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Bern University of Applied Sciences
Engineering and Information Technology

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COMSOL Conference 2010, Paris

Energy Harvesting from Variation in Blood Pressure through Deformation of Arterial Wall using Electro-Magneto-Hydrodynamics

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Outlook

> Introduction
> Simulation setup
> Simulation results
> Validation
> Conclusion

Introduction

- Arteries deform due to variation of blood pressure
  → Windkessel effect (elastic energy storage during systole)
- This cyclic deformation can be used to move an electric conductor in a magnetic field
  → an electric field is induced
- A load can be connected to the electric conductor's terminals
  → energy is extracted

http://www.physiologie-online.com/ana_site/physio07.html

Electro-Magneto-Hydrodynamics (EMHD)

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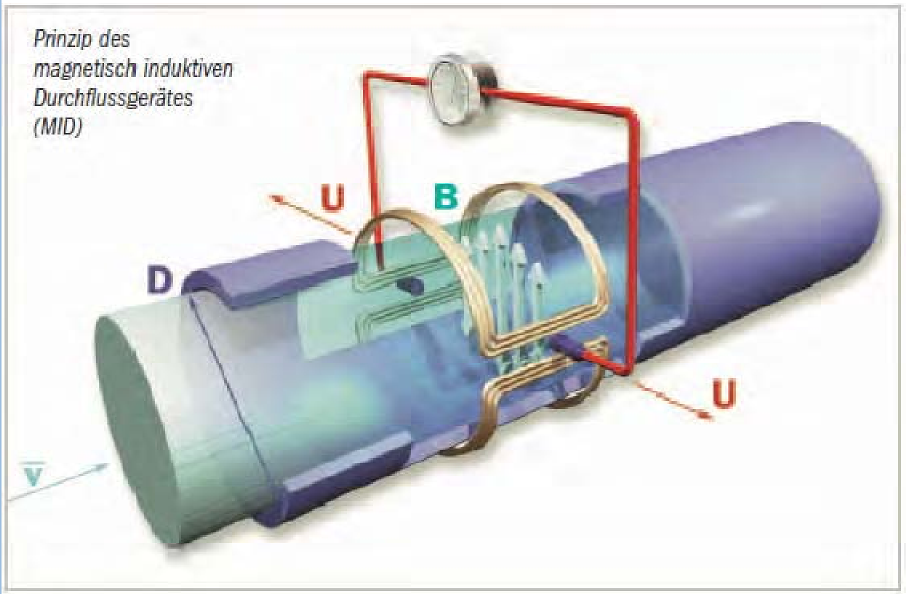

Friedrich Hofmann, Fundamental principles of Electromagnetic Flow Measurement, 3rd Edition, KROHNE Messtechnik GmbH & Co, 2003

$$E_{ind} = -u_{flow} \times B$$

> **Proposed concept:** Use deformation of arterial wall through variation in blood pressure to drive a highly electrically conductive fluid in a compartment outside the artery.

Geometry and Principle

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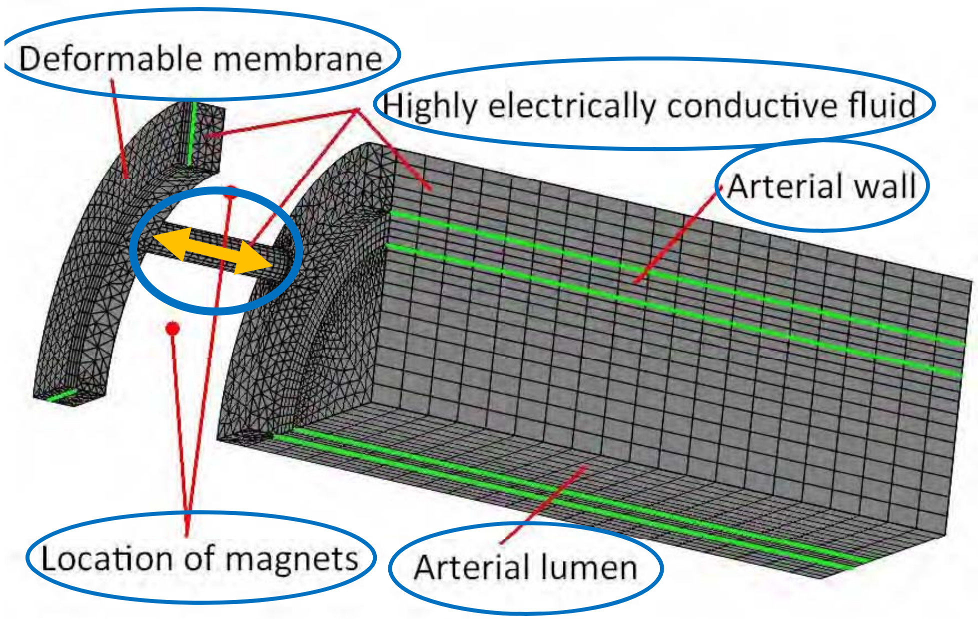
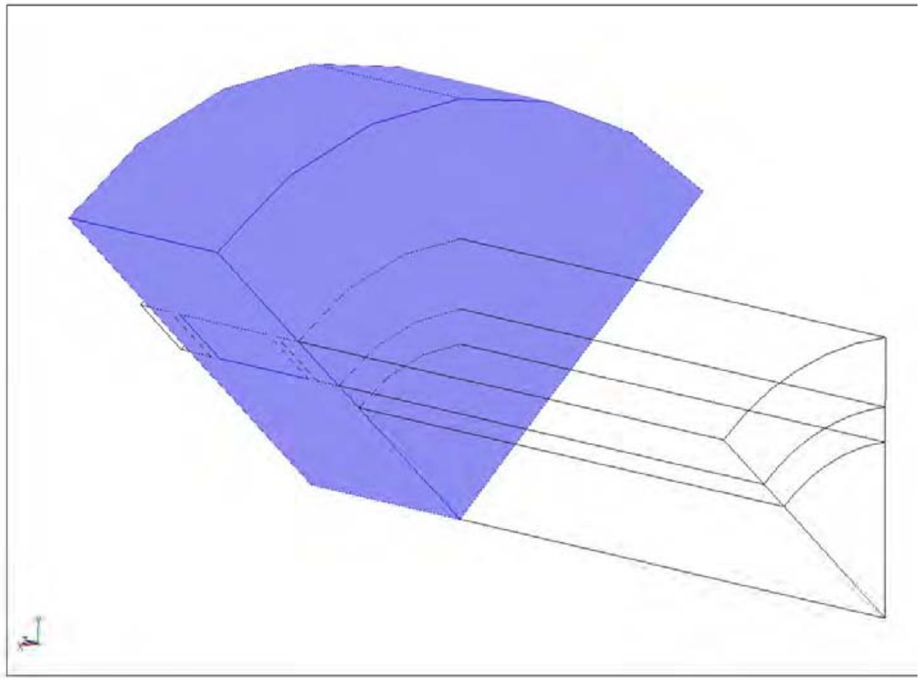
> Artery dimensions: 20 mm length, 10 mm ID, 12 mm OD





Simulation Setup

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> 5 « application modes » used in COMSOL:
  - Incompressible Navier-Stokes
  - Solid, Stress-Strain
  - Moving Mesh
  - Magnetostatics, No Current
  - Conductive Media DC

> Mesh partly drawn manually:
  - avoid element inversion due to mesh deformation
  - ensure proper meshing at the boundaries between the different physics
  - reduce computational efforts

Application Mode # 1

> Incompressible Navier-Stokes

$$\nabla \cdot \vec{u} = 0$$

$$\rho \cdot \frac{\partial \vec{u}}{\partial t} + \rho(\vec{u} \cdot \nabla)\vec{u} = -\nabla p + \mu \nabla^2 \vec{u} + \vec{F}$$

Body force, e.g. gravity

Viscosity

Pressure gradient

Convective acceleration

Unsteady acceleration

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

Lorentz-force against fluid motion

Application Modes # 2, 3 & 4

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> Solid, Stress-Strain (isotropic, linear elastic material)

$$\sigma = D \cdot \varepsilon$$

> Moving Mesh (mesh nodes are perturbed to conform with the moving boundaries)

$$x = x(X, Y, t)$$
$$y = y(X, Y, t)$$

> Magnetostatics, No Current

$$\nabla \cdot (-\mu_0 \mu_r \nabla V_m + \vec{B}_r) = 0$$

Application Mode # 5

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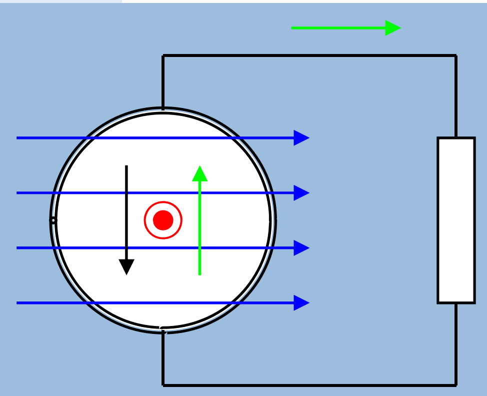
> Conductive Media DC



Lorentz and Coulomb forces

$$\vec{F}_L = q \cdot (\vec{u} \times \vec{B})$$

$$\vec{F}_C = q \cdot \vec{E}$$

$$\vec{F}_C = -\vec{F}_L \quad \Rightarrow \quad \vec{E} = -\vec{u} \times \vec{B}$$

Material law

$$\vec{J} = \sigma \cdot \vec{E}$$

$$\vec{J} = \sigma \cdot (\vec{E} + \vec{u} \times \vec{B})$$

E-field bounded due to load R

Charge conservation

$$\nabla \cdot \vec{J} = 0 \longrightarrow \nabla \cdot \left(\sigma \cdot (\vec{E} + \vec{u} \times \vec{B}) \right) = 0$$

Poisson's equation

$$\vec{E} = -\nabla \varphi - \cancel{\frac{\partial \vec{A}}{\partial t}}$$

0

$$\nabla \cdot (-\sigma \cdot \nabla \varphi + \sigma \cdot \vec{u} \times \vec{B}) = 0$$

Summary

- Equations

$\nabla \cdot \vec{u} = 0$ Conservation of mass

$\rho \cdot \frac{\partial \vec{u}}{\partial t} + \rho(\vec{u} \cdot \nabla)\vec{u} = -\nabla p + \mu \nabla^2 \vec{u} + \vec{F}$ Conservation of momentum

$\sigma = D \cdot \varepsilon$ Stress-Strain, linear elastic

$\nabla \cdot (-\mu_0 \mu_r \nabla V_m + \vec{B}_r) = 0$ Magnetic potential

$\nabla \cdot (-\sigma \cdot \nabla \varphi + \sigma \cdot \vec{u} \times \vec{B}) = 0 \quad \vec{J} = \sigma \cdot \left(\vec{E} + \vec{u} \times \vec{B}\right)$ Electric potential

- Couplings:
  - Fluid ↔ Structure: surface load, moving wall
  - Structure → Moving mesh
  - EMHD: $\vec{E} = -\vec{u} \times \vec{B}, \quad \vec{F} = \vec{J} \times \vec{B}$
- Constraints:
  - Symmetry, fixed/free walls, magnetic/electric insulation…
  - Kirchhoff's mesh rule for the generator and load resistor

Solver sequence

> Stationary:
  - Solve for internal resistance of tube
  - Solve for distribution of magnetic field

> Transient (segregated solver, two groups):
  - Group 1: Fluid-structure interaction (Incompressible Navier-Stokes + Solid, Stress-Strain + Moving Mesh)
  - Group 2: Electrical domain (Conductive Media DC + Kirchoff‘s mesh rule)

Running the Simulation

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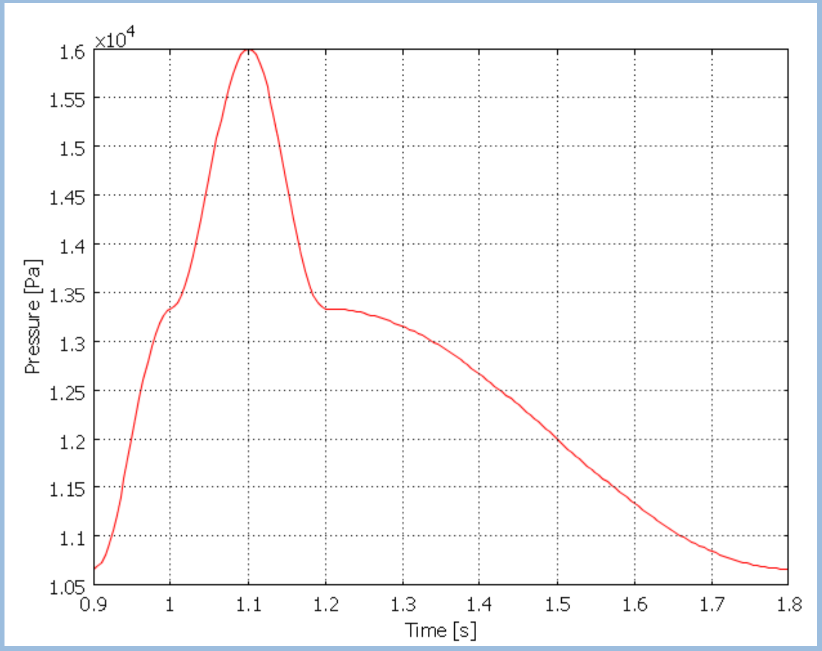
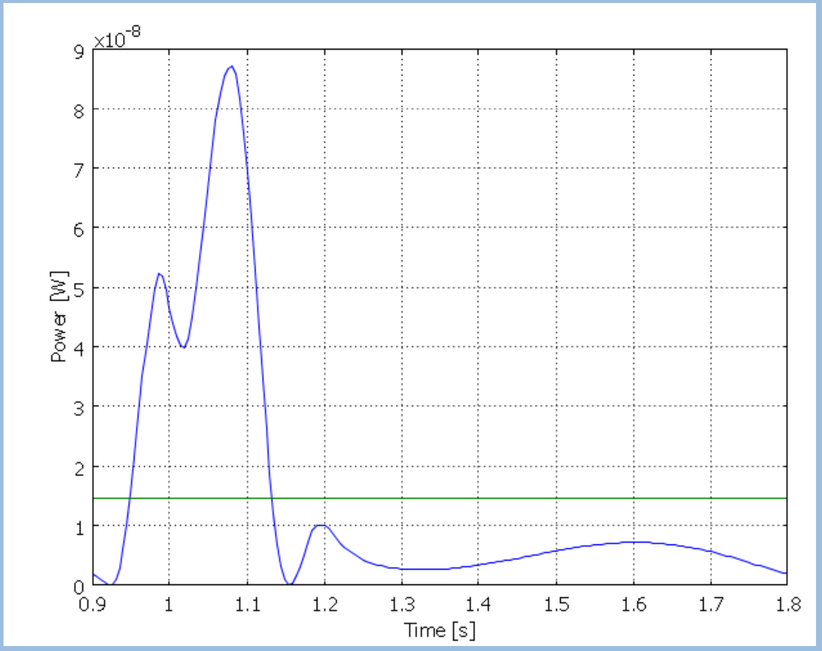
Input: pressure pulse



Output: power



Arterial Wall and Membrane Deformation x- and z-Velocity

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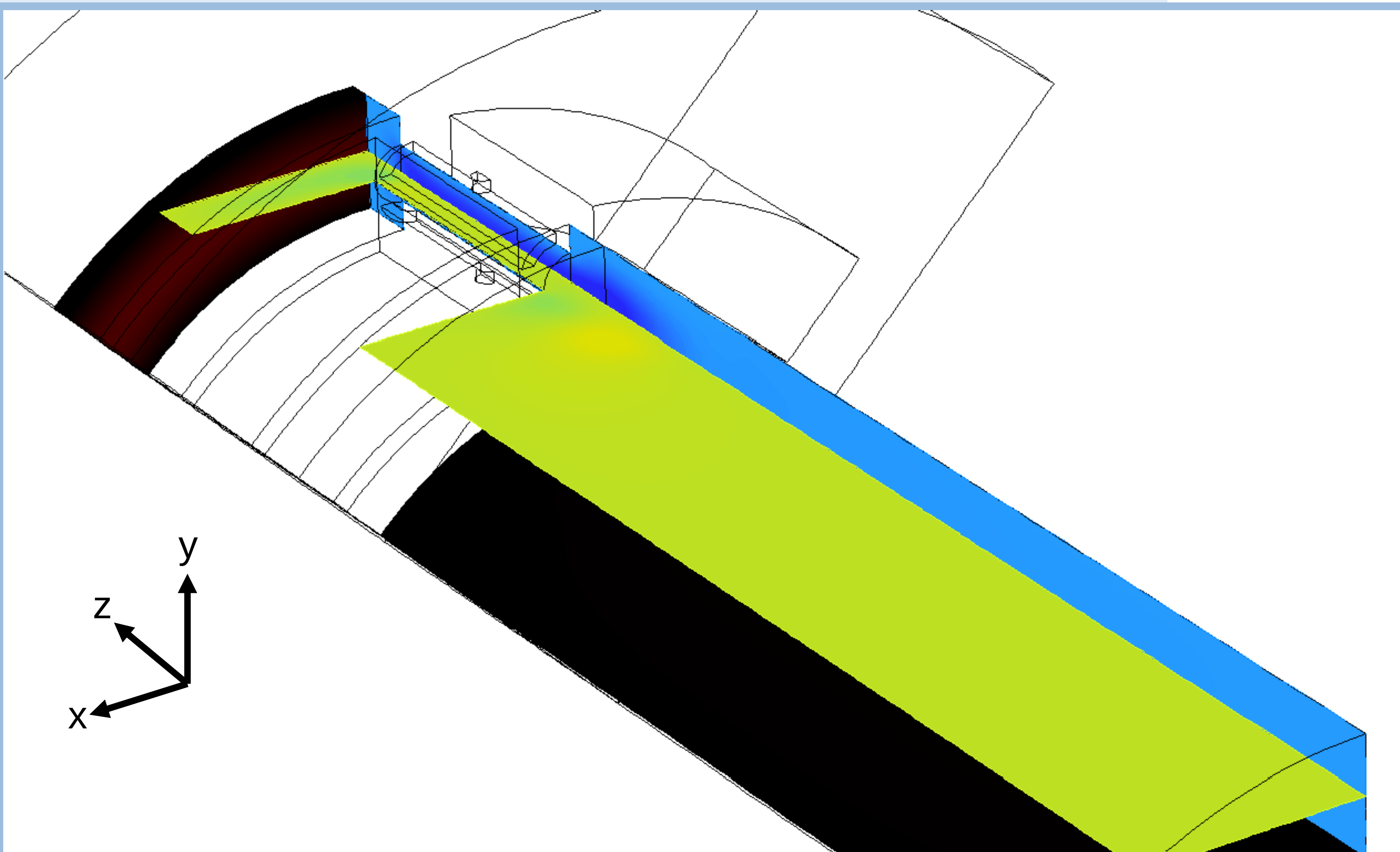

Magnetic flux density

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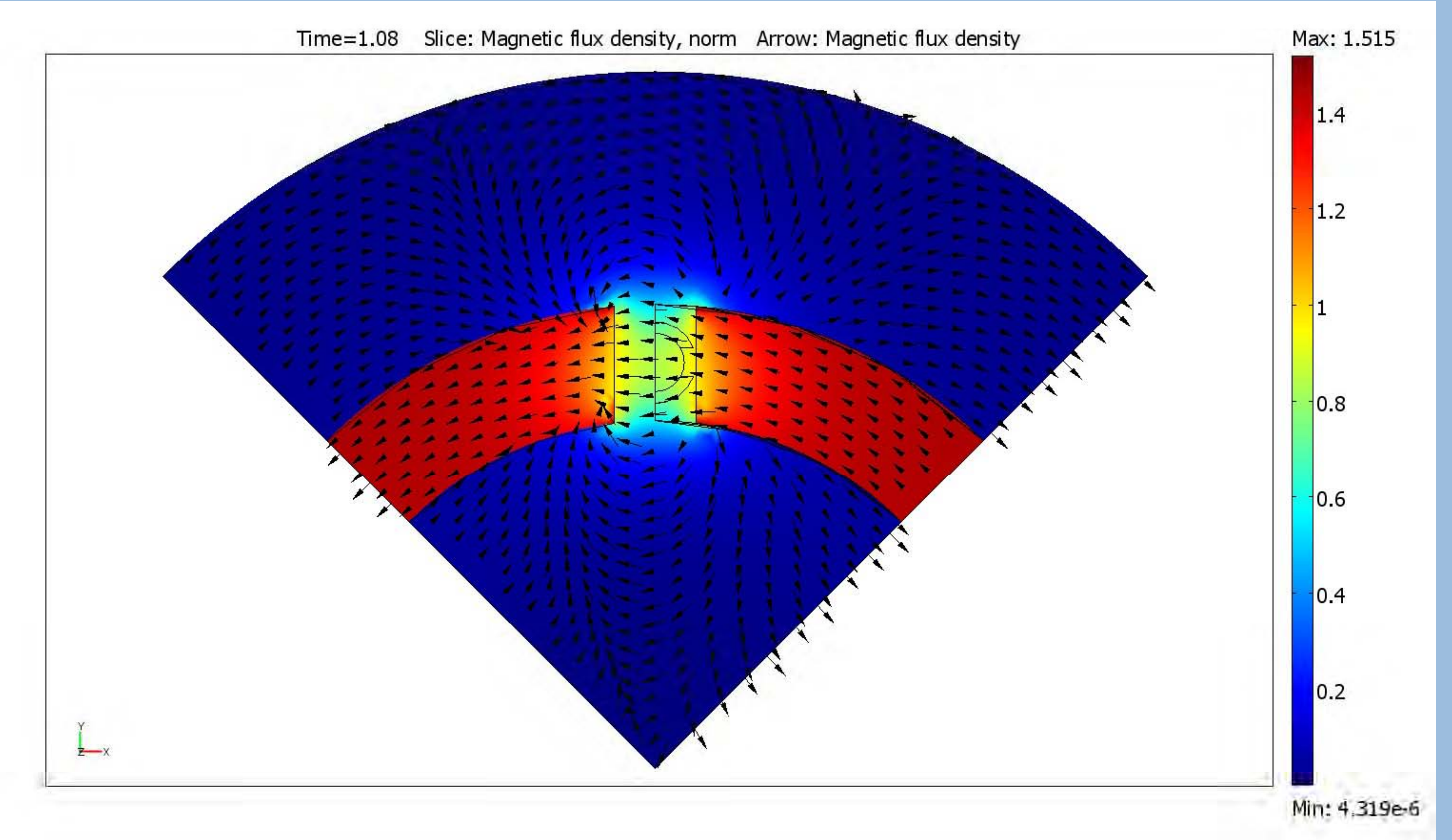

Electric Potential & Current Density

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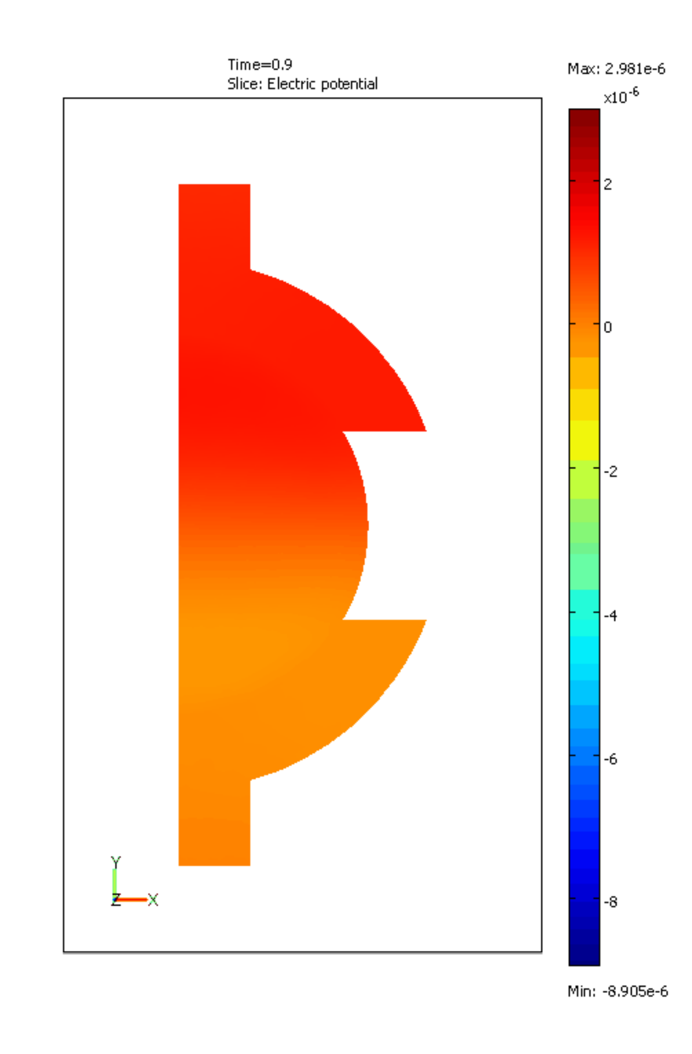

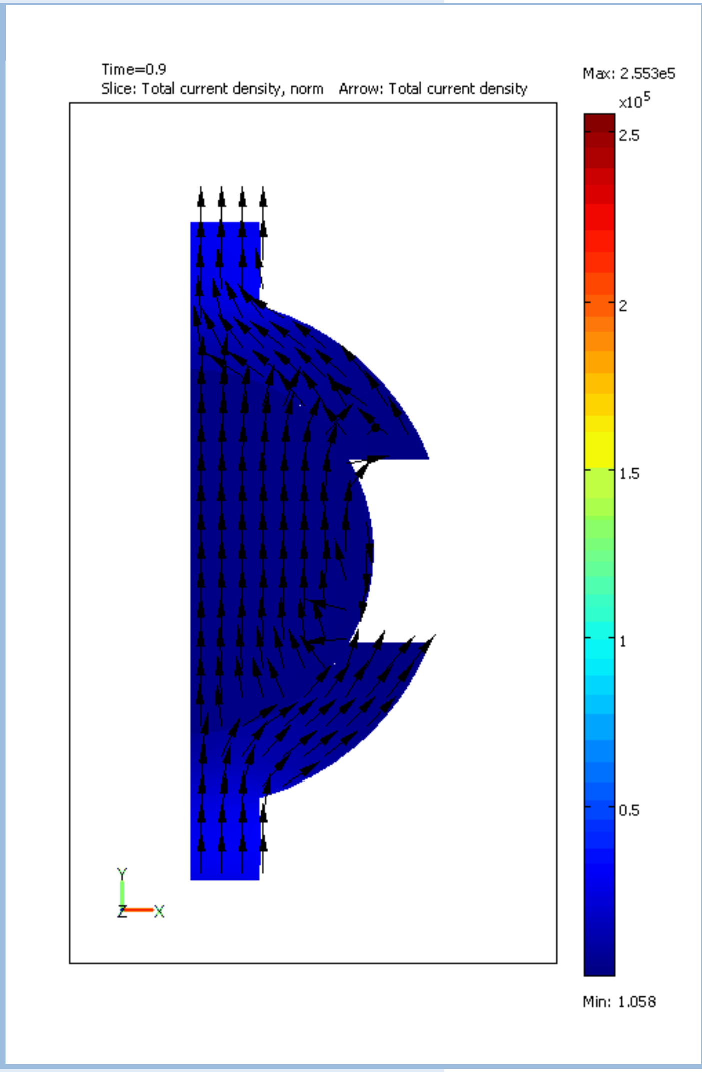

Validation of the Simulation

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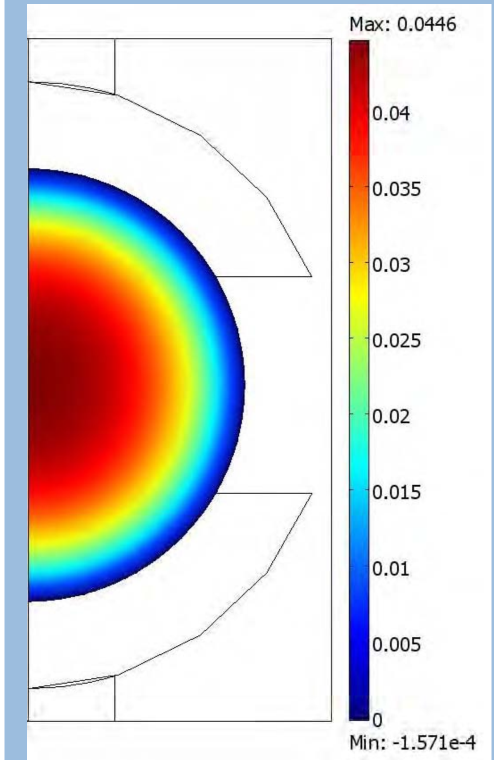
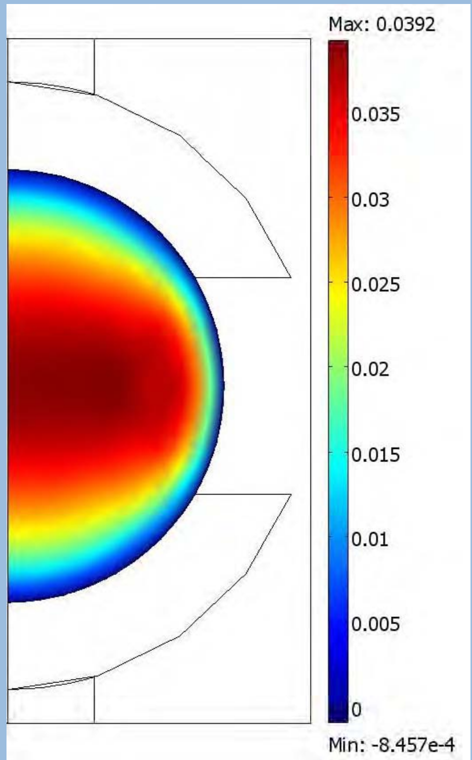
- Qualitative: Influence of force counteracting the fluid's motion
- Quantitative: Energy conservation





Energy production per cardiac cycle for 1/8 of the geometry:
+ 26.4 nJ

Difference in strain energy of arterial wall when energy is extracted:
- 29.4 nJ

→ Error: 11%

Conclusion

> Using the multiphysics capabilities of COMSOL, it was shown that the proposed concept can be simulated

> The simulation was validated by considering energy conservation: the error between loss of elastic energy stored in arterial wall and generated energy amounts to 11%

> A parameterised evaluation is necessary to find the optimal geometry in terms of generated power