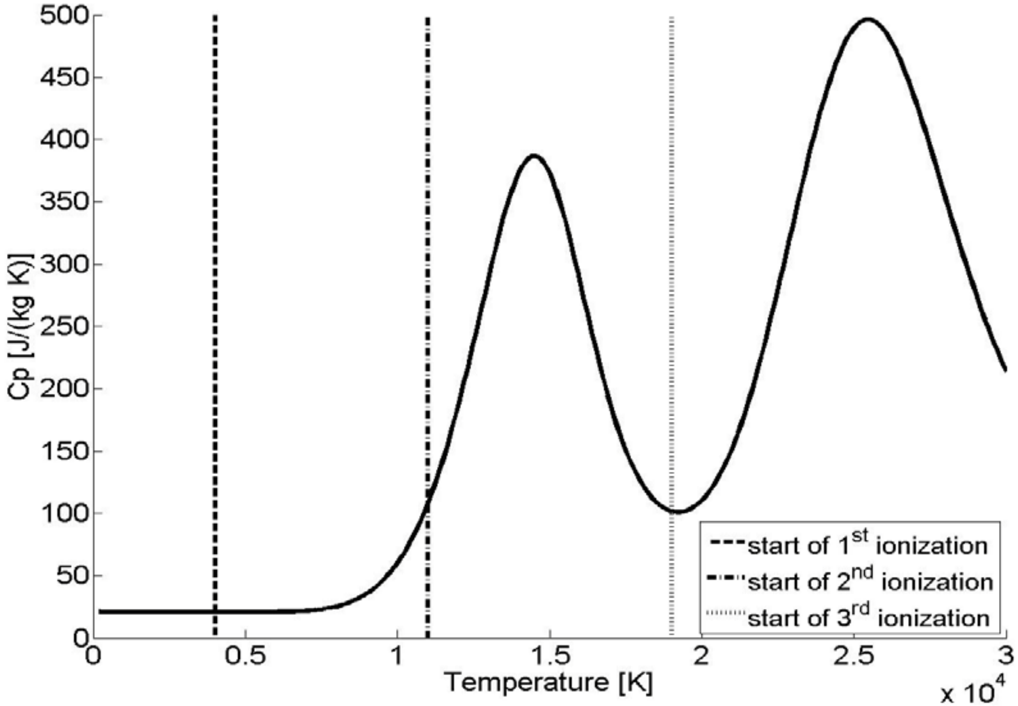
$$\rho U \nabla \cdot h - \nabla \cdot (\alpha \nabla h) = U \cdot \nabla p$$

where $\alpha = \dfrac{\kappa}{\rho C_p}$

arcFOAM solver

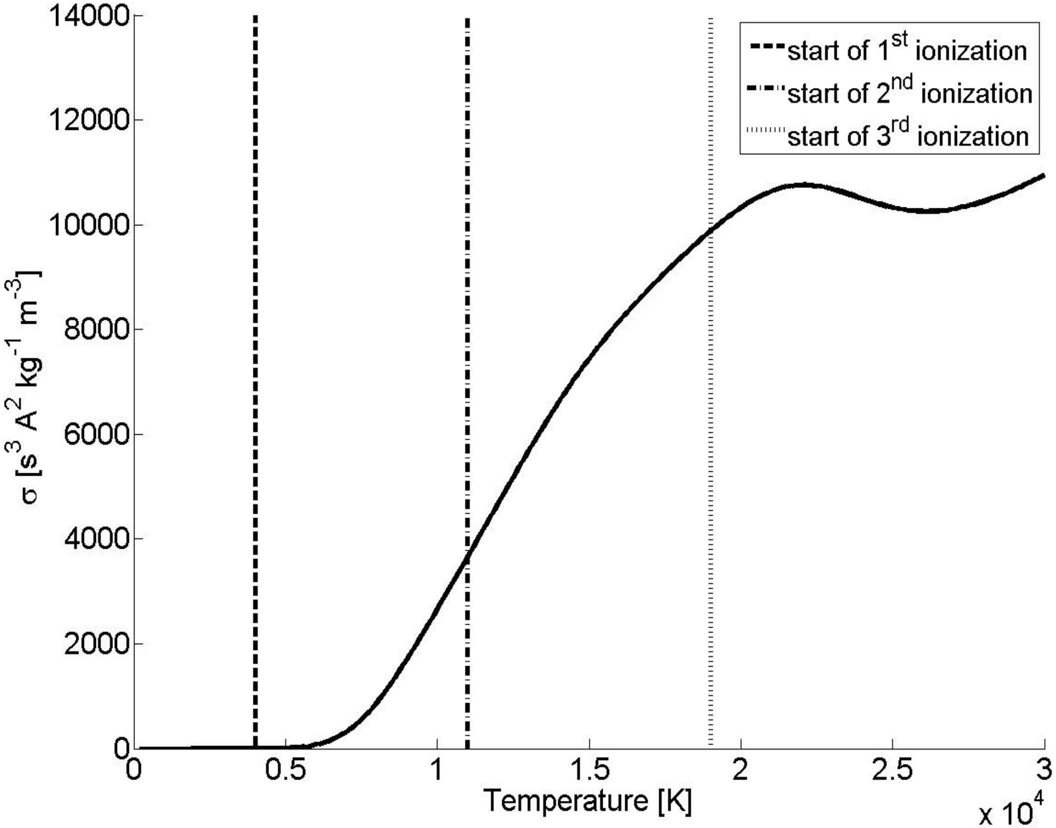
$$\frac{\partial}{\partial t}(\rho h) + \rho U \ \nabla \cdot h - \nabla \cdot (\alpha \nabla h) = U \cdot \nabla p + j \cdot E - S_r + S_e$$

where $\alpha = \dfrac{\kappa}{\rho C_p}$



Governing equations

➢ **Electric potential and magnetic potential equations:**

buoyantSimpleFOAM solver	*arcFOAM solver*
	$$\nabla \cdot (\sigma \nabla \varphi) = 0$$ $$\nabla^2 A = \sigma \mu_0 \nabla \varphi$$ 

Outline:

- Introduction and motivation
- Problem description and main assumptions
- Mathematical model
- Implementation
- Results and discussions
  - **Electromagnetic test case**
  - TIG test case
- Summary and future work

Validation of the electromagnetic part

- **Governing equations**

$$\nabla \cdot \left(\sigma \nabla \varphi\right) = 0$$

$$\nabla^2 A = \sigma \mu_0 \nabla \varphi$$

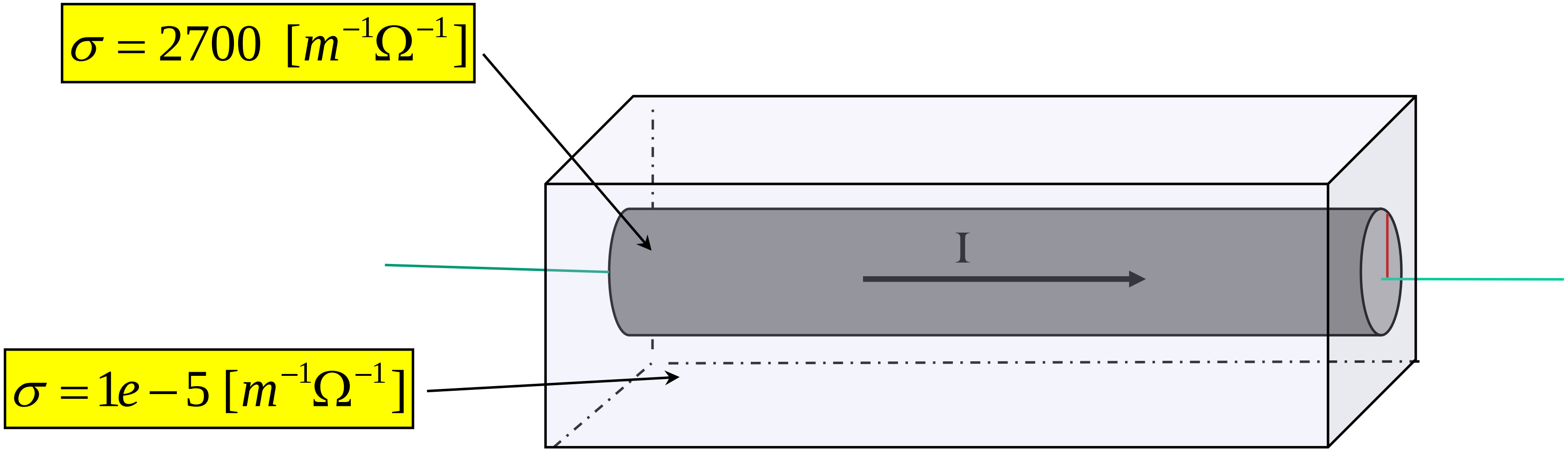


Figure: Electric rod

Validation of the electromagnetic part

- **Boundary conditions**

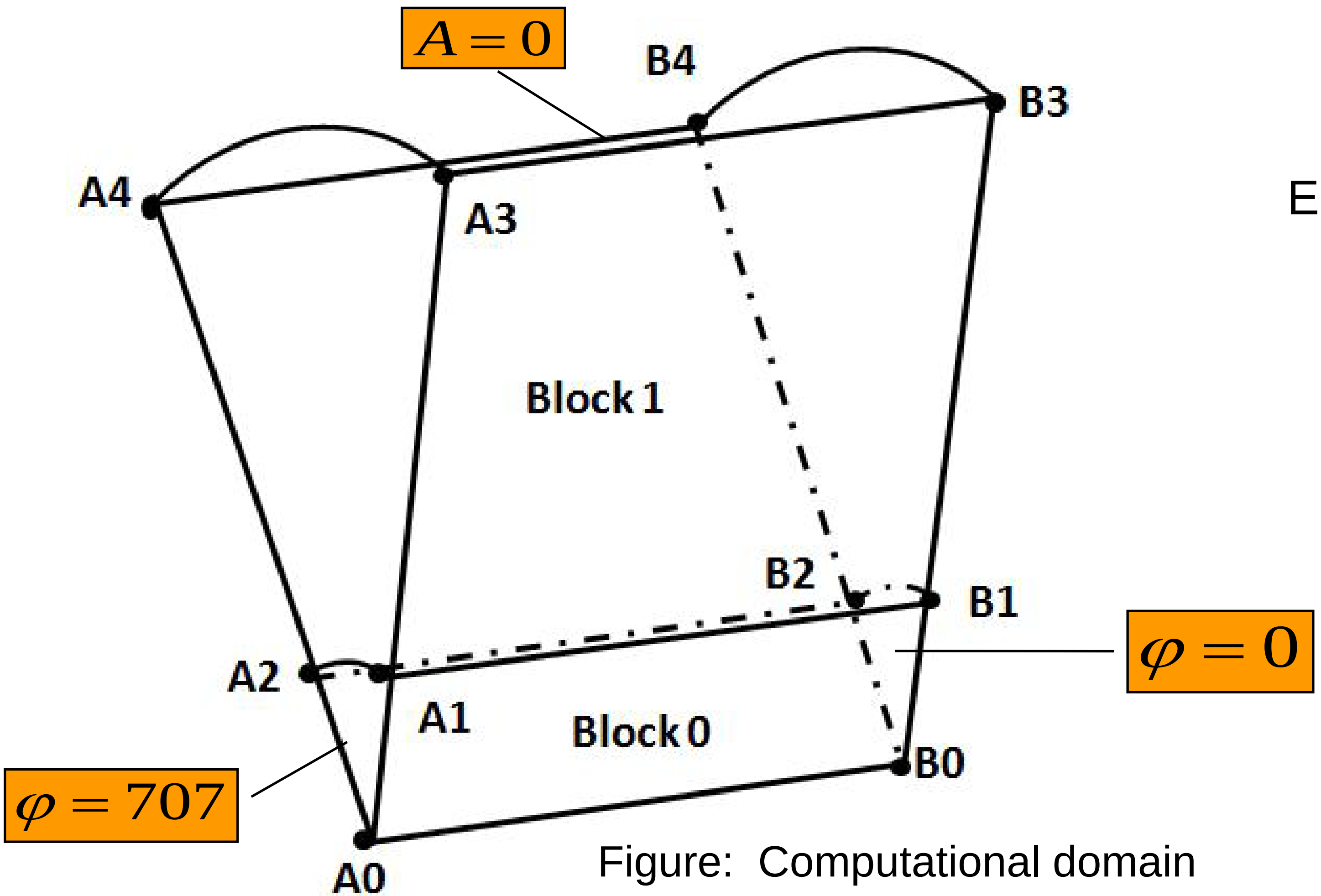


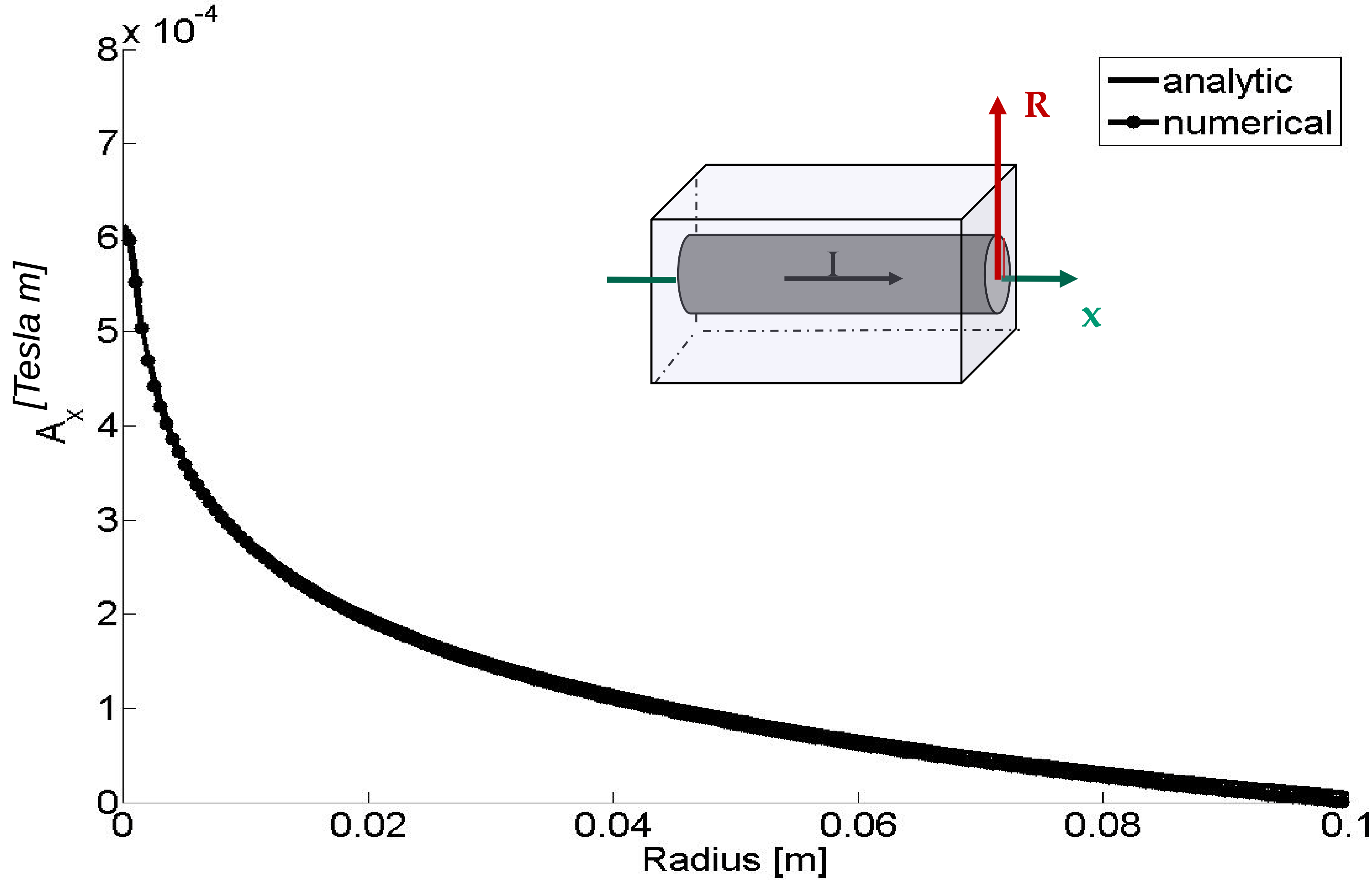
Figure: Computational domain

Elsewhere B.C.:

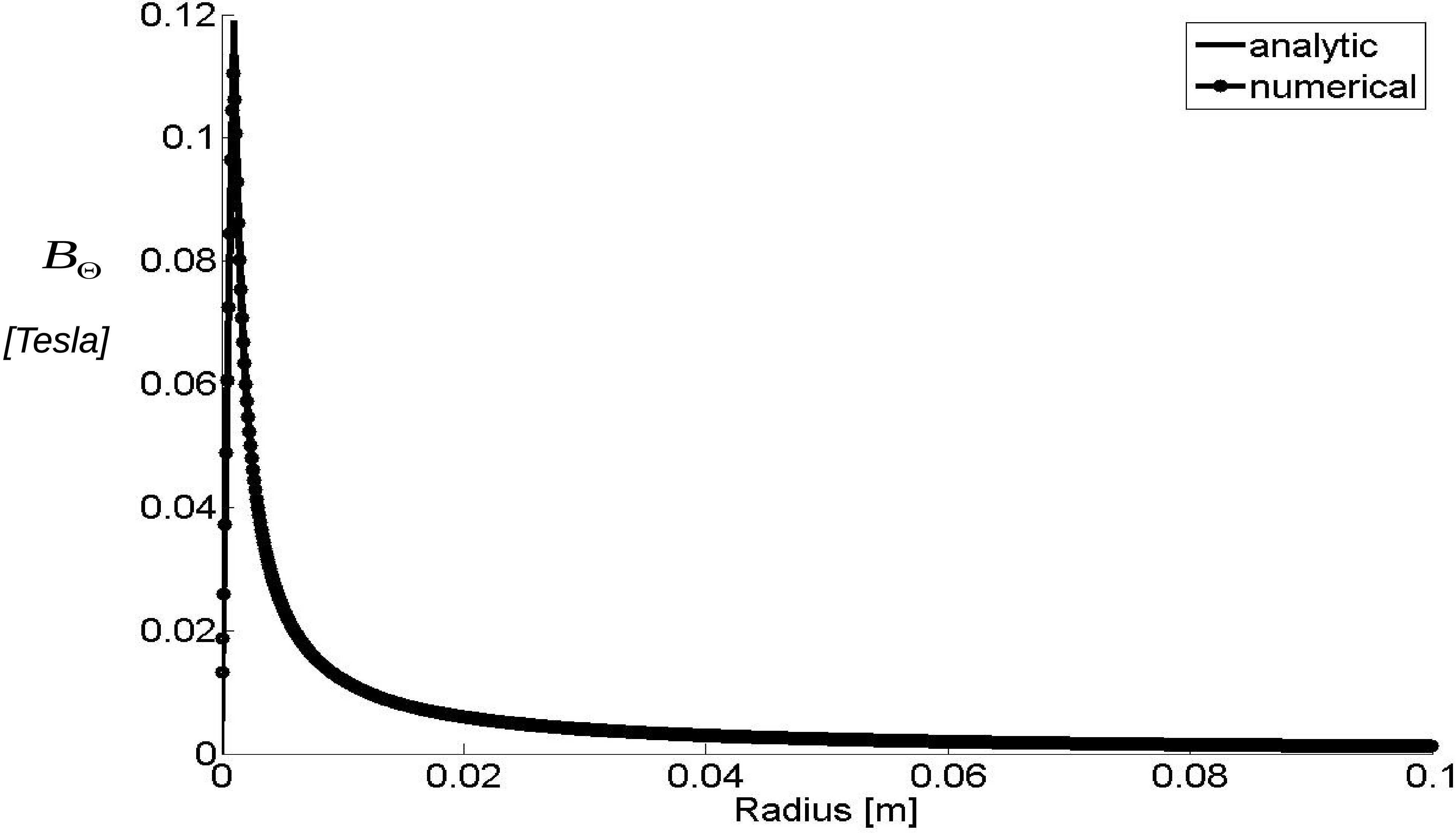
$$\frac{\partial A}{\partial n} = 0$$

$$\frac{\partial \varphi}{\partial n} = 0$$

Validation of the results

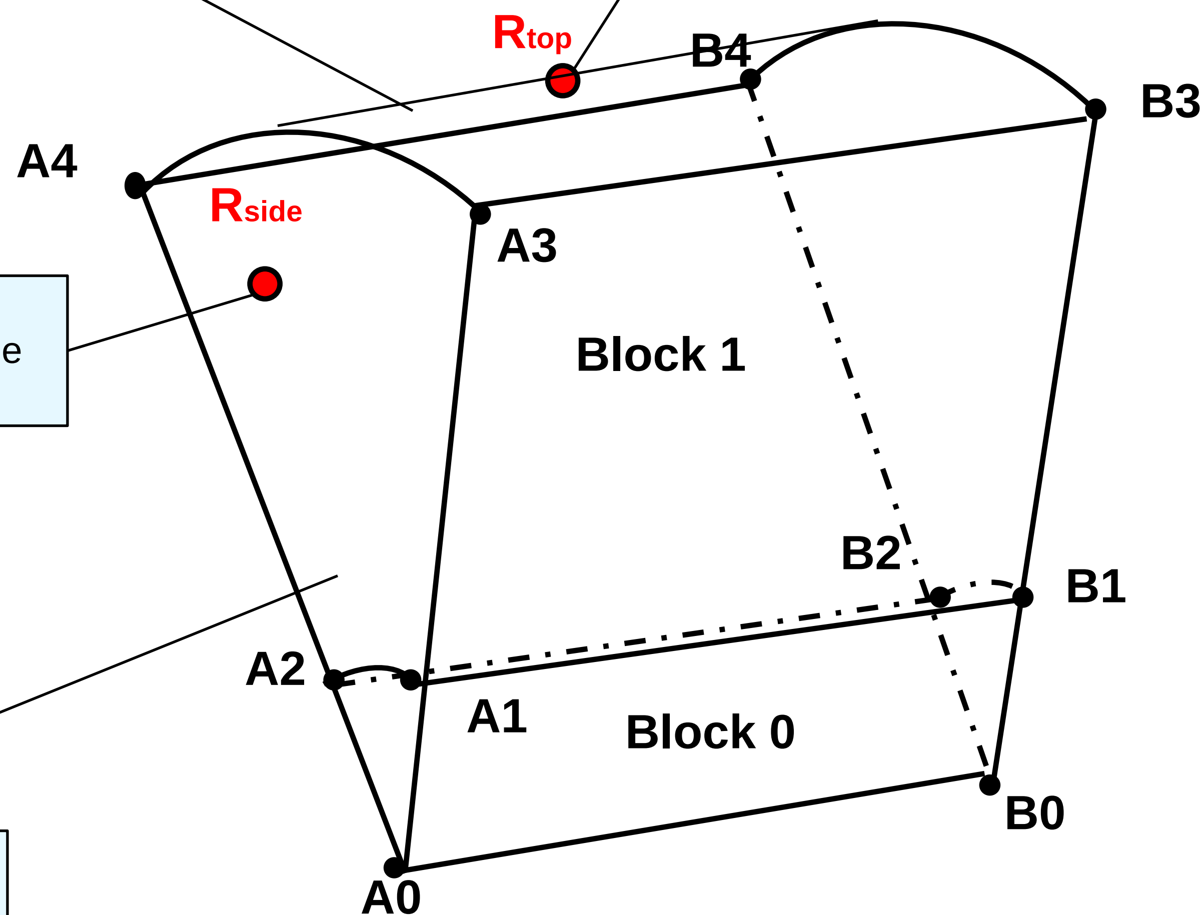


Validation of the results



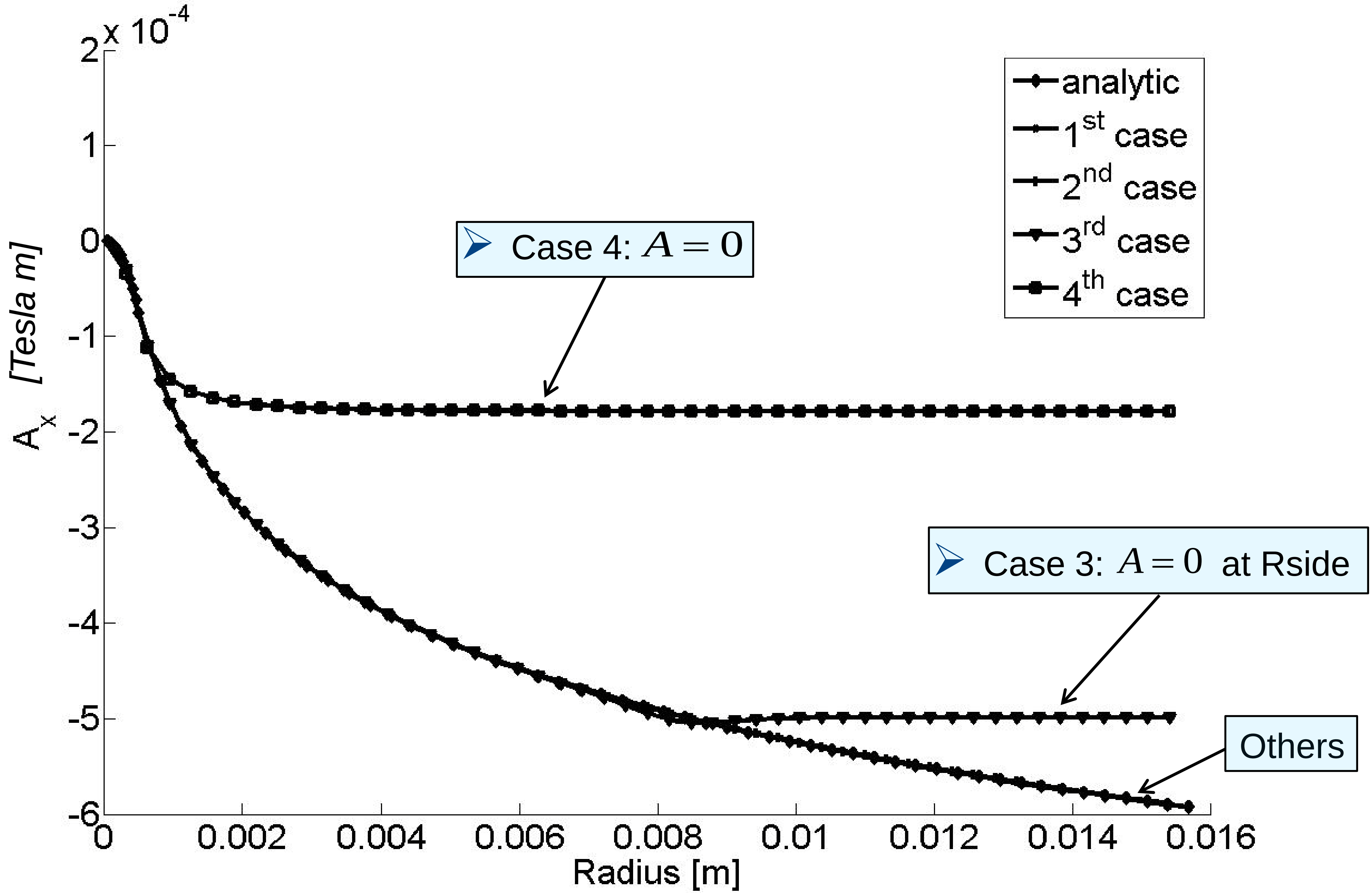
Test of boundary conditions

- Case 1: $A = 0$
- Case 2: $A = 0$ at R_{top}
- Case 3: $A = 0$ at R_{side}

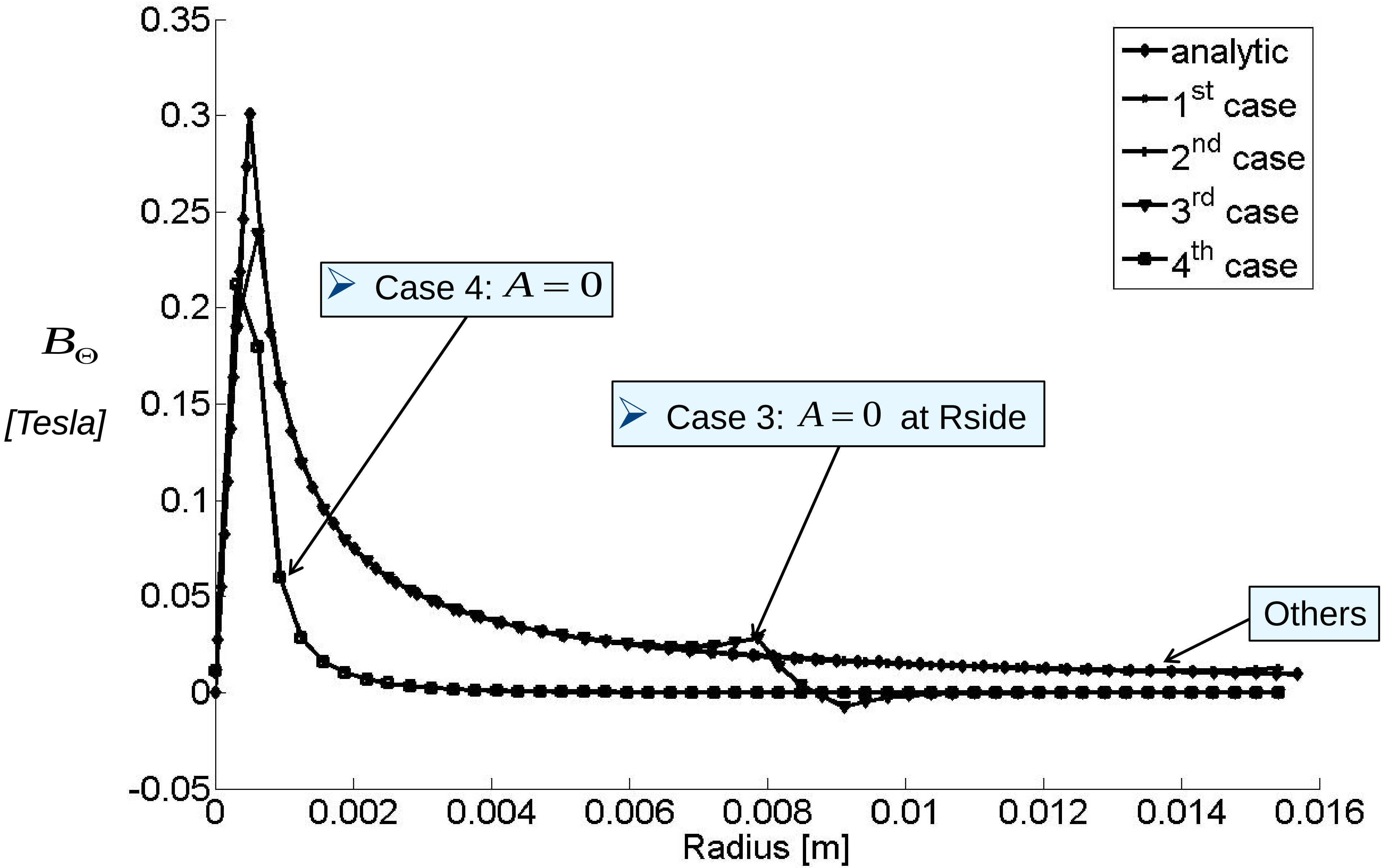


- Case 4: $A = 0$

Validation of the results



Validation of the results



Conclusion on the rod test cases

- Test with a known solution:
  - Analytical solution for magnetic potential vector and magnetic field are available
  - good agreement between the numerical and analytical solutions

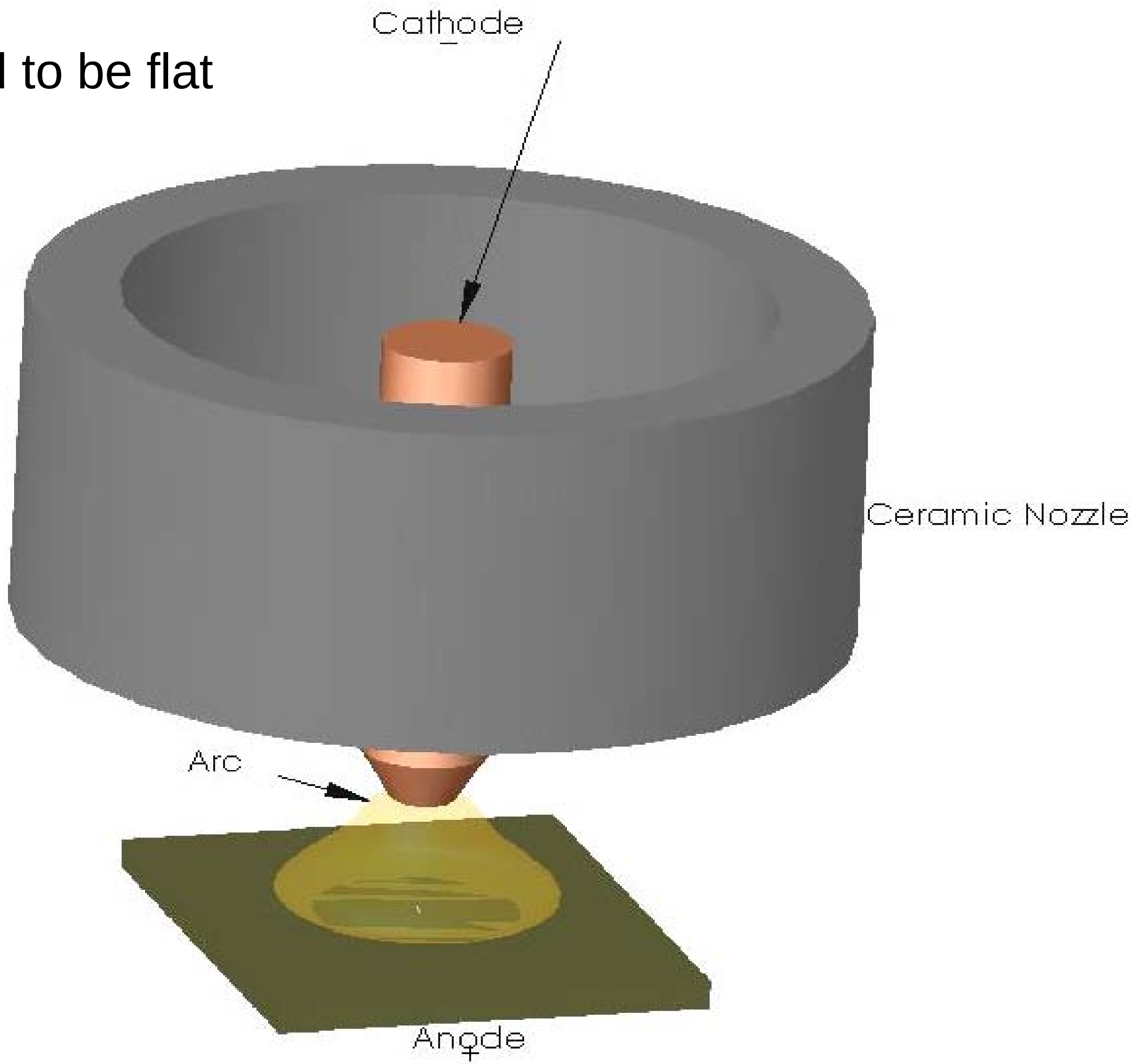
- Tests on various boundary conditions for the magnetic potentials:
  - 4 boundary conditions were tested
  - boundary condition of case 1 retained for TIG test case

Outline:

- Introduction and motivation
- Problem description and main assumptions
- Mathematical model
- Implementation
- Results and discussions
    - Electromagnetic test case
    - **TIG test case**
- Summary and future work

TIG test case:

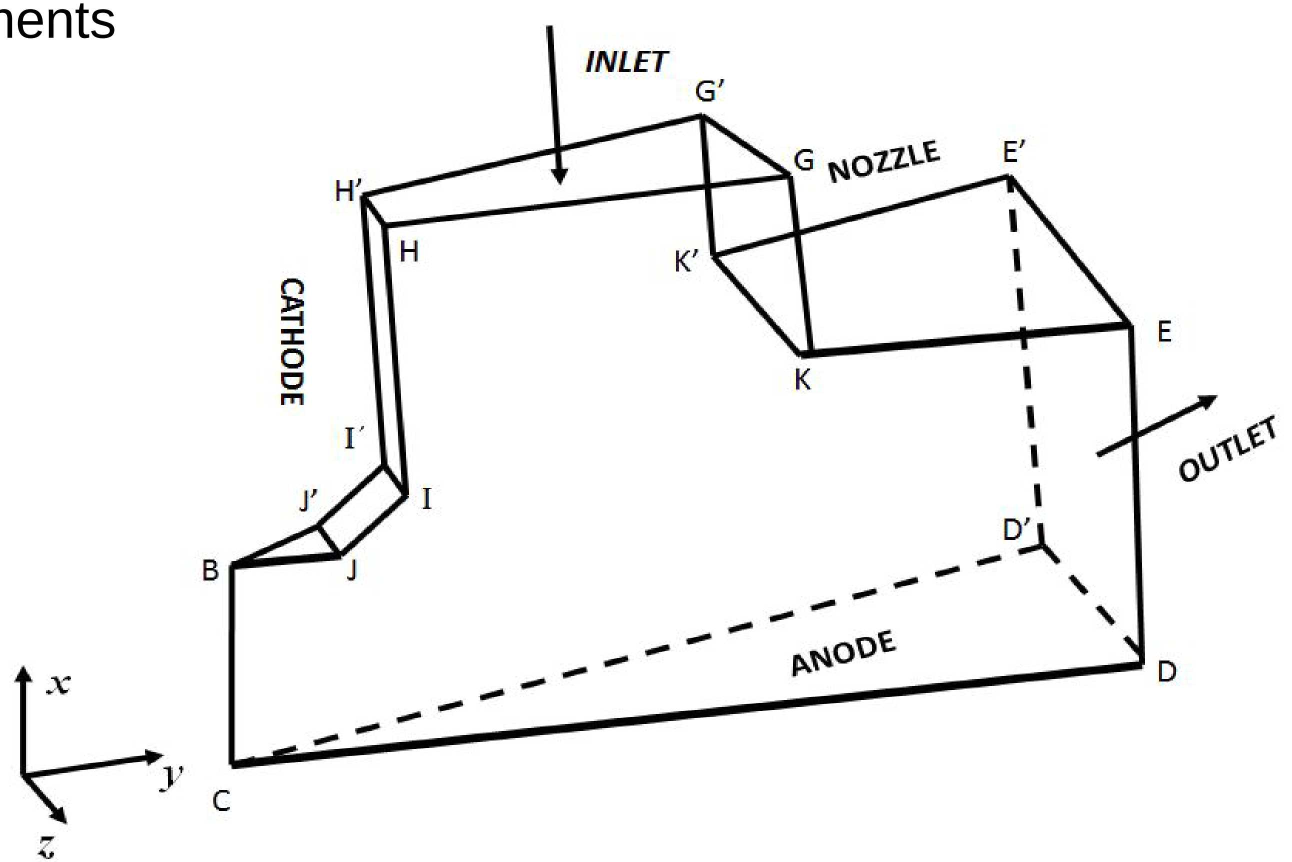
- Anode surface is considered to be flat
- Axi-symmetric geometry
- Argon shielding gas
- 200 A electric current



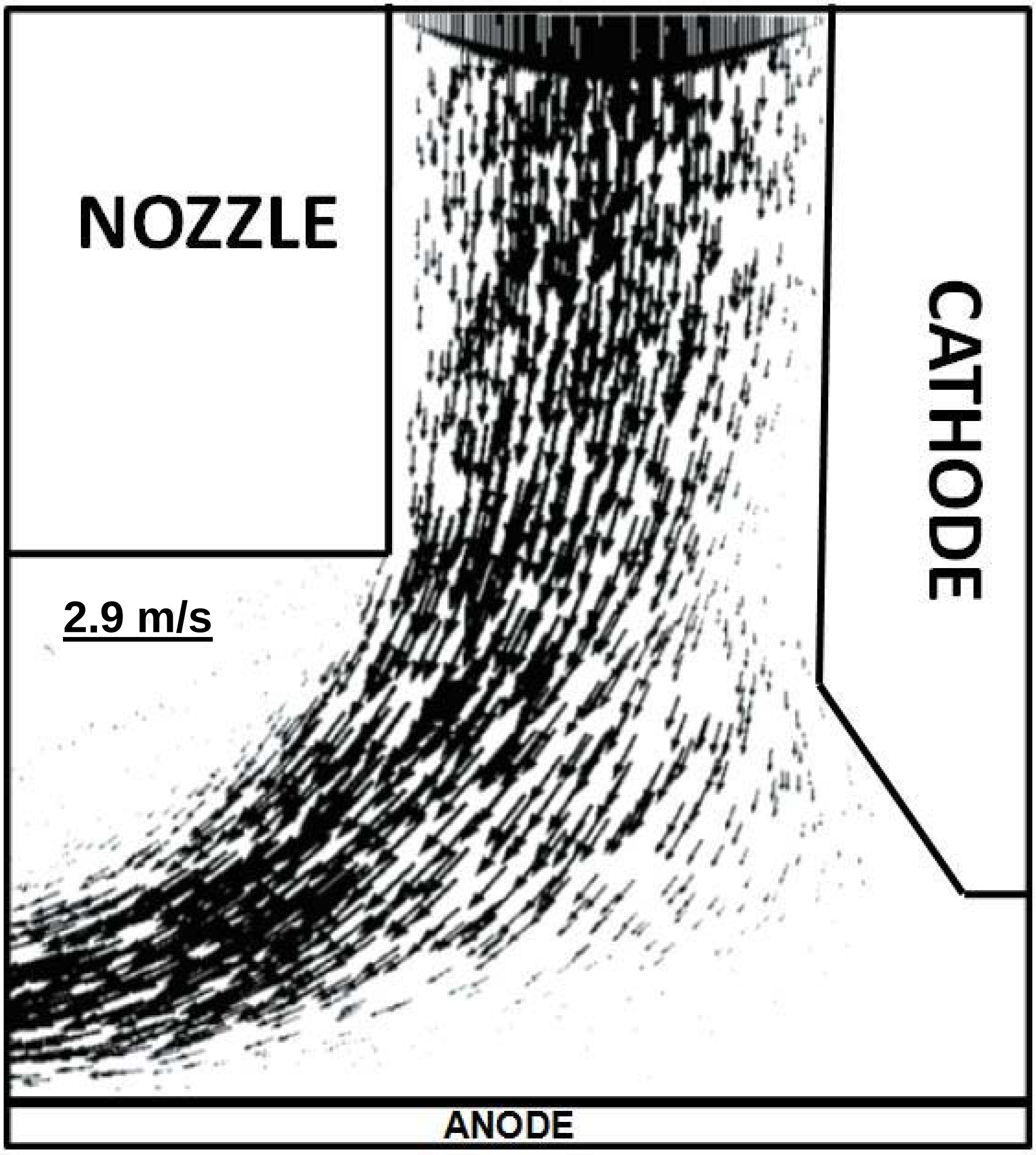
TIG test case:

Boundary conditions

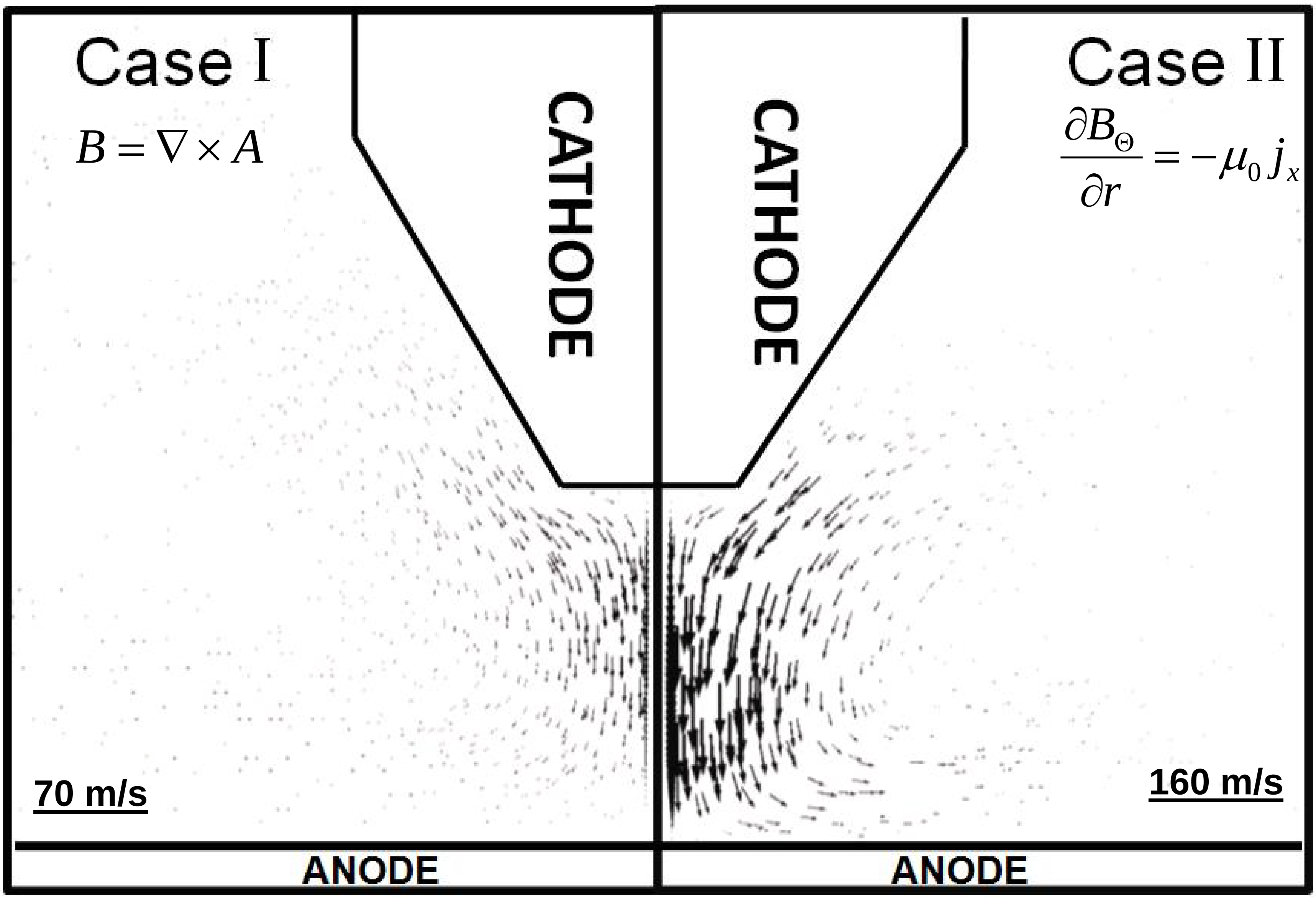
- Cathode tip at 20 000K
- Linear temperature distribution on cathode sides
- anode surface temperature distribution set using experimental measurements



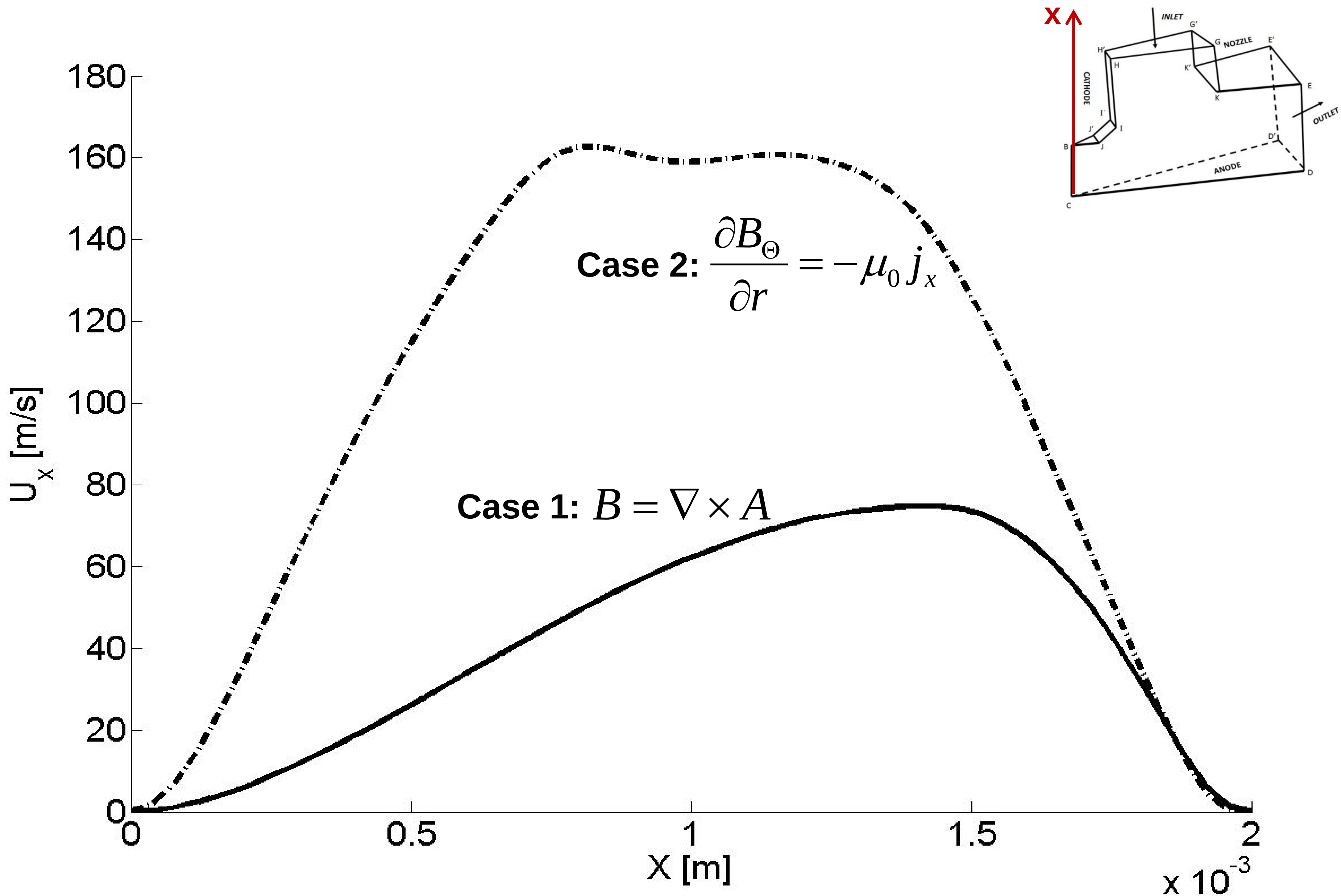
Results. Velocity vectors without electromagnetism



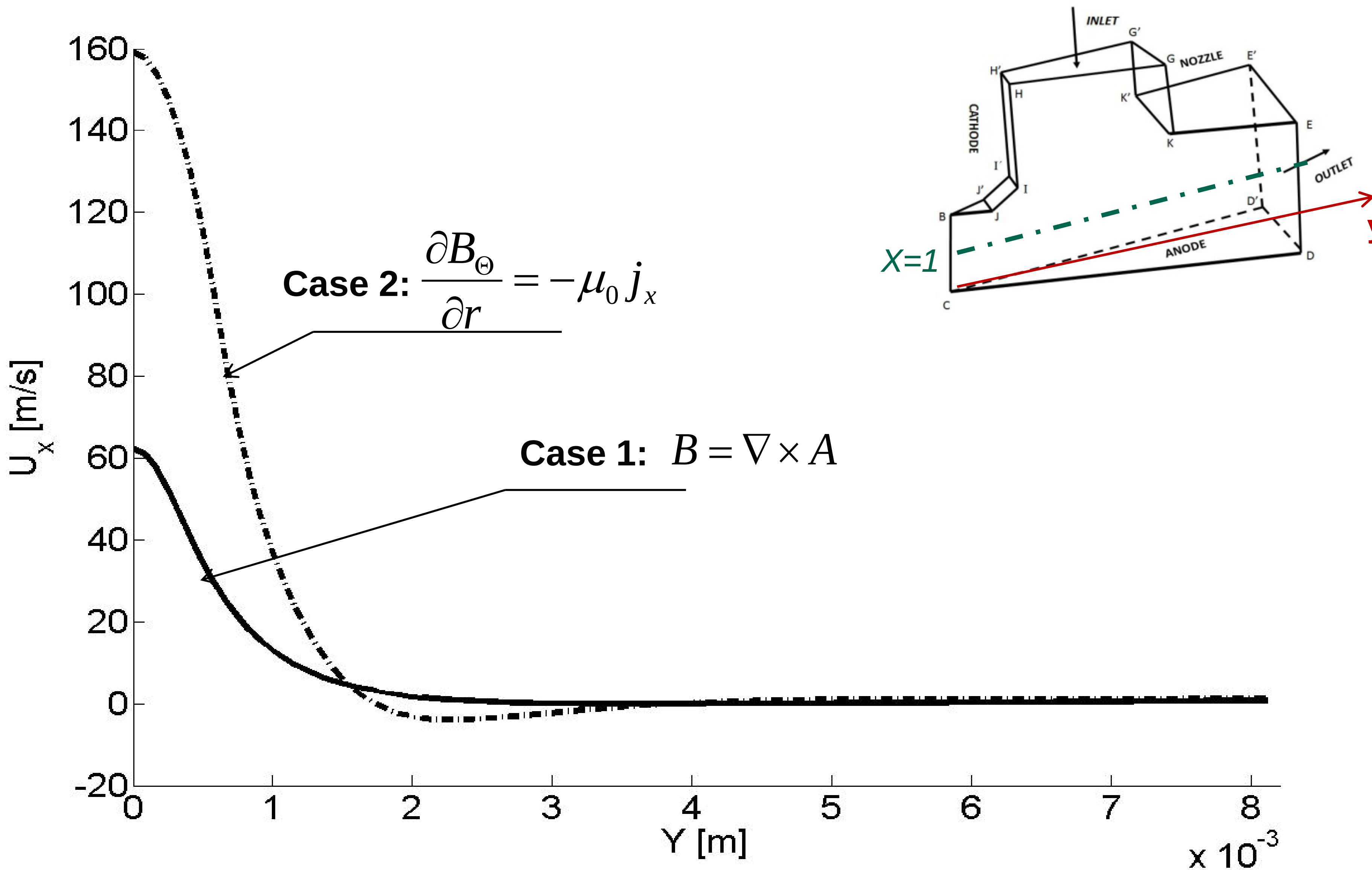
Results. Velocity vectors with electromagnetic



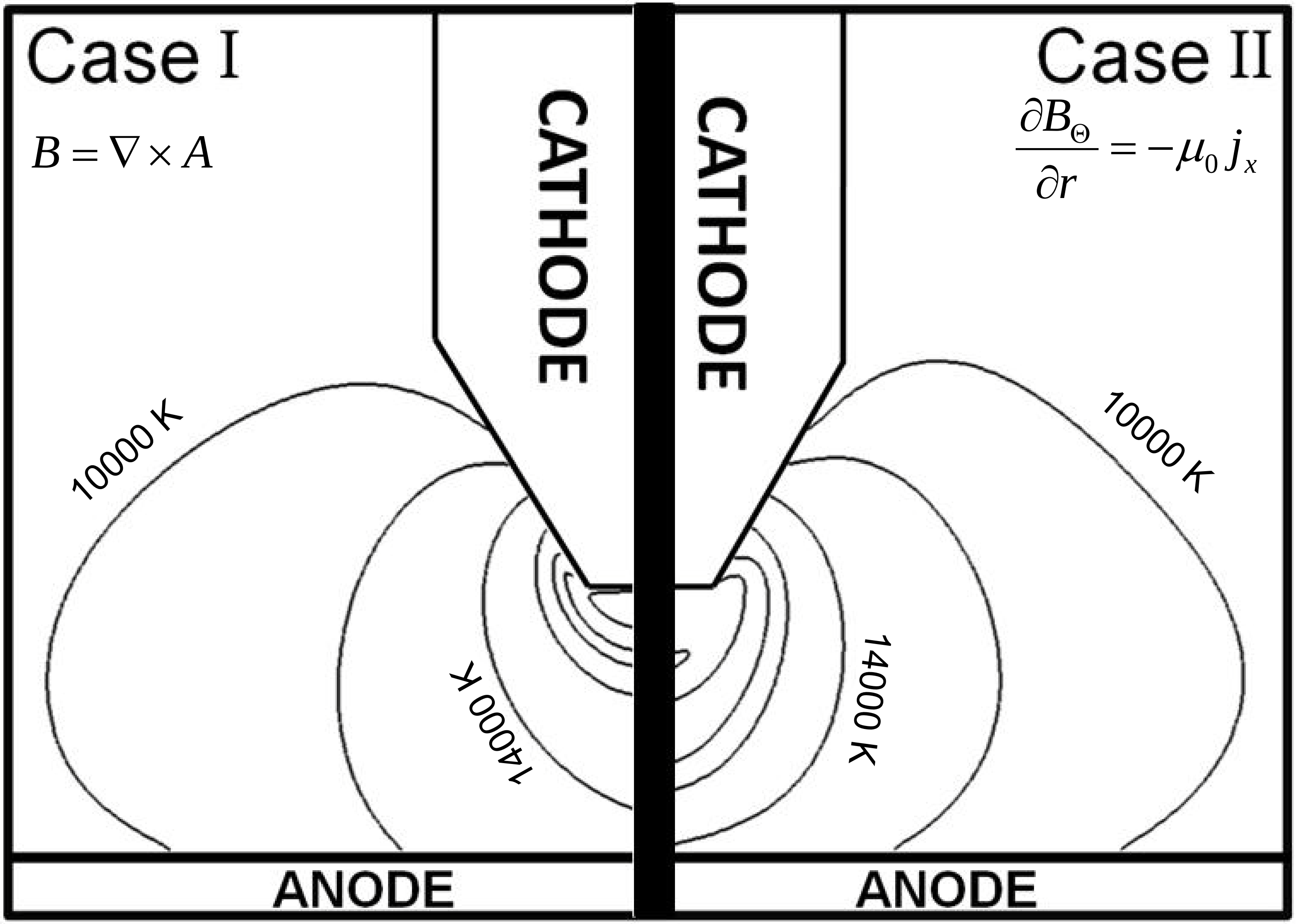
Results. Velocity evaluated along the symmetry axis for both cases.



Results. Radial distribution of the *x*-velocity for both cases evaluated x=1 mm.



Results. Temperature profile



From large radius to small radius, the isotherms correspond to 10000, 12000, 14000, 16000, 18000, 20000 and 22000 K.

Conclusion on TIG test case

- Two methods have been tested for computing the magnetic field
  - based on the electric potential (2D½)
  - based on the magnetic potentials (3D)
- Qualitatively, similar behavior was observed:
  - bell-shaped temperature profile
  - high velocity plasma jet
- Quantitative analysis showed a visible disagreement
  - 50% difference in the maximum velocity value
  - different distributions of the isotherms

- Method based on the electric potential yields better agreement with the results found in the literature

Conclusion:

- **A simulation tool that is valid within the field of tandem arc welding:**
  - Fully three dimensional tool
  - Coupled thermal fluid flow and electromagnetic fields
  - Includes thermodynamic properties suited to a plasma arc

- **The electromagnetic part of the simulation tool:**
  - Tested separately using a problem with a known analytical solution.
  - Tests of various boundary conditions for the electromagnetic potential have been done.

- **The complete simulation tool :**
  - A tungsten inert gas single arc problem (TIG)
  - Two methods for computing the magnetic field have been tested

Future work :

- Investigation of the disagreement in the results for two representations of the magnetic field.

- Supplement for tandem arc welding:
  - Implement thermophysical data tables for CO_2
  - Test case with tilted cathode geometry

- Implement heat and electromagnetic equations inside the electrodes

- Introduce the dynamics of the droplet and welding pool