IPT – Direct Power Extraction
NETL Office of Research and Development
2015 Crosscutting Technology Research Review Meeting

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Direct Power Extraction (DPE): technology which directly converts thermal/kinetic power to useable electrical power.

DPE Example: magnetohydrodynamic generator. This is our present focus, and in particular we focus on the unique challenges of this.

DPE Task Goal: Generate engineering data sets, simulation tools, and materials to further the prospect of using DPE

- Introduction
- Analysis
- Computational Simulations
- Materials Research
- Experimental Plans
- Conclusion
What is Magnetohydrodynamics (MHD)?

MHD describes the interactions of a magnetic field and an electrically conductive fluid

• In Nature
  – geomagnetic dynamo
  – solar “wind” and solar “flares”

• In Engineering
  – Materials Processing
  – Propulsion/Pumping
  – Power Generation
    • Pulsed
    • Steady
      – Compact, no moving parts
      – \textit{High Efficiency Electrical Power Generation w/CO2 capture}

\textbf{Lorentz Force Law}

\[ F = q(E + u \times B) \]

\( F \) is force vector
\( q \) is electric charge
\( E \) is electric field vector
\( u \) is velocity vector
\( B \) is magnetic field vector
**MHD Generator**

A. Turbo-generator Energy Conversion -> chemical (fuel) to thermal/kinetic to mechanical to electric

B. MHD Generator Energy Conversion -> chemical (fuel) to thermal/kinetic to electric

\[ P \propto \sigma u^2 B^2 \]

where \( B \) is applied magnetic field, \( \sigma \) is gas-plasma conductivity, \( u \) is gas-plasma velocity.
New Motivations: USDOE FE

Exhibit 3-117 Increases in Cost of Electricity Over Non-Capture Reference Case

<table>
<thead>
<tr>
<th>Study Case</th>
<th>Capital</th>
<th>Fixed O&amp;M</th>
<th>Variable O&amp;M</th>
<th>Fuel</th>
<th>TS&amp;M</th>
<th>Total (Less TS&amp;M)</th>
<th>Increase in COE (%)^a</th>
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^aRelative to non-capture reference case

Strategies for Improvement:
1. Decrease ASU cost
2. Use oxygen to enable power generation -> MHD

Note: Oxygen established benefits for rockets & melting
Analysis: Seeded Oxy-fuel Electrical Conductivity

Example Case

- **Open-Cycle MHD scenario**
- **Consider oxy-methane combustion**
  - \( \text{CH}_4 + 2\text{O}_2 \rightarrow 2\text{H}_2\text{O} + \text{CO}_2 \) at \( \phi = 1 \)
  - Utilize potassium carbonate as seed material (\( \text{K}_2\text{CO}_3 \))...K ionization \( \sim 4.3 \text{ eV} \)
- **Thermal Equilibrium**
  - Utilize NASA’s Chemical Equilibrium Analysis (CEA) code for chemistry, ionization, and gas dynamics
- **Gas Electrical Conductivity Relation (for comparative purpose):**
  - \( T_e = T_g \); Electrons all at mean speed; use \( Q_k = f(T_e) \); \( Q_{\text{H}_2\text{O}} \) from Spencer (1976)*.

\[
\sigma = \frac{n_e e^2}{m_e c_e \sum_k n_k Q_k} \quad c_e = \langle v \rangle = \frac{8 k_B T}{\pi m_e} \quad \text{-Neglects ion-electron collisions} \\
\text{-Scalar (no magnet effect)}
\]

\( n_e = \) electron number density \([\text{#/m}^3]\)  \\
\( e = \) electron charge \( = 1.60 \times 10^{-19} \text{ [C]} \)  \\
\( m_e = \) electron mass \( = 9.11 \times 10^{-31} \text{ [kg]} \)  \\
\( c_e = \) random thermal electron velocity \([\text{m/s}]\) (estimated by the Maxwell-Boltzmann mean speed, \( \langle v \rangle \))  \\
\( n_k = \) neutral species number density \([\text{#/m}^3]\)  \\
\( Q_k = \) neutral species momentum transfer collisional cross section \([\text{m}^2]\)  \\
\( k_B = \) Boltzmann constant \( = 1.38 \times 10^{-23} \text{ [J/K]} \)  \\
\( T = \) electron temperature \([\text{K}]\)
Seeding: Getting Conductive Flow

1 atm. combustion, $\phi = 1$; Introduce K$_2$CO$_3$ seed as powder or dissolved in water solution

Notes:
- Cond. $\sim 10^4$ greater with seed than without
- Adding seed cools gasses
- Optimal seed amount different for powder vs aqueous
- $\text{H}_2\text{O}$ collisions dominate
- OH radicals: $\sim 10\%$ reduction in e-
Combustion Product Chemistry

1 atm. combustion, $\phi = 1$, 5.4 mass % K (powder K$_2$CO$_3$ added)

Notes:

- Dissociation important
- Very non-linear cond.
- Very little K$^+$
- Re-association maintains T
- At 2100K cond. $\sim 10^2$ less than at $\sim 3000$K
- Higher Temp means New oxy $\sim 3$x cond. from 1980s OCMHD
Effects of Combustion Pressure

$\phi = 1$, 5.4 mass % K (powder $K_2CO_3$ added)

Notes:
- More Temp. & e- at higher P
- Lower cond. at higher P due to collisions
- Optimal seed amount not very sensitive to P
- OH radicals: more important at higher P
Effect of Supersonic Expansion (get velocity)

$\phi = 1, \ 5.4 \text{ mass } \% \text{ K (powder } \text{K}_2\text{CO}_3 \text{ added); Relative Electric } P_{\text{MHD}} = \sigma u^2/4$

Notes:
- Expansion cools gasses
- Expansion reduces pressure
- Pressure is sub-atm. in channel at peak MHD power density
- Lower cond. but more power density
- Lower P still better but gap between Ps closes
Seed Recovery

1 atm. combustion, $\phi = 1$, 5.4 mass % K (powder $K_2CO_3$ added)

No sulfur in system:

With sulfur in system (example):

K$_2$CO$_3$ in $\rightarrow$ K$_2$CO$_3$ out

K$_2$CO$_3$ in $\rightarrow$ K$_2$SO$_4$ out (sulfur scrubbing)

Side Note: Seed aerosols/particles form at $T_s$ where gas turbines operate (an issue for turbine integration)
Analysis: Collisional Cross Sections

- Summarize electron-molecule collisional cross section data sets

\[ \sigma = \frac{n_e e^2}{m_e e_c} \left[ \frac{1}{\Sigma_k n_k Q_k + 3.9 n_i \left( \frac{e^2}{8 \pi e_0 k_B T} \right)^2 \ln \Lambda} \right] \]

\[ P \propto \sigma \mu^2 B^2 \]

Using Itikawa (1978)-Pack H2O Cross Section

Example of electron collisions with powder seeded methane-oxygen combustion products

H₂O is most important species for oxy-fuel MHD systems.
Analysis: H2O- “Root” Sources

- Two “root” H2O data sources, “Pack” and “Yousfi” which multiple references derive values from
- Pack and Yousfi vary by a roughly calculated 60 to 70 % in the MHD range of interest
  - Results in differences for conductivity and power calculations
  - Example case below: kerosene + pure oxygen combustion expanding flue gas w/3 atm. combustion pressure

\[
\sigma = \frac{n_e e^2}{m_e c_e \sum_k n_k Q_k}
\]

\[P \propto \sigma u^2 B^2\]

Red: uses Itikawa (1978) with Pack (1962) data  
Blue: uses Itikawa (2005) with Yousfi (1996) data
Analysis: new conditions of Oxy-MHD

This data is at 1 atm. pressure and is for comparative purposes.

Fuel: CH₄, Oxidant case:
1a: 36% O₂ enriched at 922K
1b: 36% O₂ enriched air at 922K
2a: air at 2200K
2b: air at 2200K
3a: 100% O₂ no pre-heat
3b: 100% O₂ no pre-heat
4a: 100% O₂ at 922K
4b: 100% O₂ at 922K
5a: 100% O₂ at 922K
5b: 100% O₂ at 922K
6a: 100% O₂ at 922K

Stoichiometry for cases:
1,2,5,6: 0.9 stoic. (fuel rich)
3: 1.0 stoic.

Seeding for cases:
“a”: powder K₂CO₃ at 5.4% potassium mass input
“b”: 50/50 aqueous solution of K₂CO₃ at 1% potassium mass input
“6a”: No seeding

Note: this analysis uses 1978 Itikawa-Pack collisional H₂O data set
Analysis: Summary

\[ P \propto \sigma u^2 B^2 \]
where \( B \) is applied magnetic field
\( \sigma \) is gas-plasma conductivity
\( u \) is gas-plasma velocity

- Seeded oxy-fuel much higher conductivity then legacy open cycle MHD systems
- Powder seeding offers notable advantage to oxy-fuel MHD over aqueous solution seeding
- Oxy-fuel MHD peak power densities at Mach 2.5 to 3
- Pressure needed to drive flow, but MHD power density decreases with increasing pressure
- Uncertainty in \( \text{H}_2\text{O} \) electron-molecule cross section most significant
- Note: Costs and engineering constraints/considerations often dictate final design specifications
  - E.g. max hall parameter and critical current densities
Simulation: NETL’s 1D MHD code

Goal: Develop efficient open source code for general analysis and design of MHD generators

Programming language:
Python, Numerical libraries use C, C++ and Fortran

Key libraries:
Cantera – thermodynamics, transport and reactions
Assimulo – interface for SUNDIALS
SUNDIALS – DAE integration package from Sandia

Diagram showing 1D code design variables for MHD Power train simulation
(1) Global parameters

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(2) Stream composition

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(3) Conditions for simulation running

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| 5 | 2 | 0 | 1000 | 1000 | 39.287 | 4.341 | 377 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 6 | 3 | 0 | 1000 | 1000 | 39.287 | 4.341 | 377 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 7 | 4 | 0 | 1000 | 1000 | 39.287 | 4.341 | 377 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
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NATIONAL ENERGY TECHNOLOGY LABORATORY
Running 1D simulation and output

(1) Running 1D simulation

Composition of gas is consistent with pre-tabulated gas_table.py

Starting Channel Simulation With

T = 3028.75 (K)
p = 1.15902 (atm)
M = 0.784295
rho = 0.157333 (kg/m^3)
u = 654.351 (m/s)
sigma = 0.06532 (S/m)

Final Run Statistics: ...

Number of Steps : 310
Number of Function Evaluations : 614
Number of Jacobian Evaluations : 169
Number of F-Eval During Jac-Eval : 1014
Number of Root Evaluations : 311
Number of Error Test Failures : 64
Number of Newton Iterations : 614
Number of Newton Convergence Failures : 0
Number of Stab-Events : 0

Solver options:

Solver : BDF (BDF)
Maxerr : 5
Output alg : False
Tolerances (absolute) : [ 1.00000000e-06 1.00000000e-06 1.00000000e-06 1.00000000e-06 1.00000000e-06 1.00000000e-06]
Tolerances (relative) : 1.e-06

Simulation interval : 0.0 - 3.915 seconds.
Elapsed simulation time: 10.82 seconds.
The success : True
Heat flux : 0.952273

Excel: power table contains all numerical data

(2) Brief simulation result

(3) Output excel spreadsheet containing all numerical data

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<th>B</th>
<th>C</th>
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Simulation: 1D MHD code equations

Numerical methods: Governing equations solved as an initial value problem given the inlet conditions. The equations are a DAE (differential algebraic equation) system.

\[ \frac{d}{dx}(\rho u A) = 0 \]
\[ \rho u \frac{dY_k}{dx} = R_k W_k \]
\[ \rho u \frac{du}{dx} + \frac{dP}{dx} = J_y B_z - F_{\text{friction}} \]
\[ \rho u \left( \frac{du}{dx} + \frac{dh}{dx} \right) = (J_y E_y + J_x E_x) - Q_{\text{wall}} \]
\[ \frac{d\theta}{dx} + \frac{\theta}{u} \frac{du}{dx} \left( 2 + \frac{\delta^*}{\theta} - M^2 \right) = \frac{1}{2} C_f \]
\[ J_y = \frac{\sigma}{1 + (\omega \tau)^2} \left[ (E_y - uB_z) + \omega \tau E_x \right] \]
\[ J_x = \frac{\sigma}{1 + (\omega \tau)^2} \left[ E_x - \omega \tau (E_y - uB_z) \right] \]

- 5 main equations (mass, momentum, energy, chemical reaction, boundary layer) for the flow state.
- 2 equations (generalized Ohm’s law) for the EM field.
- Need two additional equations.
  - Electrode Configuration
  - External Load

**Segmented Faraday linear:**

\[ J_x = 0 \quad \Rightarrow \quad \begin{cases} E_x = \omega \tau (E_y - uB_z) \\ J_y = \sigma (E_y - uB_z) \end{cases} \]

**Fixed Load Resistance:** \( R_L \)

\[ K = \frac{E_y}{uB_z} \quad \Rightarrow \quad K = \frac{\sigma}{\sigma + \sigma_L} = \frac{R_L}{R + R_L} \]

\[ E_y = KuB_z \]
Simulation: Reaction/Composition Models

Species concentration are in flux due to recombinations. Non-equilibrium considered.

- **Thermophysical model is for hydrocarbon products seeded with potassium.**
  - DRM19 - methane oxidation mechanism reduced from GRI30 Mech
  - Interaction of K w/ combustion products
  - K ionization products and reaction equations
  - “Coal” model (equilibrium only) includes condensed and non-condensed ash-species

- **Equilibrium Model:**
  - Composition is in local thermodynamic equilibrium but still changes as the temperature and pressure change in the channel.
  - Composition and thermophysical properties are pre-tabulated functions of temperature & pressure
  - Code runs faster due to reduced number of equations (4 vs. 4 + N_species)
  - Reaction rates are not required to perform simulations

- **Non-Equilibrium Model:**
  - Explicitly track balance between the rates of convection, production and destruction of individual species.
  - Better estimates of unburnt fuel and electron attachment may not that critical for energy performance estimates

---

![Graphs showing temperature, conductivity, and power output over channel position](image)
Simulation: 1D MHD code equations

Numerical methods: Governing equations solved as an initial value problem given the inlet conditions. The equations are a DAE (differential algebraic equation) system.

\[
\frac{d}{dx}(\rho u A) = 0
\]

\[
\rho u \frac{dY_k}{dx} = R_k W_k
\]

\[
\rho u \frac{du}{dx} + \frac{dP}{dx} = J_y B_z - F_{\text{friction}}
\]

\[
\rho u \left( u \frac{du}{dx} + \frac{dh}{dx} \right) = (J_y E_y + J_x E_x) - Q_{\text{wall}}
\]

- 5 main equations (mass, momentum, energy, chemical reaction, boundary layer) for the flow state.
- 2 equations (generalized Ohm’s law) for the EM field.
- Need two additional equations.
  - Electrode Configuration
  - External Load

\[
\frac{d\theta}{dx} + \frac{\theta}{u} \frac{du}{dx} \left( 2 + \frac{\delta^*}{\theta} - M^2 \right) = \frac{1}{2} C_f
\]

Segmented Faraday linear:

\[
J_x = 0 \quad \Rightarrow \quad \begin{cases}
E_x = \omega \tau (E_y - u B_z) \\
J_y = \sigma (E_y - u B_z)
\end{cases}
\]

Fixed Load Resistance: \( R_L \)

\[
K \equiv \frac{E_y}{u B_z} \quad \Rightarrow \quad K = \frac{\sigma}{\sigma + \sigma_L} = \frac{R_L}{R + R_L}
\]

\[
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\]
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  - Better estimates of unburnt fuel and electron attachment may not that critical for energy performance estimates
Simulation: 1D code verification

IEE Mark-II: theoretical simulation work by UTSI & IEE in 1987

On-going MHD channel simulation work:
• Incorporating boundary voltage layer drop into model
• Running coal case for OPPB systems study
• Consider other channel geometries
• Supersonic channel case validation

* Ref: Lineberry et al., AIAA-87-1214, 1987, U.S. – China Cooperative MHD Experiments at IEE Academia Sinica
Simulation: 1D code validation

IEE Mark-II: subsonic MHD channel testing from late 1980s*

Simulation results are consistent with experimental data obtained.

* Ref: Lineberry et al., AIAA-87-1214, 1987, U.S. – China Cooperative MHD Experiments at IEE Academia Sinica
Simulation: Toward detecting arcs

We are interested in detecting arcs (or streamers) by measuring the magnetic fields they induce. We therefore wish to model these magnetic fields which may be observable outside the channel.

**Forward Model and Computation**

- Assume magnetostatic equations applicable
- Utilize NETL1D MHD code for fluid & state conditions
- Assumes Induced field $\ll$ applied field ($B_0$)

\[
\begin{align*}
\nabla \cdot \mathbf{E} &= \rho_c \\
\nabla \times \mathbf{E} &= 0 \\
\nabla \cdot \mathbf{b} &= 0 \\
\n\nabla \times \mathbf{b} &= \mathbf{J} \\
\n\nabla \times \mathbf{b} &= \mathbf{J} \\
\mathbf{J} &= \sigma (\mathbf{E} + \mathbf{u} \times \mathbf{B}_0) + \nu \mathbf{J} \times \mathbf{B}_0
\end{align*}
\]

- (Gauss’ Law)
- (Faraday’s Law)
- (Gauss’ Law for Magnetism)
- (Ampere’s Law)
- (Generalized Ohm’s Law)

$B_0$ applied magnetic flux density

$\mathbf{b}$ induced magnetic flux density

$\mathbf{u}$ fluid velocity

$\epsilon$ electrical permittivity

$\nu$ electron mobility

$E$ electric field

$\mathbf{J}$ current density

$\rho_c$ charge density

$\mu$ magnetic permeability

$\sigma$ electrical conductivity

Arcing is known to be a major problem for MHD channel materials**

*Source: Okuno Presentation (2007)

**Source: kayukawa (2003).
Simulation: 3D MHD Currents

Magnetostatic MHD current

\[ \mathbf{J} = \sigma (\mathbf{E} + \mathbf{u} \times \mathbf{B}_0) + \mathbf{J} \times \beta \]
\[ \nabla \cdot \mathbf{J} = 0 \]
\[ \mathbf{E} - \nabla V = 0 \]

Equivalent to

\[ \sigma = \frac{\sigma}{1 + \beta^2} \begin{pmatrix} 1 & \beta & 0 \\ -\beta & 1 & 0 \\ 0 & 0 & 1 + \beta^2 \end{pmatrix} \]

\[ \nabla \cdot \sigma \mathbf{E} = -\nabla \cdot \sigma \mathbf{u} \times \mathbf{B}_0 \]
\[ \mathbf{E} - \nabla V = 0 \]

This can be solved for using standard PDE based FEM (eg Comsol).

Future work: Inverse problem theory and application based on forward simulation

The interesting aspect of MHD currents is they are not necessarily perpendicular to electric field gradient

\[ \beta = \nu \mathbf{B}_0 \]
\[ \sigma \] effective conductivity

\[ \beta = |\beta| \]
\[ V \] Hall parameter

\[ V \] Voltage
Channel Materials Selection & Design

MHD Electrode Requirements

1. Good electrical conductivity
2. Adequate thermal conductivity
3. Resistance to electrochemical corrosion (seed/slag)
4. Resistance to thermal shock
5. Compatibility with other system materials
6. Resistance to/minimization of arc attack

Candidate Hot Electrodes Fabricated

1) $\text{La}_{0.95}\text{Mg}_{0.05}\text{CrO}_3$
   identified as promising from 1970s USSR-USA work
2) $88\% \text{ZrO}_2 - 12\% \text{Y}_2\text{O}_3$
   baseline from 1970s USSR-USA joint work
3) $89\% \text{ZrO}_2 - 10\% \text{Sc}_2\text{O}_3 - 1\% \text{Y}_2\text{O}_3$
   well characterized for fuel cells
4) $82\% \text{HfO}_2 - 10\% \text{CeO}_2 - 8\% \text{Y}_2\text{O}_3$
   identified as promising from 1970s USSR-USA work
5) $83\% \text{HfO}_2 - 17\% \text{In}_2\text{O}_3$
   PNNL selection from late 1980s but untested

- Oxide powders generated using co-precipitation
- Samples fabricated via both “spark plasma sintering” (SPS) and pressureless sintering.

Fabricated sample goal: Establish baseline characterizations for hot electrodes using known materials

NETL Thermo-mechanical FEM Analysis of 1MWt round copper electrode MHD Channel

- FEM Highlights problems due to CTE mismatches and mechanical fastening
- Stress concentrations in ceramic insulators can cause failure
Electrical resistivity measurements

- Measurements taken with 4-wire approach
  - DC resistivity
  - AC resistivity (impedance spectroscopy)
    - 1Hz- 5 MHz

- 4 pressureless sintered compositions tested converged to resistivity values on order of 20 to 40 Ω-cm at 900°C
  - Comparable to existing literature values (with T extrapolation)

- All samples exhibited contact resistance due to Pt electrodes
  - Will be a consideration in the design of MHD systems
  - In addition, non-Ohmic behavior was seen in some samples
  - Could be due to work function mismatch or electrode/ceramic reactions

- All samples showed grain/grain boundary mechanisms
  - Electrically heterogeneous – oxygen non-stoichiometry

- On-going work:
  - Compare to SPS samples (preliminary results show some differences)
  - Increase testing temperature
    - Note resistivity very sensitive to T

- High temperature cell
  - NorECs Probostat in Carbolite tube furnace
Microstructure & Phase Analysis of SPS Samples

- SEM imaging of microstructure
  - SEM-EDS for surface chemistry profiling
- XRF for bulk chem. and XRD for phase identification
- Optical Microscopy for surface analysis

88 mol. % ZrO₂
12 mol. % Y₂O₃

88 mol.% ZrO₂ – 12 mol.% Y₂O₃
(Target) 79.73wt.% ZrO₂ – 19.72wt.% Y₂O₃ (XRF)

88 mol. % ZrO₂
12 mol. % Y₂O₃

83 mol. % HfO₂
17 mol. % In₂O₃

82 mol. % HfO₂
10 mol. % CeO₂
8 mol. % Y₂O₃

89 mol. % ZrO₂
10 mol. % Sc₂O₂
1 mol. % Y₂O₃

- SPS samples had numerous cracks -> processing far from optimized
- Carbon contamination likely from SPS system (coloration above) -> could be causing issues
- Microstructure suggests high porosity which varies through cross section -> may be related to carbon
- 12%YSZ single phase -> multiple phases in others due to powder prep. and/or sintering issues
Seed Material Interaction with Samples

- Expose samples to $K_2CO_3$
  - Based on ASTM test C987
  - 24 hrs at 1500$^\circ$C in air (semi-closed w. lid)

Exposure of 92% ZrO$_2$ – 8% Y$_2$O$_3$

- Extra sample made using SPS

Optical (above) and SEM of cross sections indicate potassium penetration and interaction leading to a degradation of material

Future work:
Utilize Yonejkura “hot stage” Confocal scanning laser microscope (Olympus)
NETL MHD Laboratory

Under construction: 7/10/2015 scheduled completion date

- Lab goal: Build “Test bed” for simulation validation and MHD materials performance and durability studies
  - System flexibility is important
  - Leverage existing commercial equipment/knowledge to extent possible
  - Incremental Design/R&D approach
  - Low “TRL” level: not doing demonstration projects

Initial Conditions:
- Fuel: K-1 kerosene
- Oxidant: 100% oxygen
- Seed: K2CO3 powder w/ argon

Nominal 1 MWt sized system is target
MHD Laboratory Equipment

- Major Test Hardware
  - TAFA 8200 console, powder feeder, and HVOF combustor
    - Up to 10 bar combustion
    - Nominal Mach 1.8 output
    - Up to 0.5 MWt through console
  - GMW custom electromagnet
    - Adjustable 2 Tesla field at ~50mm gap
    - Adjustable pole caps with optical access
  - Up to 12,000 cfm bag house and blower
  - 150 GPM at 70F delta chiller
  - 248nm Excimer laser
  - Up to 10,000 cfm liquid oxygen vaporizer
  - 20’L x 12’W sound insulated test chamber
Planned Experiment: Back-powered channel

- HVOF powered circular hall channel -> power supply controls current into channel
  - No magnetic field in this test
- Establish effective plasma conductivity using various insulator lengths
- Establish spatial and temporal arc characteristics in channel

**Power Supply & Impedance Analyzer**

**FEM predicted water cooled channel material temperature [K]**

- **Flowing Plasma Source**
- **Cathode**
- **Anode**
- **Electrical Insulator (variable lengths)**
- **Array of magnetic flux density vector sensors**

FEM electromagnetic model -> see slide 20

**Figure showing concept of experiment**

Commercial sensors measure these induced fields nT to µT
Experimental: Photoionization

What we know:

- Combustion driven MHD plasma is a partially ionized system which rapidly reaches thermal equilibrium
  - Very little seed introduced actually ionizes (~1% of it)
  - Ionization rapidly drops as temp decreases -> limits low temp. of cycle (MHD open cycle low temp: ~ 2200 to 2500K)
  - However, local non-equilibrium likely persists near wall due to large gradient and arcing
- Ionization potential of K is 4.34 eV
  - So “photoionization” of potassium using UV photons < 285nm
- Good spatial and temporal control of directed energy with lasers

What we would like it to do:

1. Apply directed laser sheet across electrode surfaces
   To control and mitigate arcing issues
2. Apply laser beam to enhance ionize within a MHD channel
   Decrease seed use
   Extend low temperature

Initial Experiment:

- Flash potassium seeded HVOF combustion products with Excimer laser (248nm)
  - Measure absorption
  - Measure relaxation time scales

Electron transitions for K
Group Publications (last 9 months)

- Kim, Hyoungkeun et.al.; “Numerical modeling and simulation of magnetohydrodynamic generators”, 2014 APS meeting.
- Woodside, Rigel; “Retrospective and Prospective Aspects of MHD Power Generation”, Presentation at MHD workshop, 10/01/2014.
- Woodside, Rigel et.al.; “MHD Energy Conversion R&D”, Poster and Presentation of NETL MHD R&D at MHD Workshop, 10/02/2014.
Questions?

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