Magnetohydrodynamic Energy Conversion R&D

Woodside[1], Richards[1], Ochs[1], Huckaby[1], Oryshchyn[1], Kolczynski[1], Felman[1,2], Kim[1], Weiland[1], Bedick[1,4], Haworth[3], Dasgupta[3], Cann[2], Singh[3], Nielsen[1], McGregor[1,2], Gibson[2], Bokil[2], Celik[4], Escobar[4], Lineberry[5]

Generating a knowledge base, data sets, and tools toward predicting and improving MHD power generation technology performance

CFD simulation of MHD generator

1D Steady State Model

$$\frac{d}{dx}(\rho u A) = 0 \qquad \rho u A\frac{dY_k}{dx} = AR_k$$

$$\rho u A\frac{du}{dx} + A\frac{dP}{dx} = -AJ_y B_z$$

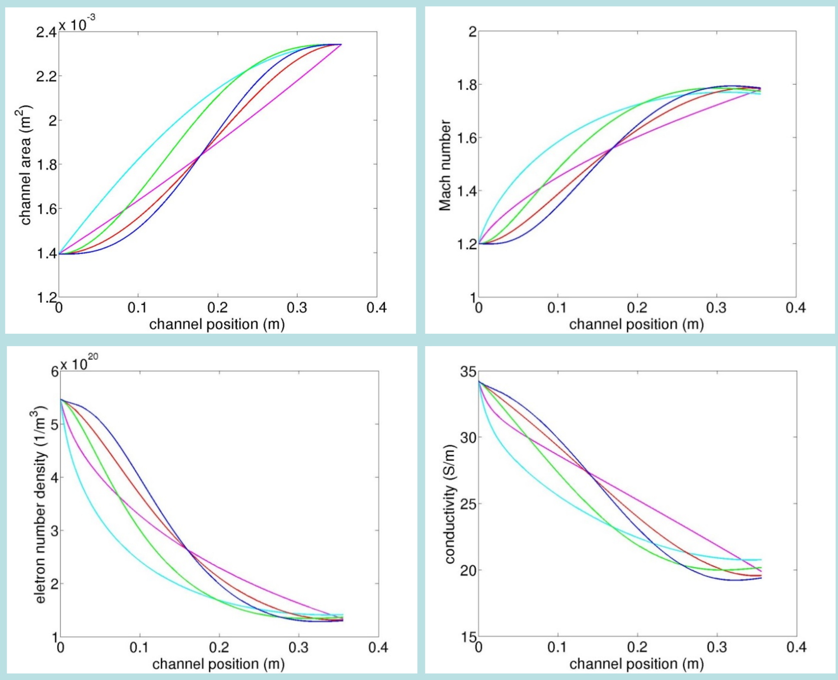
$$\rho u A\frac{d}{dx}\left(\frac{u^2}{2} + h\right) = -Q\frac{dS}{dx} + A(J_y E_y + J_x E_x)$$

$$J_y = \sigma_{yy}(E_y - uB_z) + \sigma_{yx}E_x$$

$$J_x = \sigma_{xx}E_x + \sigma_{xy}(E_y - uB_z)$$

$$h = h(T,P,Y_i),\ R_k = R_k(T,P,Y_i)$$

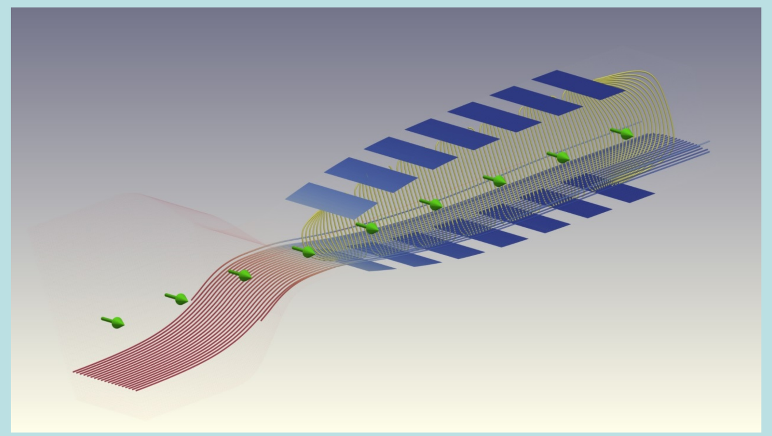
$$\sigma_{ij} = \sigma_{ij}(B_z, T, p, Y_i)$$



Simulations of a preliminary design for the NETL MHD generator experiment Sensitivity to channel profile

Multidimensional CFD

- Adjustable complexity of physical models.
- Based on OpenFOAM CFD Toolbox
- Fluid Dynamics:
  - Equilibrium and non-equilibrium models for composition (ionization), momentum and energy
- Maxwell's equations:
  - electric potential and full Maxwell's equation approaches
- Transport & Collision
  - Cross-section and transport properties from open databases, additional calibration to NETL experiments



Tokyo Institute of Technology Segmented Linear Faraday Channel
Green – Magnetic Field, Yellow - Potential Lines,
Red-Blue – Velocity Stream Linear

Simulations with different fidelity developed for:

- Experimental design
- System performance
- Detailed generator optimization

New submodels are being developed for:
Wall functions*, ionization
***Classical log-law does not apply with magnetic field**

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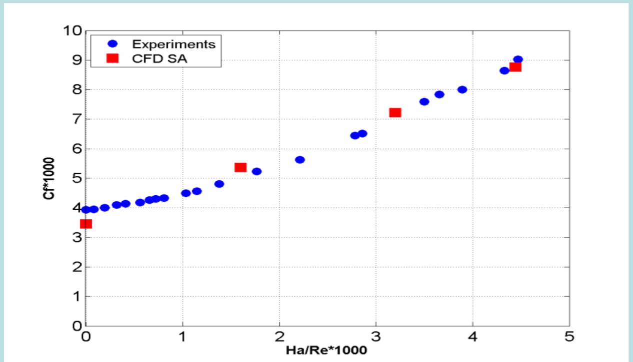
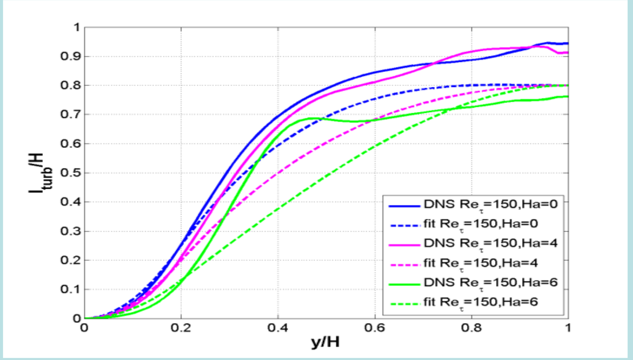


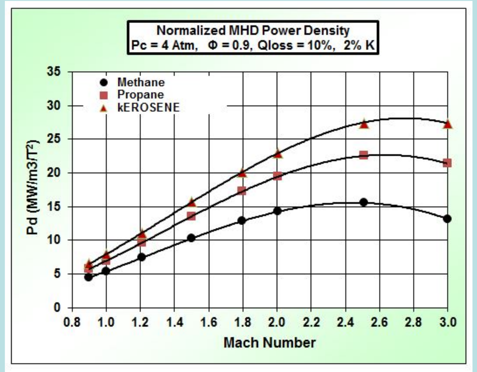


Simulation of Hartmann flow cases (i.e. with Lorentz force). Comparison of DNS to CFD with wall functions.

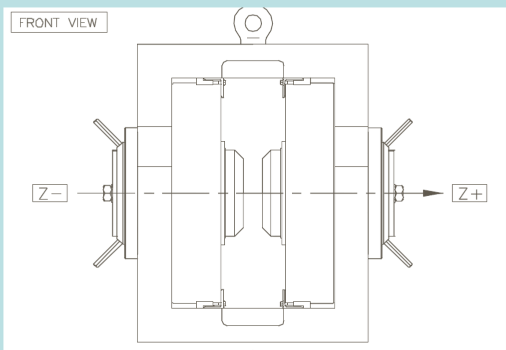
MHD bench scale experiment (planned) –

A staged approach to provide experience and model validation.

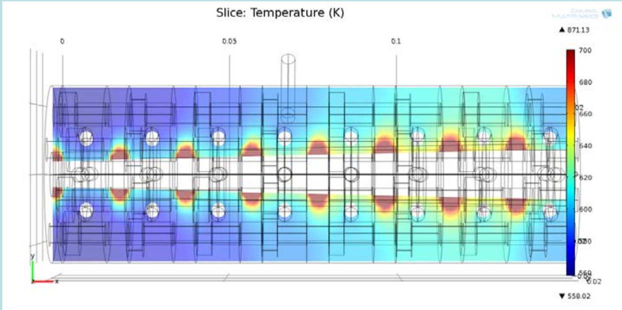
Test System Design Phase Work:



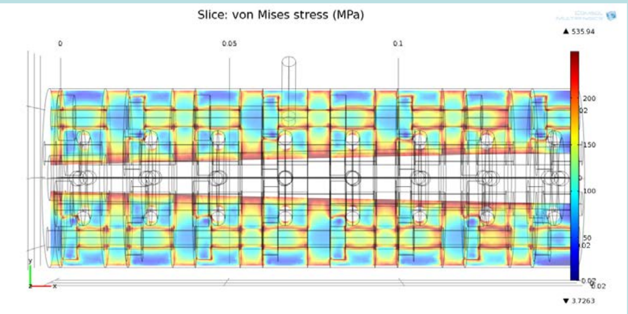
Comparison of potential MHD power density for various fuels as a function of Mach #. Kerosene was selected.



A 3T (max) 10" iron core bore fully adjustable electromagnet was selected.
-field reversal capable



A designed "Hall Channel" showing calculated material temperatures (above) and thermal stresses (below).



1. Component testing
   - Systems shake down
   - Establish HVOF combustion system heat losses/fluxes
   - Channel material exposure to temperature and flow

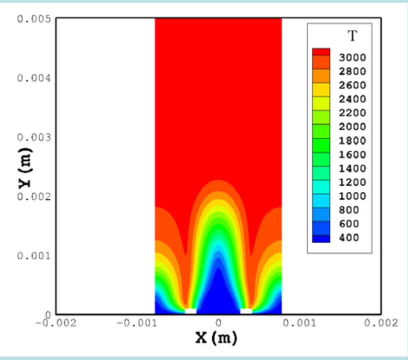
2. Back-powered "Hall Channel" experiment
   - Establish plasma ionization & conductivity in channel
   - Demonstrate current density spatial profiling (see below)
   - Channel material exposure to temperature, flow, and electricity

3. Combined, bench-scale MHD experiment
   - Validate and improve MHD simulations
   - Channel material exposure to full open-cycle MHD conditions

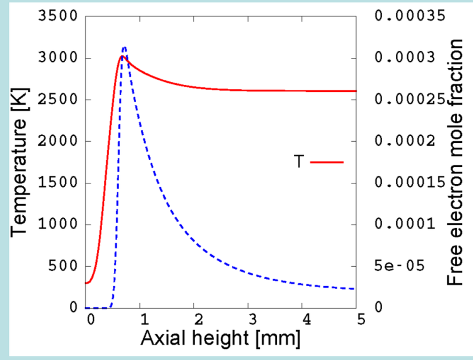
CFD simulation of combustion and ionization

Open-Foam models for (undiluted) oxy-coal combustion are being developed.

Ionization and ion transport models compared to lab measures (below).

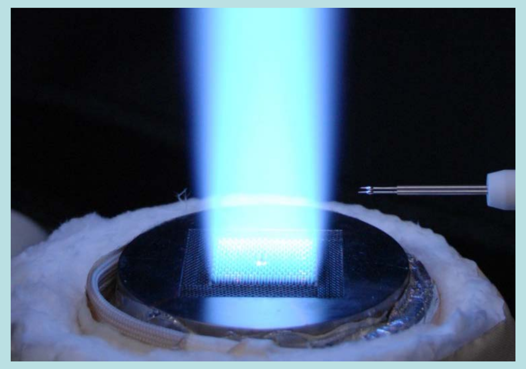


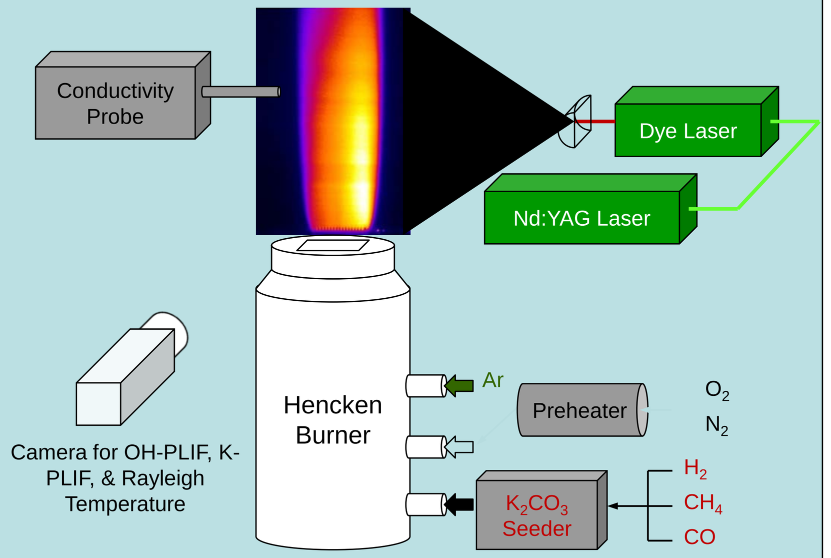
Simulation of discreet flame element In experimental burner face (below)



Predicted temperature and free electron concentration (seeded).

Measurement of electrical conductivity in seeded **oxy-fuel** flames



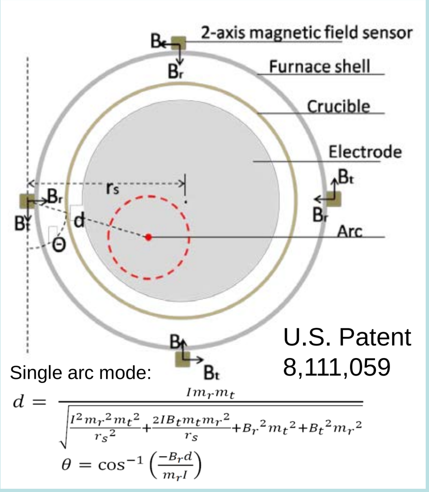


Conductivity measurements used to validate predictions:
-Literature cross sections lead to >2x uncertainty in conductivity.
-Oxy-fuel operation has high CO2 concentration versus earlier studies.
-Double Langmuir probe (transient) in 25mm oxy-fuel flame.
-Planar laser induced fluorescence used to characterize flame profile

Electric Current Density Detection for MHD

The goal is to model, detect and eventually control arcs in a MHD generator.
Inverse problem: current flux via external measures of induced magnetic field.

Idea from NETL developed technology for VAR Furnace



Complexity in MHD generator requires developing new concept.

$\mathbf{u}, p, \rho, T$ are fixed and independent of $\mathbf{b}, \mathbf{e}, \mathbf{j}$

$$\nabla \times \mathbf{e} = 0$$

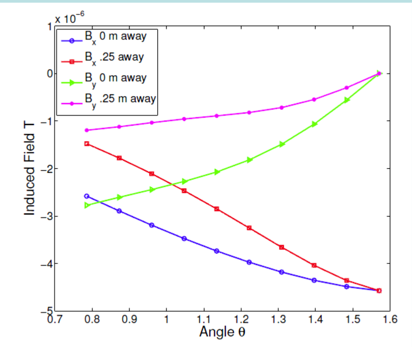
$$\nabla \cdot \epsilon \mathbf{e} = \rho_c$$

$$\nabla \times \mu^{-1}\mathbf{b} = \mathbf{j}$$

$$\nabla \cdot \mathbf{b} = 0$$

$$\mathbf{j} = \sigma\left(\mathbf{e} + \mathbf{u} \times (\mathbf{b} + \mathbf{b}_0)\right) + \frac{\beta}{|\mathbf{b} + \mathbf{b}_0|}\mathbf{j} \times (\mathbf{b} + \mathbf{b}_0)$$

-Simplified PDE equation system (above)
-Discretize with MFD to solve problem

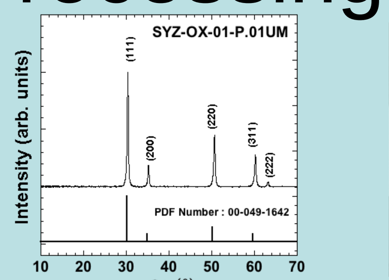


Prediction of induced field; A test case.

Ceramic Electrode Processing and Characterization

Baseline "Hot" Electrodes:

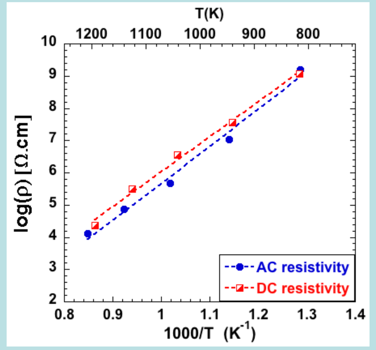
1) $La_{0.95}Mg_{0.05}CrO_3$
2) 88% ZrO_2 – 12% Y_2O_3
3) 89% ZrO_2 – 10% Sc_2O_3 – 1% Y_2O_3
4) 82% HfO_2 – 10% CeO_2 – 8% Y_2O_3
5) 83% HfO_2 – 17% In_2O_3

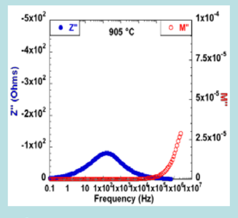


XRD analysis showed single phase fluorite for ZrO_2 and HfO_2 powders (above), and single phase perovskite for $La_{0.95}Mg_{0.05}CrO_3$

FAST fabricated specimens sintered to densities above 95% theoretical density ($La_{0.95}Mg_{0.05}CrO_3$ shown above)

-Ceramic specimens were fabricated through Field Assisted Sintering (FAST) and conventional pressureless sintering
-Crystal structure via x-ray diffraction
-Electrical conductivity characterized via high temp. impedance spectroscopy





Electrical measurements on 82HfO_2-10CeO_2-8Y_2O_3 revealed an electrical conductivity (σ) of **0.016 S/cm at 900°C.**

*** Contact email: Rigel.Woodside @netl.doe.gov**

NETL 1 · OSU Oregon State University 2 · PENNSTATE 3 · West Virginia University 4 · LyTec LLC 5 · U.S. DEPARTMENT OF ENERGY