Performance Baseline for an Oxy-Coal MHD Power Plant with Carbon Capture

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“Direct Power Extraction” (DPE)
Making Oxy-fuel Combustion an Advantage

- Oxy-fuel combustion greatly simplifies carbon capture because the combustion products are CO₂ and H₂O, but, producing oxygen requires a lot of energy.
- If you make significant extra power because of the available oxygen, oxy-fuel combustion would be an advantage.
- The high temperatures possible with pure oxygen combustion can be used to operate a magnetohydrodynamic (MHD) “topping” cycle:
  - MHD exits to conventional steam boiler system (“bottoming cycle”).
  - Provides “capture-ready” feature of oxy-fuel.
  - Could be retrofit to coal steam plants

**MHD generator concept**

High-temperature oxy-fuel combustion (with conductivity seed) accelerates through magnetic field to produce current. Hot exhaust used in conventional steam boiler.
MHD Power Generation Efforts

• Concept proven in both U.S. and USSR in 70’s and 80’s:
  – Electricity transferred to grid

• U.S. Direct-Fired Coal Open Cycle MHD program discontinued in 1993:
  – Slag retention problems in combustor
  – Channel operation problems, particularly with electrode damage
  – Concerns about the cost-effectiveness of seed regeneration process
  – Uncertainties in fully integrating MHD systems
  – Uncertainties in scaling up MHD systems

• **Objective:** Reassess MHD power generation feasibility with recent technology advances and oxy-fuel combustion advantage for carbon capture
## MHD: Then and Now

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>No CO₂ capture</td>
<td>CO₂ Capture</td>
<td>High Temperature Oxy-fuel combustion for CO₂ capture enables MHD.</td>
</tr>
<tr>
<td>Large demos</td>
<td>Simulation &amp; bench scale experiments</td>
<td>Validated models for different generator concepts &amp; conditions, not demos.</td>
</tr>
<tr>
<td>Inefficient oxygen production</td>
<td>Efficient oxygen production</td>
<td>ASU power requirements have dropped 40% since 1990.</td>
</tr>
<tr>
<td>SOx and NOx control</td>
<td>Capture GPU</td>
<td>No emissions! Use oxy-fuel gas processing unit (GPU).</td>
</tr>
<tr>
<td>Low temperature superconducting magnets</td>
<td>High temperature superconducting magnets</td>
<td>Liquid helium cooled magnets are no longer the only superconductor option</td>
</tr>
<tr>
<td>Magnets &lt; 6 Tesla</td>
<td>Magnets &gt; 6 Tesla</td>
<td>Advanced magnets exist today, with large scale deploy (LHC &amp; CERN)</td>
</tr>
<tr>
<td>Analog electronics</td>
<td>Digitally controlled electronics</td>
<td>New MHD generator measurement &amp; control possibilities</td>
</tr>
<tr>
<td>Conventional manufacturing</td>
<td>Advanced manufacturing</td>
<td>New channel construction approaches.</td>
</tr>
<tr>
<td>Seeded flows</td>
<td>“Excited” plasma</td>
<td>“clean gas” or new ionization approaches in MHD power systems may be possible</td>
</tr>
</tbody>
</table>
Direct Power Extraction (via MHD)

• **To generate MHD power:** $Power \propto \sigma u^2 B^2$
  - $\sigma = \text{gas/plasma electrical conductivity}$
    - Generated with very high (oxy-fuel) temperature and ionizing seed materials (e.g., potassium)
  - $u = \text{gas/plasma velocity}$
    - Accelerate plasma to near sonic velocities
  - $B = \text{magnetic field}$
    - Use superconducting magnets for high field

• **To extract power:**
  - Need robust electrodes capable of withstanding high temperatures, thermal gradients, slagging, arcing, and high electric fields
  - Extract thermal energy in high temperature exhaust for high overall power plant efficiency
• Nominal plant input of 1000 MW\textsubscript{th} sub-bituminous (PRB) coal, dried to 5% moisture, dry-fed with 8 wt% recycled CO\textsubscript{2}.
• Cryogenic Air Separation Unit (ASU) with 95% purity oxygen (195 kW/tonne O\textsubscript{2}).
• Oxy-coal combustion with 90% slag rejection.
• Injection of recovered and makeup potassium seed to generate plasma.
• MHD power extraction and conversion to AC electrical power.
• Heat Recovery Steam Generator (HRSG) for Advanced Ultra-Supercritical (A-USC) bottoming cycle with reheat (1350 °F/1400 °F/5000 psig).
• CO\textsubscript{2} purification and compression unit (CPU) for pipeline-quality CO\textsubscript{2}.
Seed Recovery Process

- **Potassium recovery required for economic MHD plant operation**
  - Precipitates out as $\text{K}_2\text{SO}_4$ in the HRSG, captured with ash in the ESP
- **Based on the Formate seed recovery process from the University of Tennessee Space Institute**
  - ~1.3 wt% potassium loading to recover coal sulfur as gypsum
  - Requires natural gas partial oxidation to generate CO for reaction

**Formate Reaction:**

$$\text{K}_2\text{SO}_4 + \text{Ca(OH)}_2 + 2\text{CO} + 2\text{H}_2\text{O} \rightarrow \text{CaSO}_4 \cdot 2\text{H}_2\text{O} + 2\text{KCOOH}$$

**Diagram:**

- Nat. Gas $\rightarrow$ Partial Oxidation $\rightarrow$ H$_2$/N$_2$ Fuel Gas to HRSG
- O$_2$ $\rightarrow$ H$_2$ Membrane $\rightarrow$ CO
- Lime, Water $\rightarrow$ Slaker $\rightarrow$ Ca(OH)$_2$, Water $\rightarrow$ Formate Reactor
- K$_2$SO$_4$, Ash, Water $\rightarrow$ Clarifier $\rightarrow$ K$_2$SO$_4$, Water $\rightarrow$ Formate Reactor
- Gypsum Separation & Dewatering $\rightarrow$ Evaporator $\rightarrow$ KCOOH $\rightarrow$ KCOOH, Water
- Water $\rightarrow$ Slaker $\rightarrow$ Ca(OH)$_2$, Water $\rightarrow$ Formate Reactor
- Ash $\rightarrow$ Clarifier $\rightarrow$ K$_2$SO$_4$, Water $\rightarrow$ Formate Reactor

1-D Model for Channel Design

- NETL 1-D MHD channel model tailored to meet channel and overall plant design needs
  - Includes block calculations for combustion, slag rejection, & seed addition
- Forward-integrated 1-D calculations include:
  - Nozzle, MHD channel, diffuser for specified area or Mach number
  - Profiles of: heat loss, power extraction, temperature, pressure, etc.
DPE Channel Design Assumptions

- Assume 6 Tesla superconducting NbTi magnet, channel wall temperature of ~1650 °C, and diffuser exhaust at atmospheric pressure

- Evaluate plants for two channel designs:
  - DPE-1 (current state-of-the-art): Mach 0.8 flow, fuel-rich combustion, modern channel electrical parameters
  - DPE-2 (advanced channel design): Mach 0.95, stoichiometric combustion, advanced electrical design for higher power density

- Channel Processes Modeled:
  - Convective and radiative heat losses to the channel walls
  - Boundary layer viscous losses
  - Electrode voltage drops due to loss of plasma electrical conductivity in the thermal wall boundary layer
  - Tapered magnetic field to meet electrical channel constraints

- Channel designs optimized using a second law thermodynamic work potential function
Channel Design Results

- **Stoichiometric combustion for DPE-2:**
  - Increases mass flow
  - Increases channel inlet temperature

- **Higher power density and Mach number for DPE-2 allows for:**
  - Higher power extraction with increased pressure
  - Reduced channel length and lower heat losses

<table>
<thead>
<tr>
<th>Parameter</th>
<th>units</th>
<th>DPE-1</th>
<th>DPE-2</th>
</tr>
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<tbody>
<tr>
<td>Stoichiometry</td>
<td></td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>Combustor Pressure</td>
<td>bar</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>Mass Flow</td>
<td>kg/s</td>
<td>121.4</td>
<td>129.3</td>
</tr>
<tr>
<td>Mach Number</td>
<td></td>
<td>0.8</td>
<td>0.95</td>
</tr>
<tr>
<td>Combustor Exit Temperature</td>
<td>°C</td>
<td>2891</td>
<td>2919</td>
</tr>
<tr>
<td>Channel &amp; Diffuser Length</td>
<td>m</td>
<td>22.6</td>
<td>19.5</td>
</tr>
<tr>
<td>Diffuser Exit Temperature</td>
<td>°C</td>
<td>2265</td>
<td>2302</td>
</tr>
<tr>
<td>Convective Heat Loss</td>
<td>MW</td>
<td>56</td>
<td>53</td>
</tr>
<tr>
<td>Radiative Heat Loss</td>
<td>MW</td>
<td>63</td>
<td>61</td>
</tr>
<tr>
<td><strong>MHD DC Power output</strong></td>
<td>MW</td>
<td>168</td>
<td>184</td>
</tr>
<tr>
<td>Electric Field, $E_x$</td>
<td>V/m</td>
<td>2496</td>
<td>3909</td>
</tr>
<tr>
<td>Current Density, $J_y$</td>
<td>A/cm²</td>
<td>0.80</td>
<td>1.00</td>
</tr>
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</table>
Channel Design Results

- **MHD profiles include:**
  - Nozzle (first 2 meters)
  - Constant Mach number MHD channel
  - Diffuser (last 2-3 meters)
- **Heat losses partially recovered in bottoming cycle**
Air-fired vs. Oxy-fired MHD

- **Absence of nitrogen from air is significant**
  - For a given fuel input, channel mass flow and cross-sectional area are reduced
    - Larger impact of heat losses to the channel walls due to higher surface area to volume ratio.
    - Reduced channel cross-sectional area reduces costs of channel and superconducting magnet
  - Fuel derived material is a larger fraction of channel mass flow
    - Ash and sulfur mass fractions increase
    - Potassium seed requirements more driven by sulfur recovery than plasma conductivity needs
  - Final oxy-combustion temperatures reduced
    - Higher heat capacity of CO₂ and H₂O relative to N₂
    - Increased impact of CO₂ dissociation to CO & O₂
    - Air combustion dependent on air preheating to achieve thermal plasma temperatures
Sensitivity to Channel Assumptions

- Due to change in primary channel fluid from $N_2$ to $CO_2$, many modeling assumptions require validation for the oxy-coal combustion case
  - Overall radiative heat transfer emissivity
  - Boundary layer development and electrode voltage drops
  - Plasma electrical conductivity

- Experiments and/or CFD modeling efforts are underway at NETL to refine these assumptions
DPE Power Plant - Process Flow Diagram

1-D MHD Model

Balance of plant modeled with Aspen Plus and integrated with 1-D MHD model to iterate on recycle streams
Temperature/Heat Duty Analysis

- **Very large temperature differences lead to inefficiency (exergy destruction)**
  - Cooling water losses (and costs) dictate shorter MHD channels
  - Higher electrode temperatures would improve MHD efficiency
- **Large ΔT in HRSG and afterburner limited by AUSC steam conditions**
  - High quality thermal energy better utilized in legacy MHD program via high temperature air preheating
    - Preheating oxygen presents a safety concern
  - Potential for improvement:
    - Closed (disk) MHD “middle” cycle
    - Coal gasification
Conclusions and Future Work

- **Developing the first pure oxygen-fired coal MHD system performance analysis with CCS**
  - Net plant thermal efficiency expected to be competitive with competing oxy-coal technologies

- **Currently completing balance of plant design and estimating capital costs to determine COE, completing a baseline systems study**
  - Large magnet cost in legacy systems is reduced ~75% for oxy-coal DPE
  - Obtain channel and combustor costs by updating legacy cost scaling algorithms to present day dollars
  - Seed recovery process cost estimated with Aspen Plus Economic Analyzer

- **Several future analyses being considered to extend this work**
  - Investigate effects/dependency on channel wall temperature
  - Optimization of seed recovery process to improve cost & performance
  - Look at alternate fuels (e.g., petcoke), supersonic channels, non-equilibrium plasma effects, triple cycles, and other improvements
NETL R&D – High Temperature Materials

- **R&D Focuses on MHD Electrodes**
  - Good electrical conductivity & adequate thermal conductivity
  - Resistance to electrochemical corrosion (seed/slag)
  - Resistance to erosion by high velocity particle laden flow (seed/slag)
  - Resistance to thermal shock
  - Compatibility with other materials in system
  - Resistance to/minimization of arc attack/erosion

- **Internal NETL Activity**
  - Electrode exposure characterizations ->

- **University Funded R&D on “Hot” Electrodes**
  - Carbon nanotubes in ceramic matrix: Univ. Nebraska
  - Nanostructured SiC based materials: Univ. of Washington
  - Boride based materials: Univ. of Idaho
  - Combustion synthesis of Boride based materials: UTEP
  - Carbide and Boride Ceramics: FIU
• **Experimentation in NETL’s FC lab**
  – Custom oxy-fuel Hencken burner
  – Potassium carbonate solution seeding
  – Double Langmuir probe for conductivity measure

• **Experimentation in NETL’s MHD lab**
  – Operation of liquid fueled high velocity oxy-combustor (supersonic) w/ seed injection
  – Goal is bench scale MHD channel testing
  – Studying non-equilibrium plasma generation in the channel wall boundary layer
  – 2-D and 3-D channel simulations to validate

• **Experimentation at UTEP**
  – Developing and testing a high velocity oxy-methane combustor
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For More Information, Contact NETL

the ENERGY lab

Delivering Yesterday and Preparing for Tomorrow
1-D Channel Code Methodology

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

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

- 5 main equations (mass, momentum, energy, chemical reaction, boundary layer) for the flow state.
- 2 equations (generalized Ohm’s law) for the EM field.
- Additional equations for Channel to account for:
  - Electrode Configuration
  - External Load

The code calculates the variable power outputs along channel length.
DPE Channel Design

- Channel designs optimized using second law work potential function
- Design procedure:
  - Vary pressure and electrode spacing at desired values of current density, $J_y$
  - Maximize work function at reasonable values for axial electric field, $E_x$
  - Limit channel length based on boiler feedwater heating duty of steam cycle
  - Taper magnetic field to meet exact $E_x$ specification
ASU Sub-Model

- Granular model developed to attain target specific power
  - Specific power = 195 kW/tonne O₂

- Oxygen product purity is 95 mole percent O₂
  - 2.8 mole percent Ar
  - 2.2 mole percent N₂

- Aspen System Model used “Black box” ASU Representation
  - Split fractions tuned to give same output as granular ASU model
  - MAC outlet pressure adjusted to yield target specific power
• Granular CPU model not embedded into DPE system model
  – No integration of CPU with other portions of DPE process
  – This sped up convergence significantly
  – Granular model run once after system model converged

• CO$_2$ purity 99.99 mole percent
  – O$_2$ concentration in CO$_2$ product 10 ppmv
  – Ar concentration in CO$_2$ product 62 ppmv
  – NO$_x$ concentration in CO$_2$ product 10 ppbv
  – SO$_x$ concentration in CO$_2$ product 4 ppbv
  – N$_2$ concentration in CO$_2$ product < 1 ppbv

• CO$_2$ recovery 96.3 percent