Simulation of the plasma arc in a thermal spray gun

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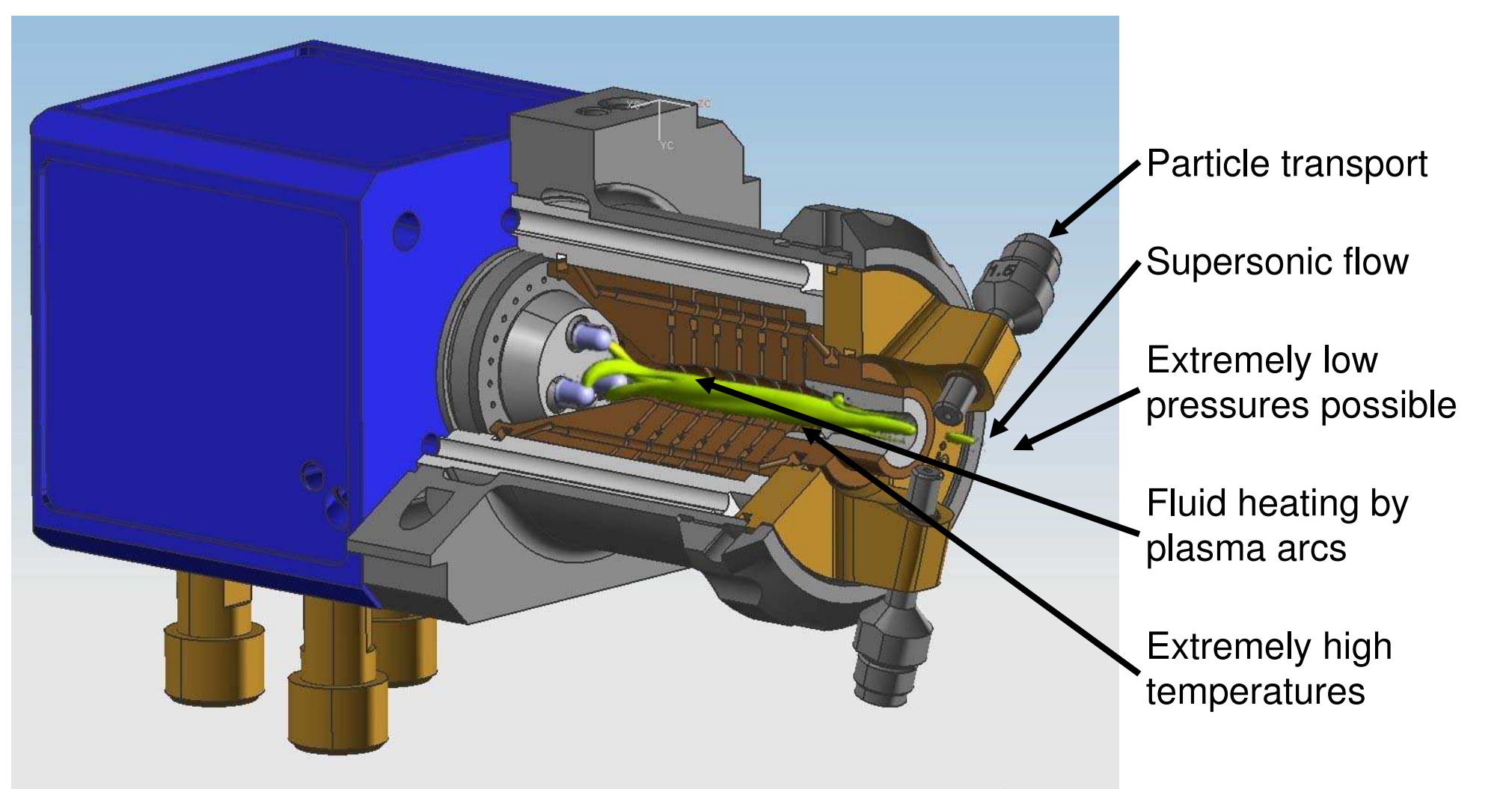
Abstract

THE use of computation fluid dynamics (CFD) to model the operation of thermal spray processes has gained interest in the thermal spray community; able to provide an understanding as to how a process functions, and better yet how to make a process work more effectively. Advancements to the science of modeling now permits the ability to create a comprehensive model of a plasma gun that not only simulates the dynamics of the gas but also the mechanics of arcs, thermodynamics, and entrained particulates to form a nearly complete model of a working thermal spray process. The arc model includes the magnetic field (Lorentz forces), the interaction of the energy flow in the formation of plasma, and the electrical field potential that determines the arc path in the gas stream. Work presented includes the methods and procedures used to validate the model to a plasma spray gun of Sulzer Metco and exploration of the operating regime to give an in depth and insightful look into the physics behind the operation of such a gun.

1. Introduction: Main flow phenomena in a spray gun

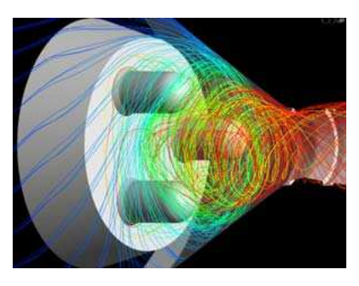


→ Commercial CFD codes need additional modeling to cover all these phenomena

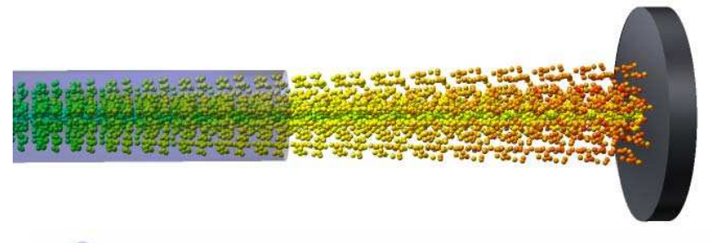
→ Thorough validation necessary to use CFD as a design tool for spray guns

2. Different CFD setups useful for spray gun development

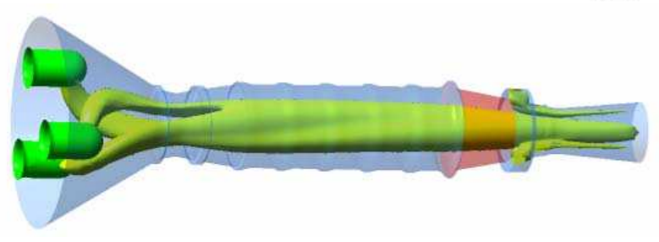
- Simulation of the supersonic gas-only flow
  - Initial assessment of gas dynamic performance



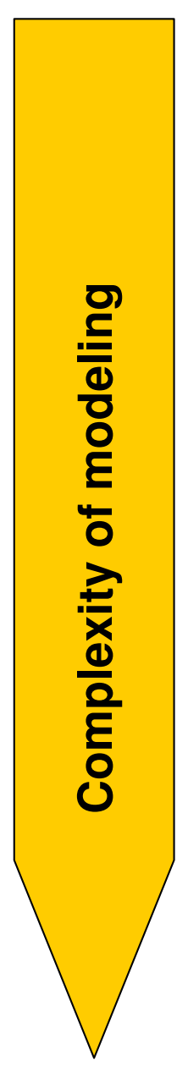
- Simulation of the supersonic gas flow with particles
  - Replicates gas dynamic conditions without complex arc modeling



- Modeling of the plasma arc
  - Replicates spray gun operation without powder

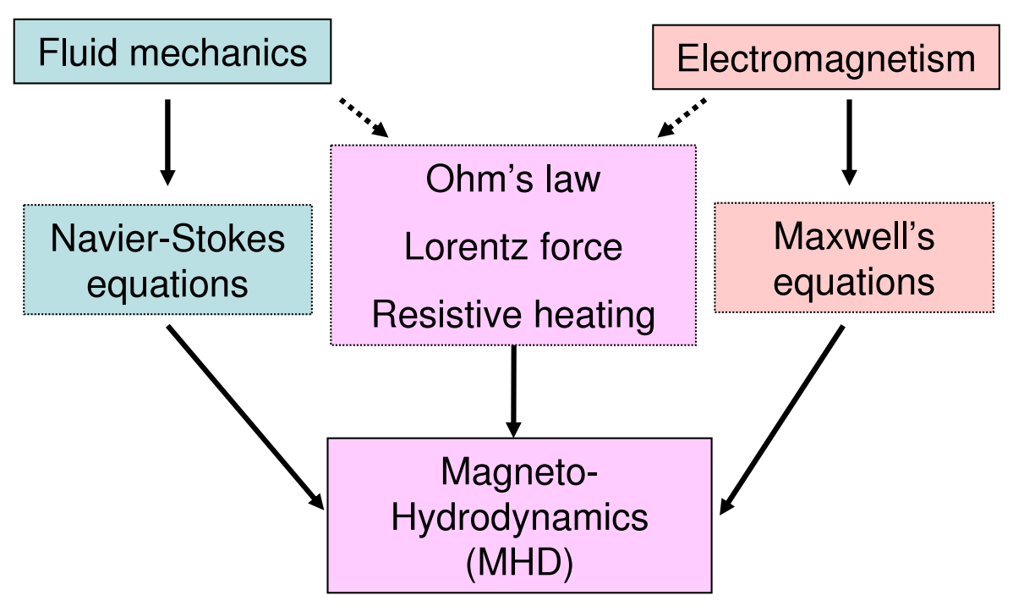


- Plasma arc with particles
  - Almost simulates the real world of plasma spraying



3. Modeling of the plasma arc - Implemented equations

- MHD - combination of fluid dynamics (Navier-Stokes) and electromagnetism (Maxwell)

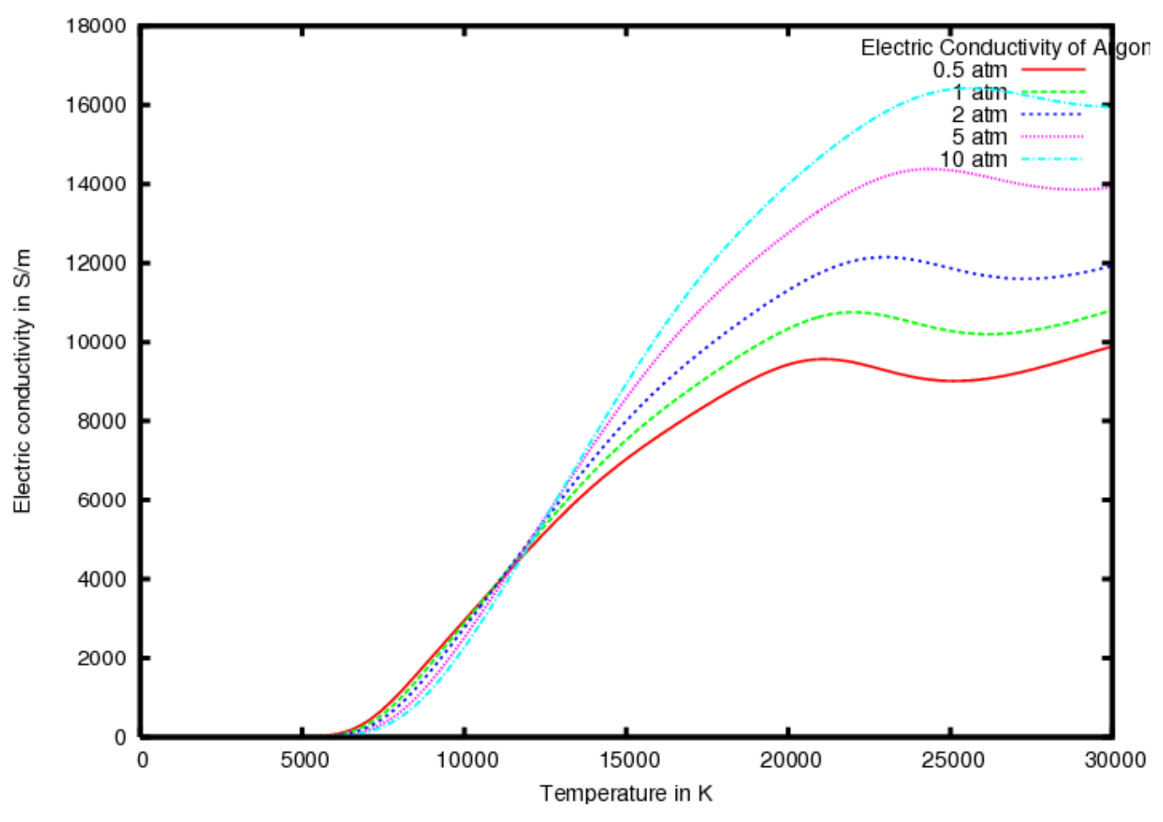


Fluid mechanics
Electromagnetism
Navier-Stokes equations
Ohm's law
Lorentz force
Resistive heating
Maxwell's equations
Magneto-Hydrodynamics (MHD)

- Maxwell equations are implemented into commercial CFD code
  - Ohm's law (algebraic): $\vec{j} = \sigma(-\mathrm{grad}\,\Phi + \vec{u} \times \vec{B})$
  - Charge conservation (Poisson equation): $\mathrm{div}\ \sigma\ \mathrm{grad}\,\Phi = 0$
  - Magnetic potential (Poisson equation): $\Delta\,\vec{A} = -\mu_0 \vec{j}$
  - Induced magnetic field (algebraic): $\vec{B} = \mathrm{curl}\ \vec{A}$
  - Resistive heating (algebraic energy source): $S_h = j^2 / \sigma$
  - Lorentz force (algebraic momentum source): $\vec{f}_L = \vec{j} \times \vec{B}$

4. Modeling of the plasma arc - Material properties

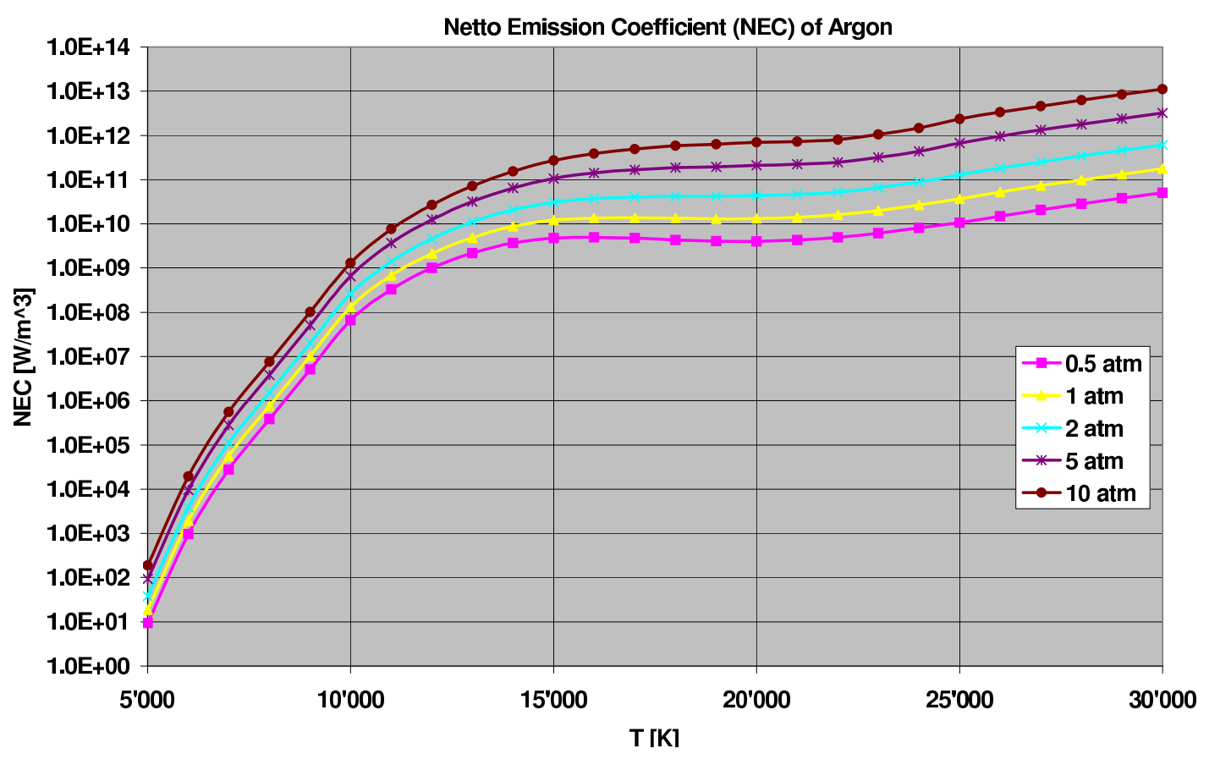
- Extremely high temperatures are common
- Material properties consider different species via tables (e.g. Ar, Ar^+, Ar^{++}, etc.)
- Implementation of pressure and temperature dependencies
  - Density via ideal gas law
  - Electric conductivity
  - Thermal conductivity
  - Viscosity
  - Specific heat capacity



5. Modeling of the plasma arc - Radiation model

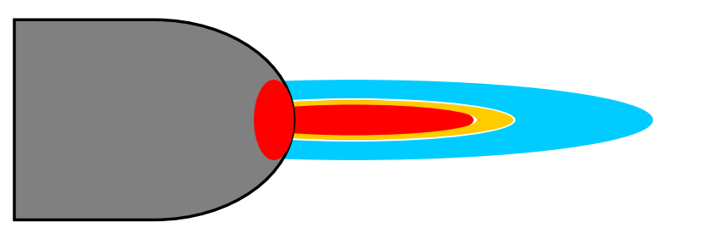
- Argon radiation according to Speckhofer is not in local thermal equilibrium (energy sink)
- Implementation of pressure and temperature dependencies via:

$$NEC_1(T, p) = NEC_0(T) \cdot (p_1 / p_0)^{m(T)} \qquad p_0 = 1\ \text{bar}$$

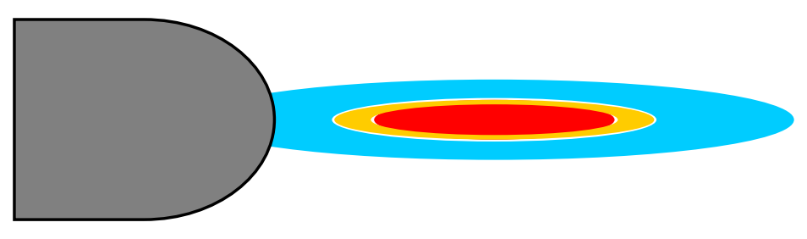


6. Modeling of the plasma arc - Sheath regions

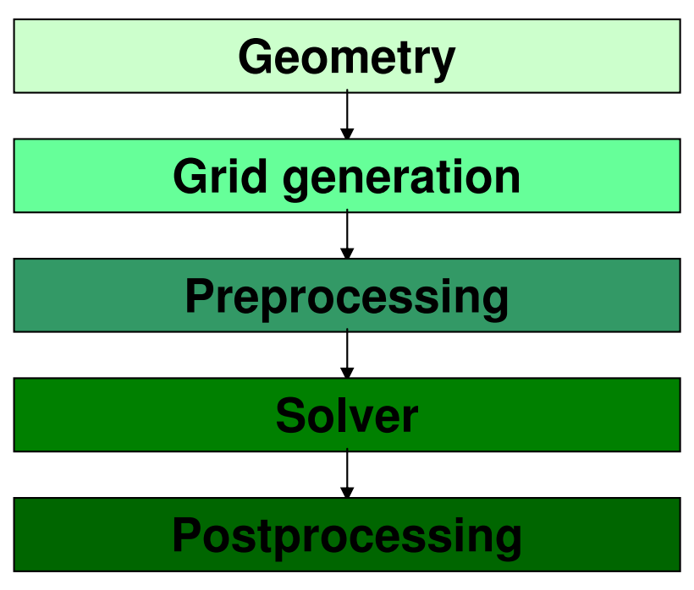
- Sheath regions are not considered in the model
  - Electrodes are adiabatic → unreal temperatures on electrodes
  - High temperature gradients at electrodes can be avoided → allows a coarser mesh
  - Results in slight reduction of voltage



- Sheath regions could be included
  - Additional transport equation for electron concentration
  - Makes the process more unstable
  - Very fine mesh required → increase in CPU-time



7. Typical setup of a CFD calculation

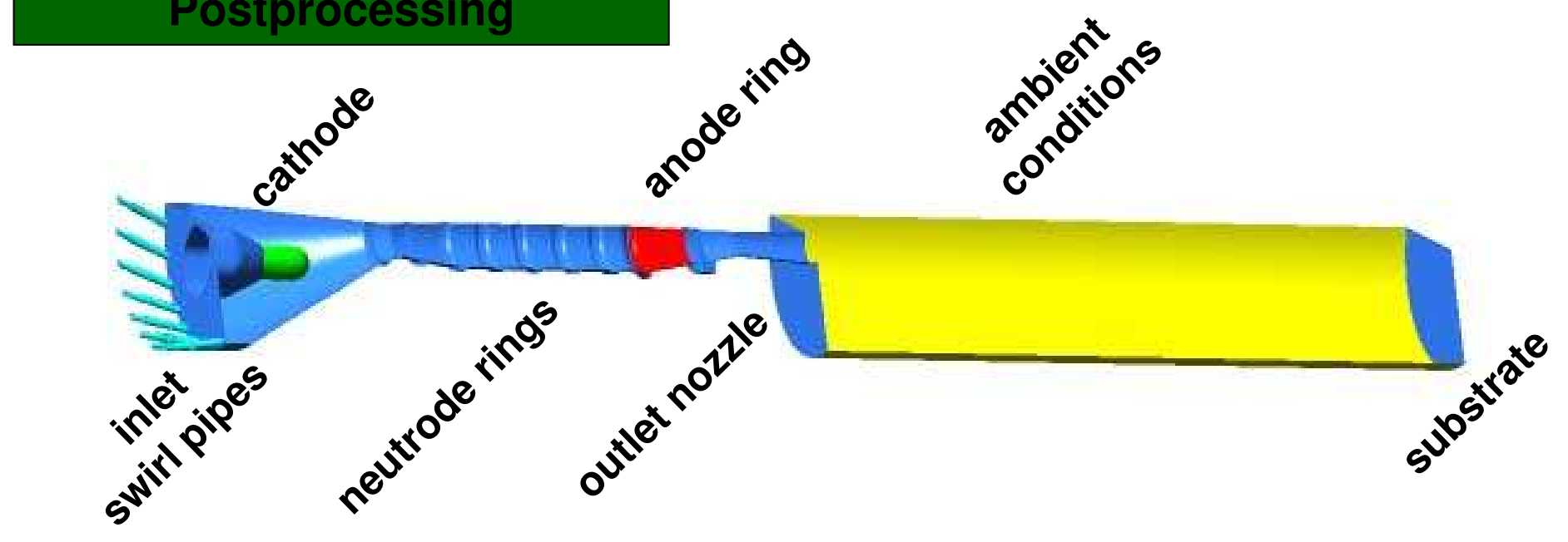


Geometry
Grid generation
Preprocessing
Solver
Postprocessing

- CFD simulation includes
  - Models
  - Assumptions
  - Simplifications
  - Idealizations

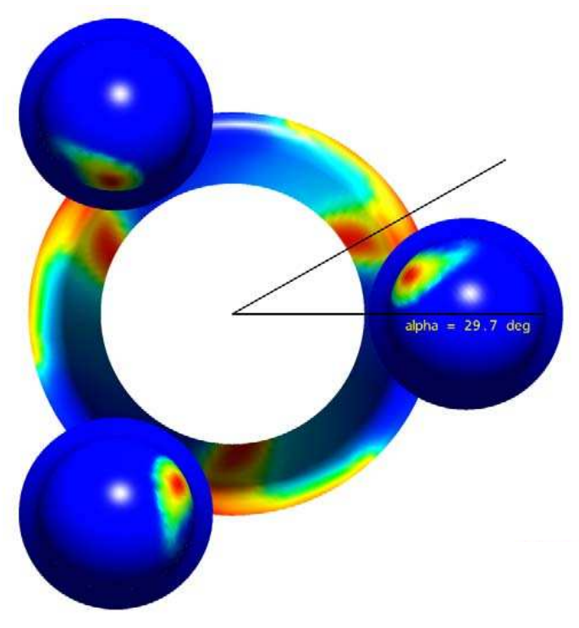
→ Validation necessary

→ Calibration necessary



8. Validation of simulation tools

- Simulation input
  - Gas flow rates
  - Electric current
- Output used for comparison with test data
  - Back pressure (Pa)
  - Voltage (V)
  - Visible plume length (mm)
  - Consolidation point
  - Heat flux into cooling water (W) (scaled radiation in the gun + convective heat flux on the walls)
  - Wear pattern at electrodes (angle between hot spots on cathode and anode)
- Challenging environment for accurate measurements
- First validations for Sulzer Metco TriplexPro^{TM}-200



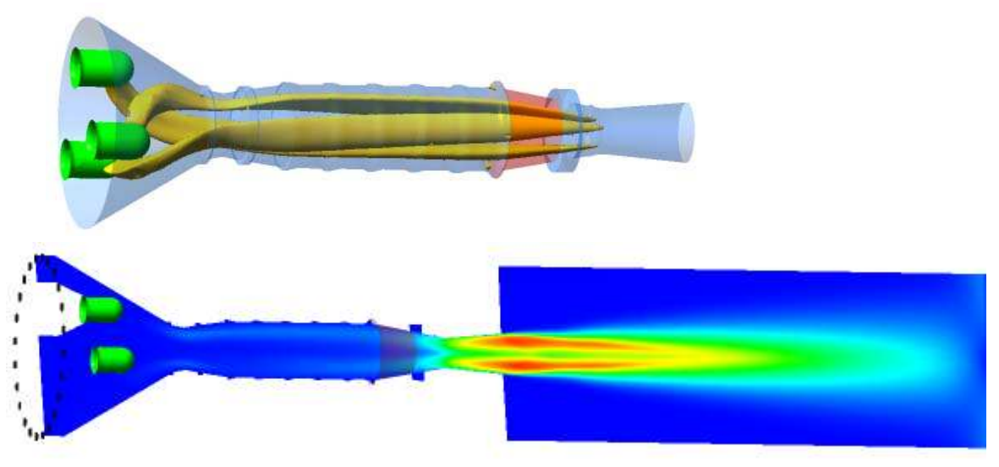
9. First experiences - Lorentz force

- Lorentz force needs to be activated in order to predict realistic arc behavior
- Illustrates necessity of direct coupling between fluid dynamics and electromagnetism

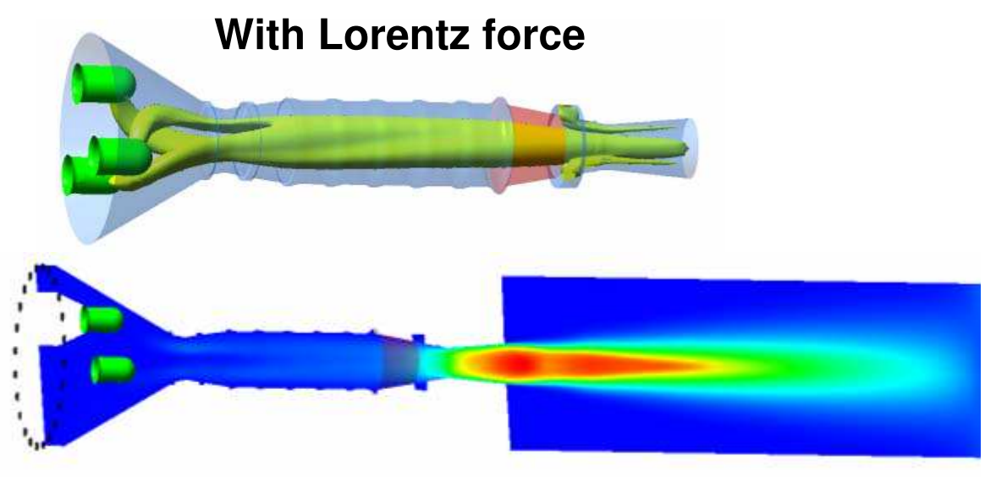
Top view:
Iso-thermal surfaces

Bottom view:
Velocity distribution

Without Lorentz force

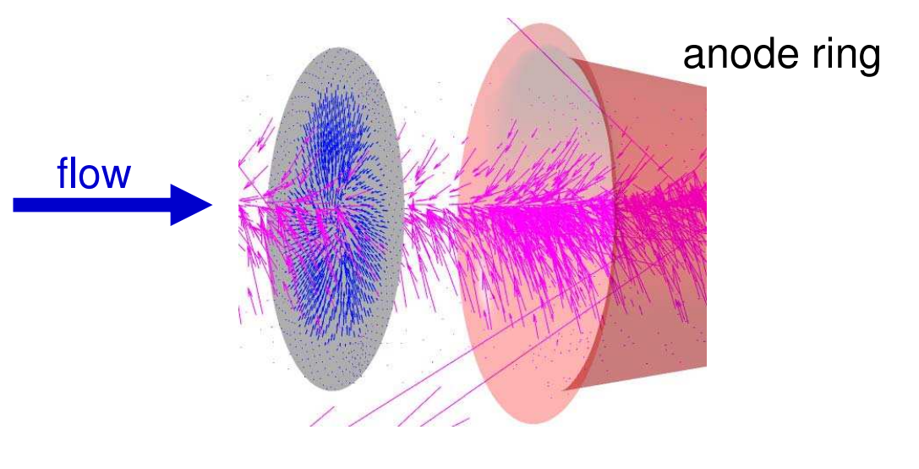


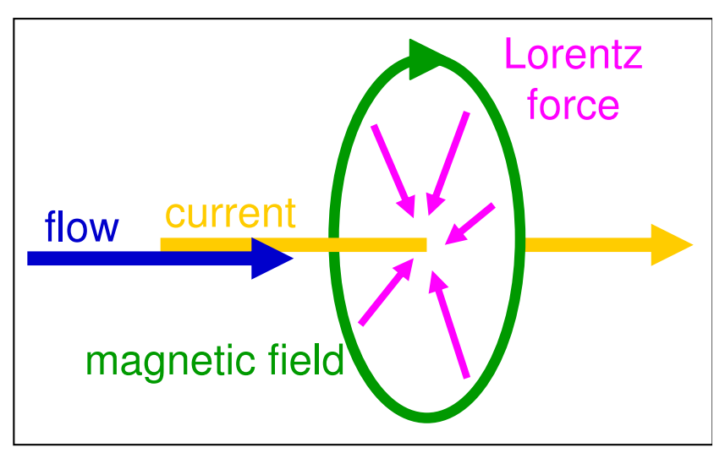
With Lorentz force



10. First experiences - Magneto-hydrodynamics

- Interaction magnetic field – current density → Lorentz force





- Fluid movement in external electric field → Current density → Electric field

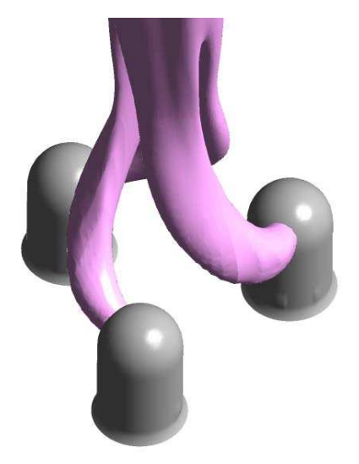
11. First experiences - Validation

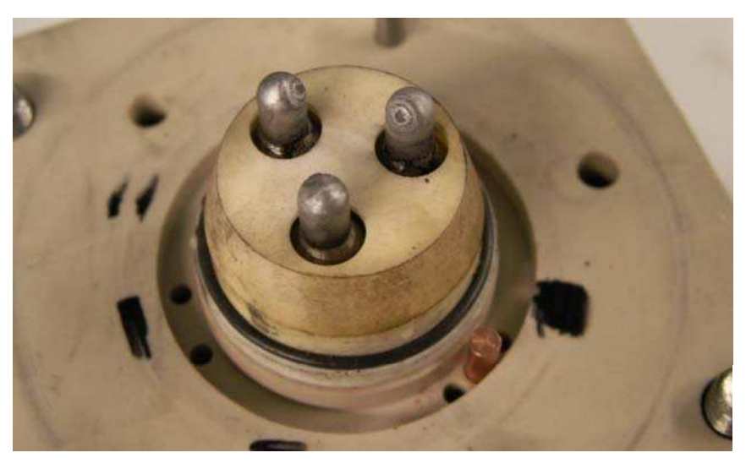
- Calibration of the model on the basis of an Argon test case (TriplexPro^{TM}-200)
- Multi component simulations possible (eg. Argon-Helium Mixtures) with correct adaptation of material properties and radiation model

	Argon l/min	Helium l/min	current A	voltage V	plume length mm	back pressure bar (rel.)	heat loss kW
test	140	0	400	**129**	**45**	**4.05**	**25.5**
sim	140	0	400	**114.1** -14.9 V	**49.5** + 6.6 %	**3.66** -9.6%	**25.1** - 1.8 %

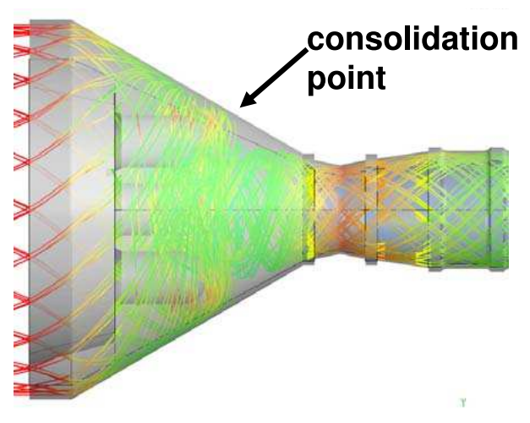
Absolute value due to non-consideration of sheath regions!

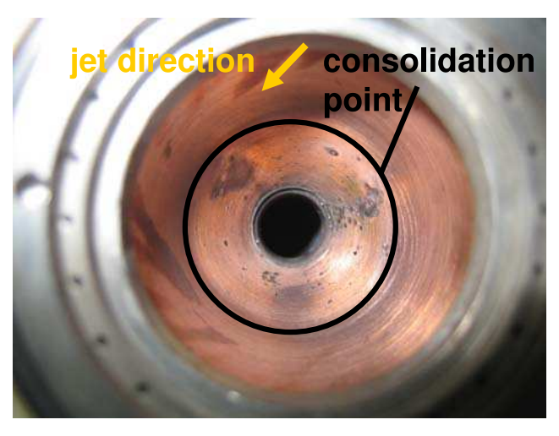
- Emission points at cathodes





- Direction of the individual gas jets in the chamber
- Consolidation point: Individual gas jets merge into a single swirl flow





12. Advantages of Simulation Tools in the Spray Gun Design

- Simulation tools give insights into various physical phenomena previously not accessible
- Validated simulation tools considerably reduce need for prototyping and experimental studies
- Reduction in time to market of new or modified products
- Development of more advanced and optimized spray guns feasible
- New operating regimes and areas of application can be explored without any physical risk

13. Conclusions - Outlook

- Numerical models have been introduced into the design and modification process of spray guns
- Starting from standard CFD applications the modeling has been extended to include particles and the plasma arcs
- Extensive testing and validation revealed the accuracy and limitations of the simulation tool
- The need of a direct coupling between fluid dynamics and electromagnetism could be nicely illustrated
- Integrating the CFD and MHD codes into optimization software could lead to an automatic optimization of certain parts of a spray gun in the future
- The use of CFD in solving problems provides an economical alternative to physical prototyping