Analysis, Simulation, & Experimental Validation for MHD Energy Conversion

NETL – Research and Innovation Center
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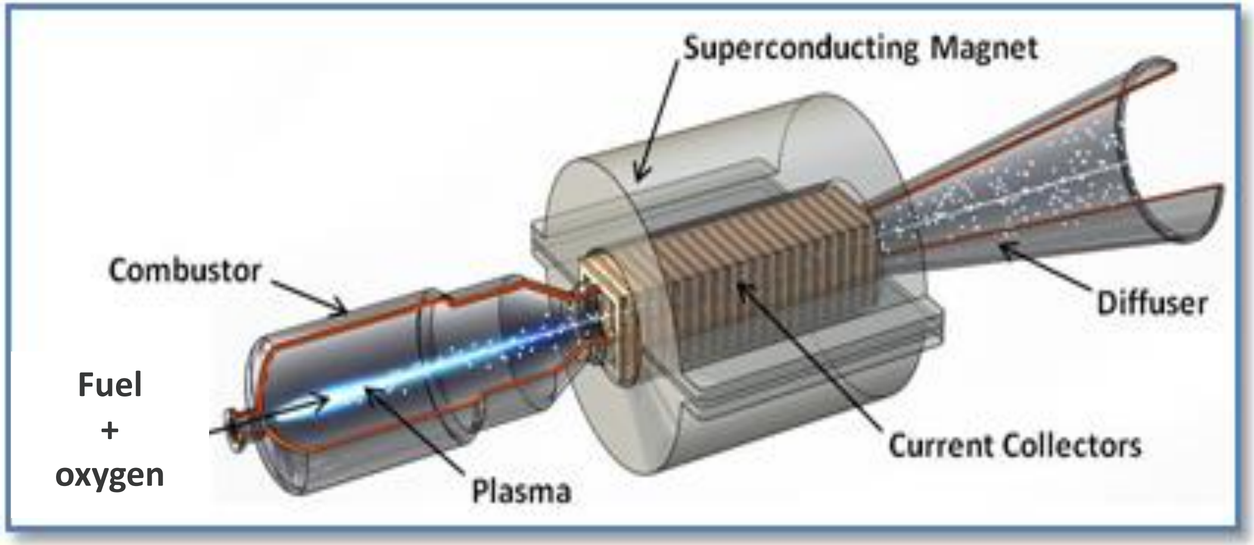
2017 NETL Crosscutting Research Conference

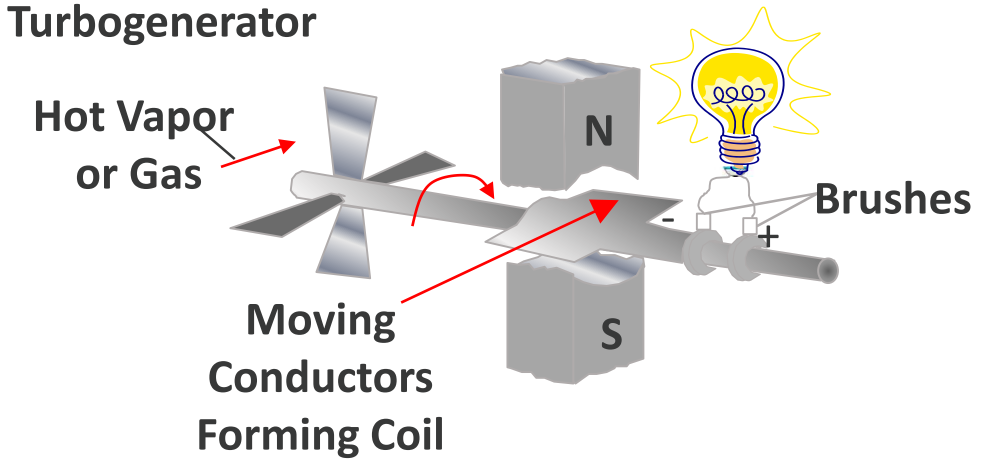
Introduction

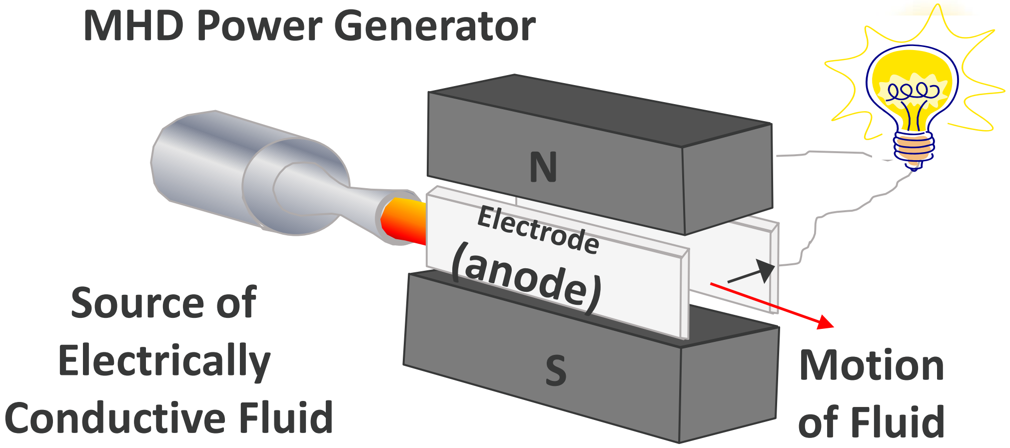
Direct Power Extraction (DPE): The concept of directly converting thermal/kinetic power to useable electrical power.
Magnetohydrodynamics (MHD): The branch of physics which describes the interaction of an electrically conductive fluid with a magnetic field.

$$P \propto \sigma B^2 u^2$$

P is the power density
B is applied magnetic field
σ is gas-plasma conductivity
u is gas-plasma velocity

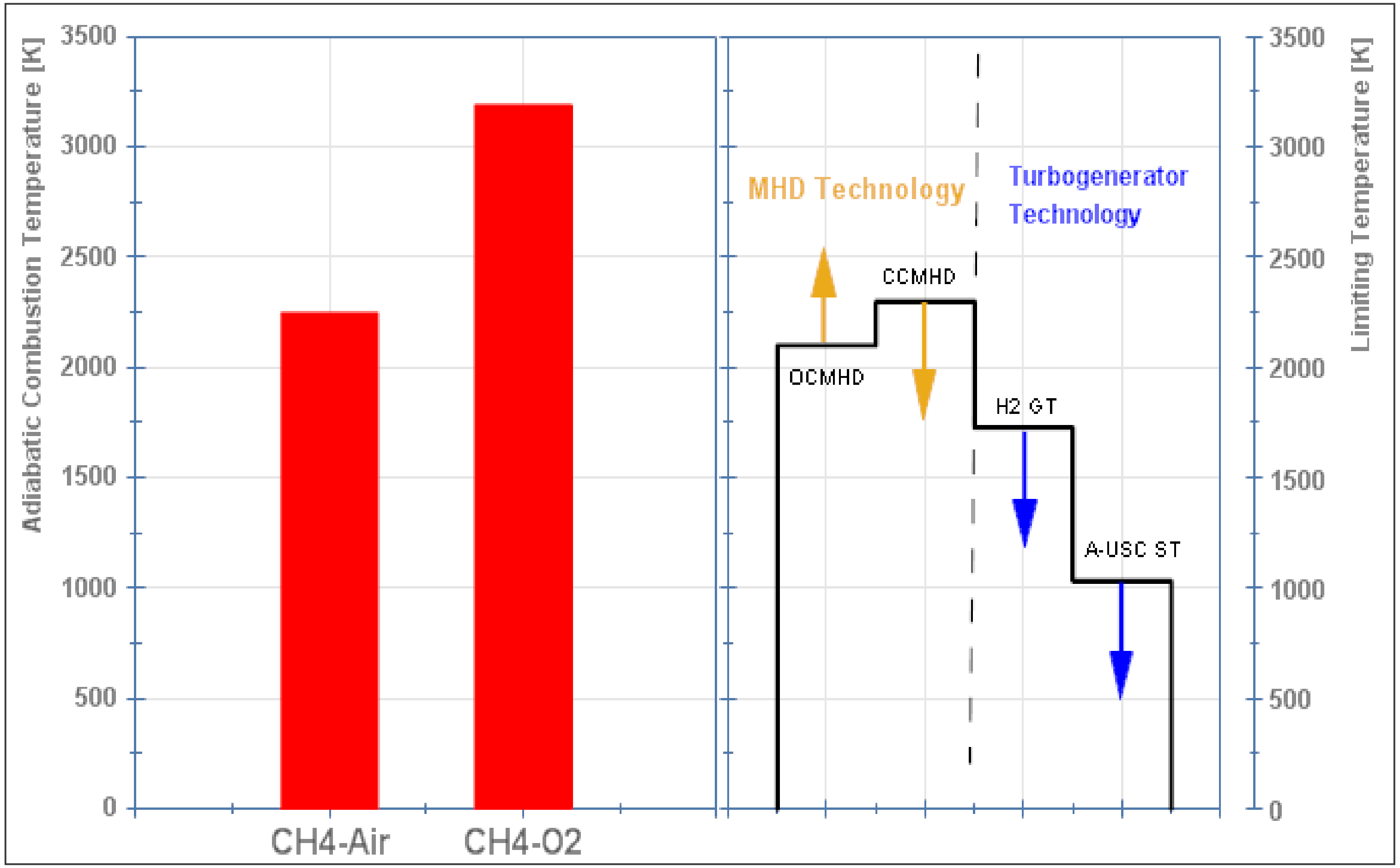






Motivation & Benefits

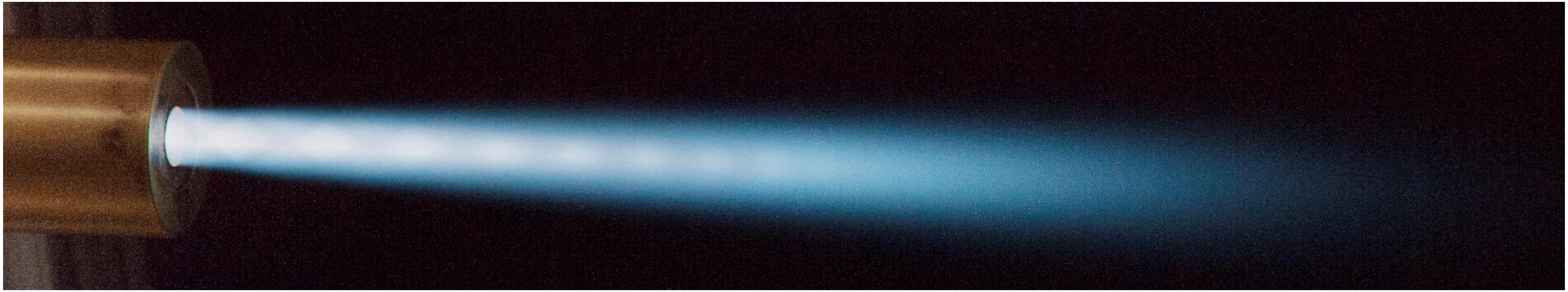
- **Increased power generation efficiency**
  - Topping on existing cycles
  - New combined cycles
  - Synergy with CO_2 capture
- **Fuel Flexible**
  - Thermal power input
- **Compact Generation**
  - Small footprint & potentially portable
- **DC Power Output**
  - Future grid transmission?
- **Dynamic Load Response**
  - Good for grid performance and reliability



Outline

FY17 NETL RIC Activity Focus - Energy Conversion Engineering

- **Oxy-Fuel Combustion Plasma Conductivity Analysis & Experiment**
- **Computational MHD Tool Development For Analysis & Design**
- **HVOF Heat and Mass Balance Simulation & Experiment**
- **Photoionization Simulation & Experiment**



Combustion & Ionization

Predictive Model

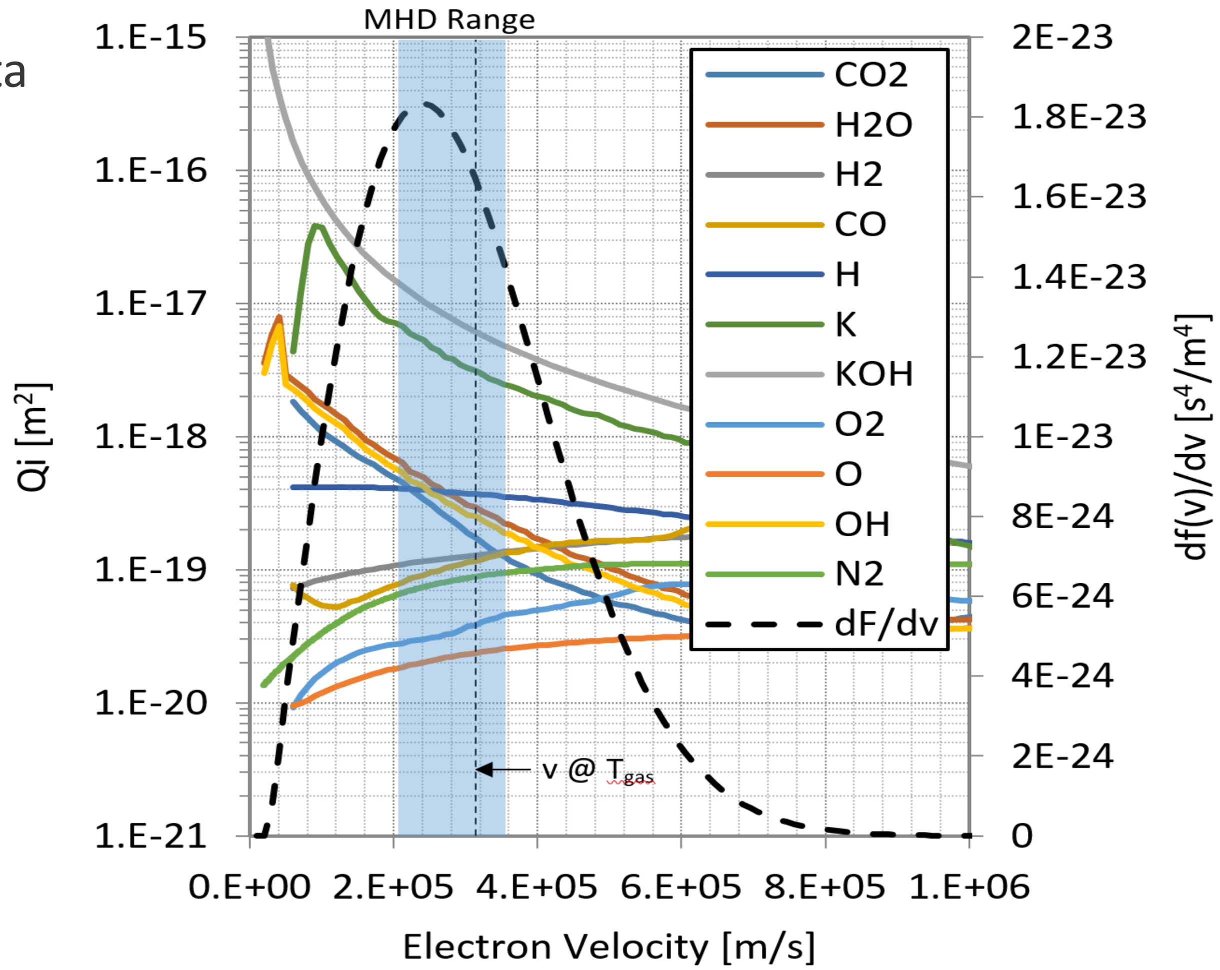
$$P \propto \sigma B^2 u^2$$

- Compiled relevant electron-molecule MTCS data
- Model conductivity uses existing approaches
  - Combustion & species from Cantera
- Considering both electron-ion & electron-molecule collisions

$$\frac{1}{\sigma} = \frac{1}{\sigma_{en}} + \frac{1}{\sigma_{ei}}$$

$$\sigma_{en} = \frac{e^2 n_e}{m\left[\frac{8kT}{\pi m}\right]^{1/2} \sum_{i=1}^{N} n_i Q_i}$$

$$\sigma_{ei} = 1.975 \frac{n_e e^2}{\overline{v_{ei}}}$$



Note: Curve represents T_{gas} = 3000 K

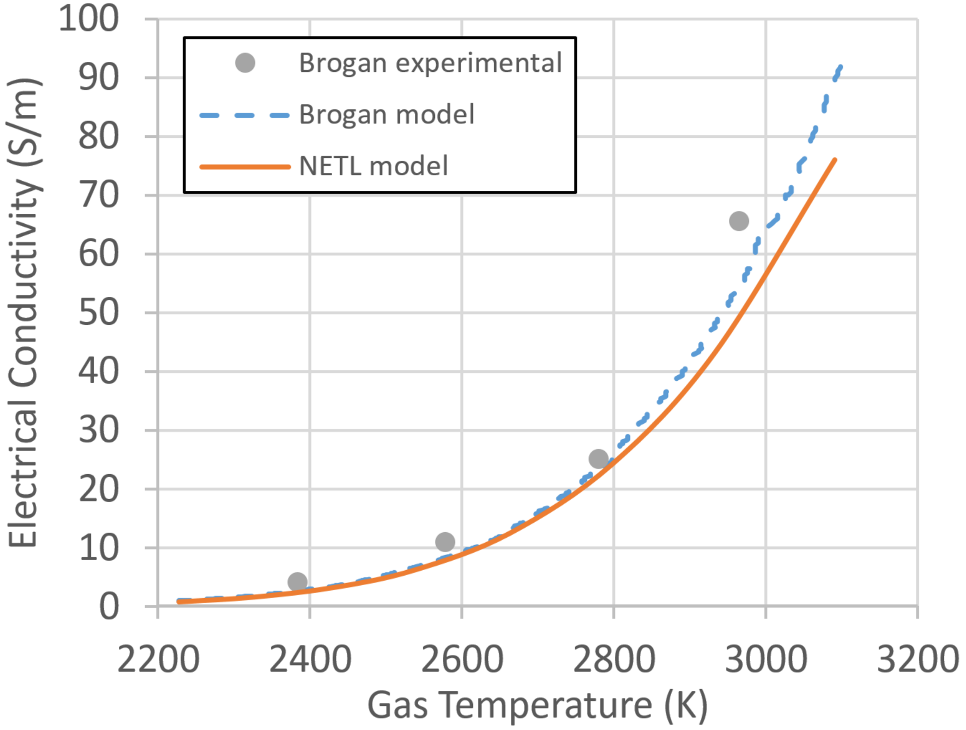
Qi data sources: Itikawa, Spencer, & Collins (various years)

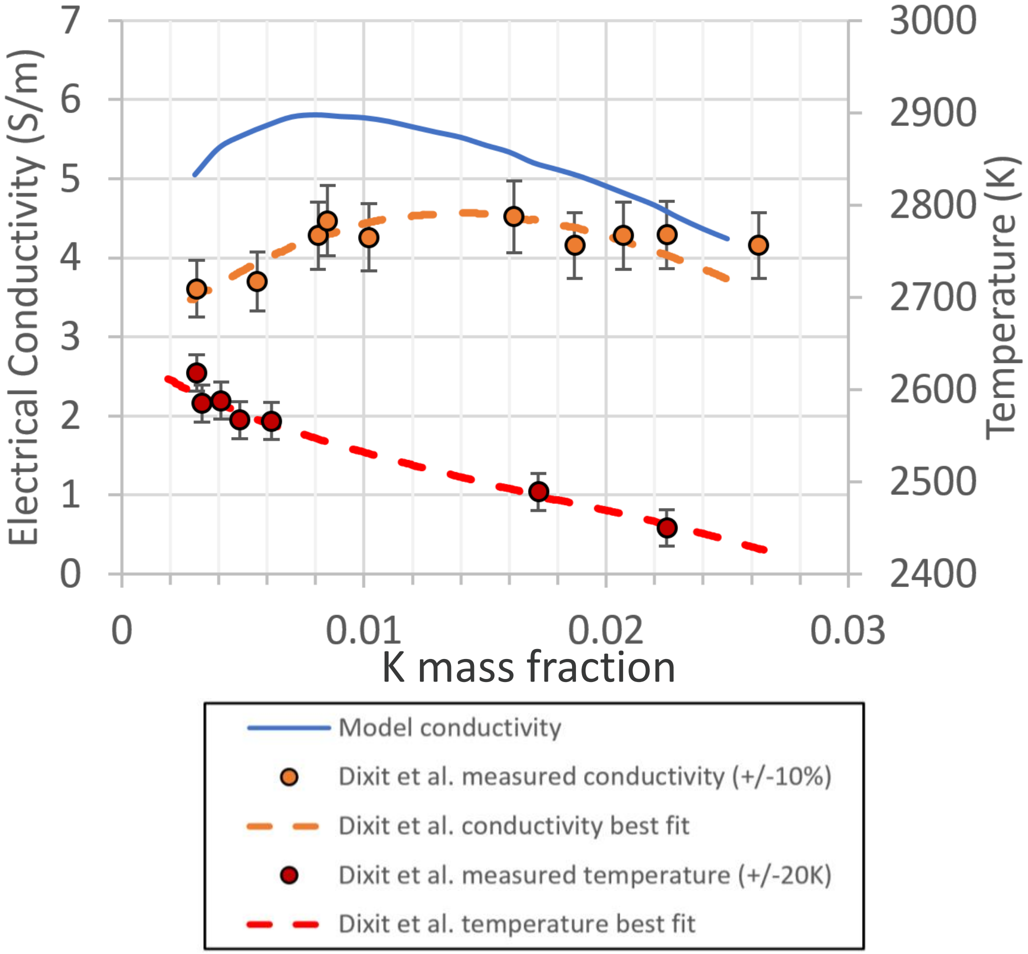
Combustion and Ionization

Comparing predictions versus legacy experiments

Very limited validation data

- high uncertainty
- disagreement between sources



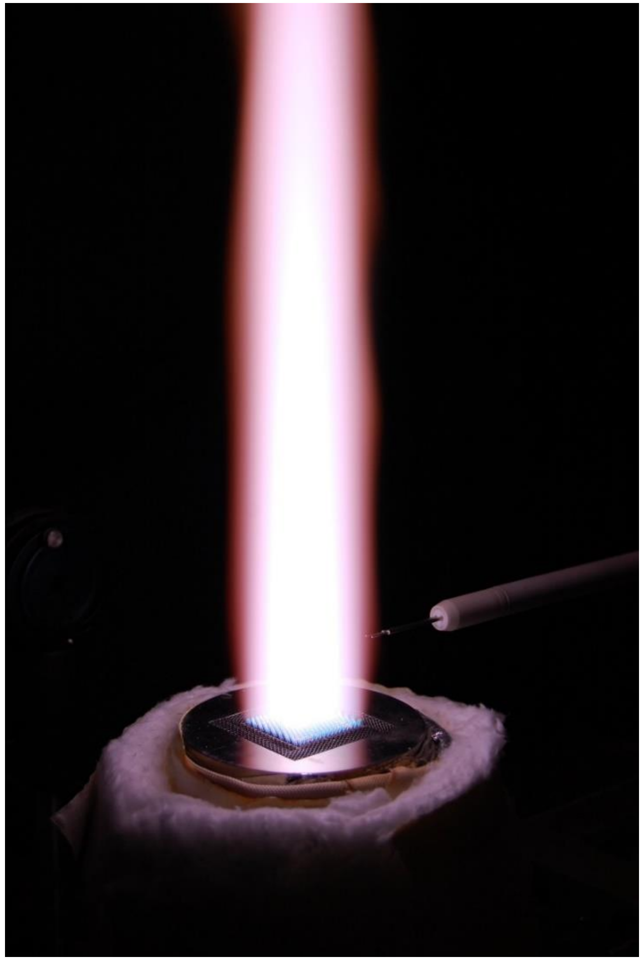


Note: conductivity model presented here is slightly new and uses different H_2O cross section then prior reports (and current NETL MHD 1D code results in slides).

Combustion Validation Testing

Directly measure electrical conductivity of seeded oxy-fuel flame

- Using well-defined flame environment (Hencken burner)
- 3 independent measurements needed
  - Electrical conductivity via Langmuir double probe
  - Gas temperature via spectroscopy
  - Atomic potassium concentration via spectroscopy
- Full seed vaporization challenge (lab scale), Currently:
  - Syringe pump of ~50/50 aqueous solution of K_2CO_3 to O_2 line
  - Spray solutions and discard large drops
  - Eliminate water droplets by diffusion drying
  - Thus small K_2CO_3 conveyed to burner w/ O_2
- Langmuir probe tip durability
  - Trying both platinum or tungsten tips
  - Short insertion times, via rapid traverse system
  - Calibration in aqueous solutions

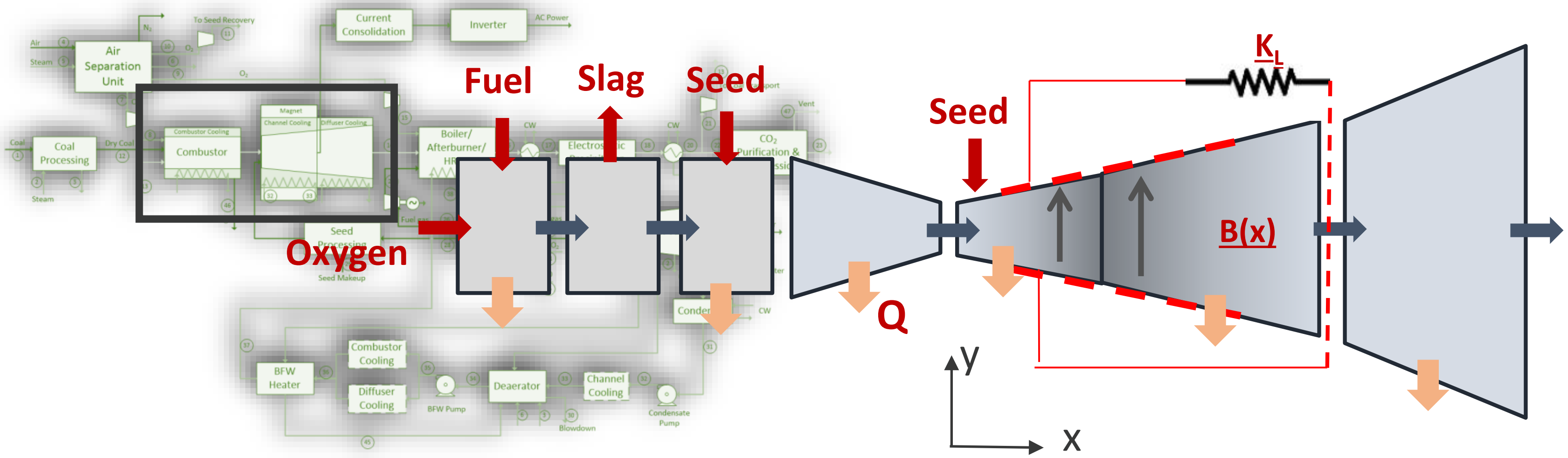


K Seeded Oxy-fuel Flame

Computational Tool Development

NETL's MHD Engineering Design Code $P \propto \sigma B^2 u^2$

- **1D Flow of a multi-phase mixture in varying area channel interacting with an electro-magnetic field and external circuit**
- **Current Activities**
  - Comparison of equilibrium vs. non-equilibrium predictions
  - Input parameter sensitivity studies
  - Additional developments to further refine of supersonic flow capabilities



Conservation Equations

Mass	$\frac{d}{dx}(\rho u A) = 0$
Species	$\rho u \frac{dY_k}{dx} = R_k W_k$
Momentum	$\rho u \frac{du}{dx} + \frac{dP}{dx} = F_{EM} - F_{friction}$
Energy	$\rho u\left(u\frac{du}{dx} + \frac{dh}{dx}\right) = P_{EM} - Q_{wall}$
Lorenz	$F_{EM} = J_y B_z$
EM power	$P_{EM} = J_y E_y + J_x E_x$

Generalized Ohm's Law

$$J_x = \frac{\sigma}{1+\beta_H^2}\left[E_x - \beta_H\left(E_y - uB_z\right)\right]$$

$$J_y = \frac{\sigma}{1+\beta_H^2}\left[\beta_H E_x + E_y - uB_z\right]$$

Electrode configuration

$$J_x = 0 \qquad E_y = K_L u B_z$$

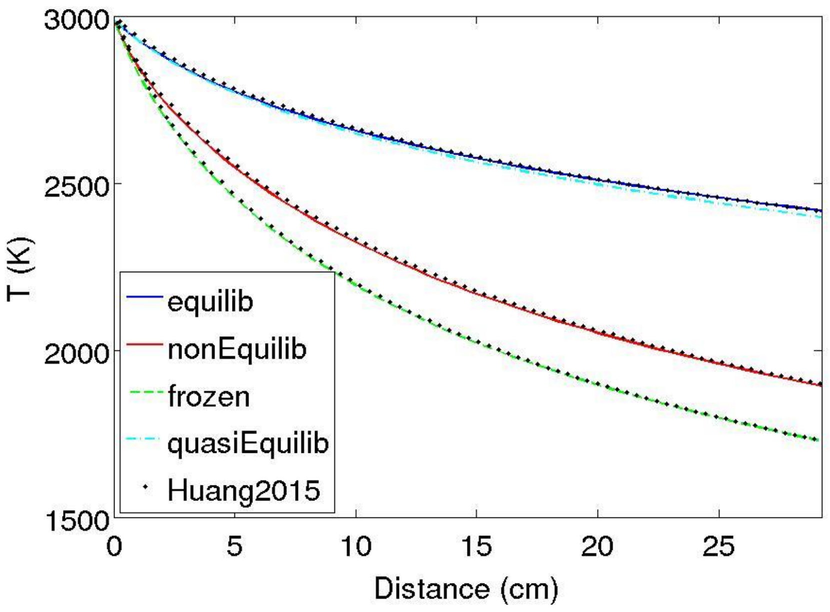
$$E_x = -\beta_H u B_z (1-K)$$

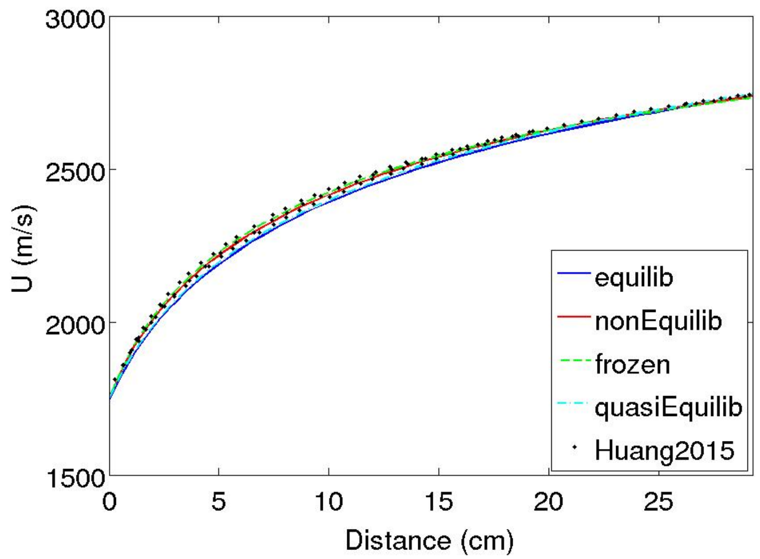
$$J_y = -\sigma u B_z (1-K)$$

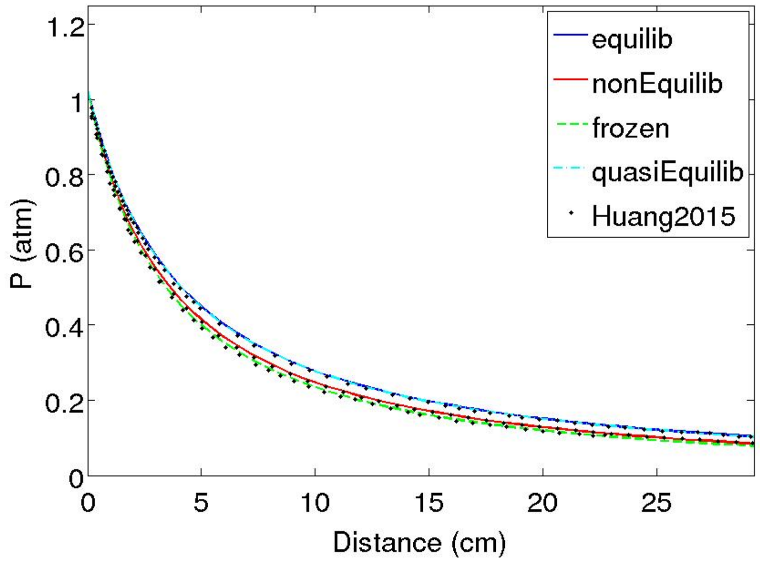
1D code with Finite Rate Chemistry

Computational verification for non-equilibrium chemistry

- Compare different code outputs downstream of nozzle throat to published simulation data for H_2-Air scramjet [Huang, 2015]







- Code outputs consistent w/ literature downstream of nozzle throat
- Note temperature results (expected to impact MHD Power)

1D code with Finite Rate Chemistry

The impact on supersonic Oxy-MHD Electrical Conductivity – An Example Problem

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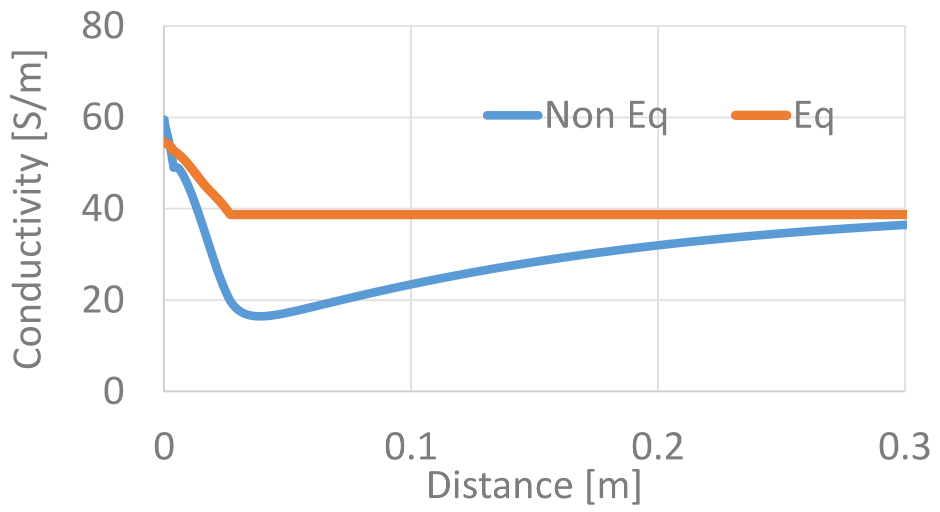
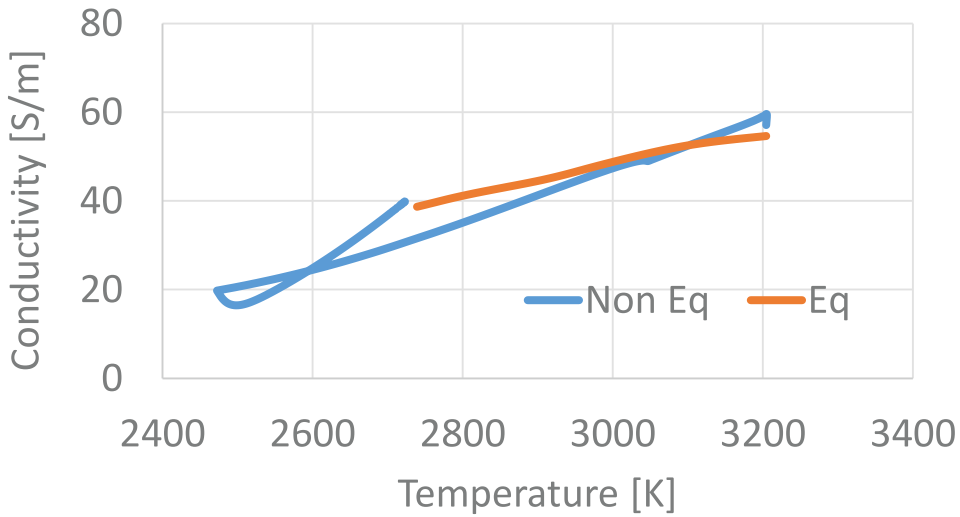
Note simulations still assume L.T.E (Te = Tg)

- **Inputs**
  - Fuel: $C_{12}H_{26}$
  - Oxidant: 100% O_2
  - Combustion Pressure = 3 Bar
  - Seed: K_2CO_3 powder; K mass loading 4.94% by weight of total inputs
  - Input Temperatures: 300K
- **Aspects for Analysis**
  - Complete combustion & seed decomposition
  - No wall heat losses
  - Fixed Mach channel (2.1 M)
- **Results**
  - Non-Equil chemistry important for supersonic Oxy-MHD consideration
  - Equil and Non-Equil do converge for fixed Mach channel
  - Results suggest seed kinetics also matter

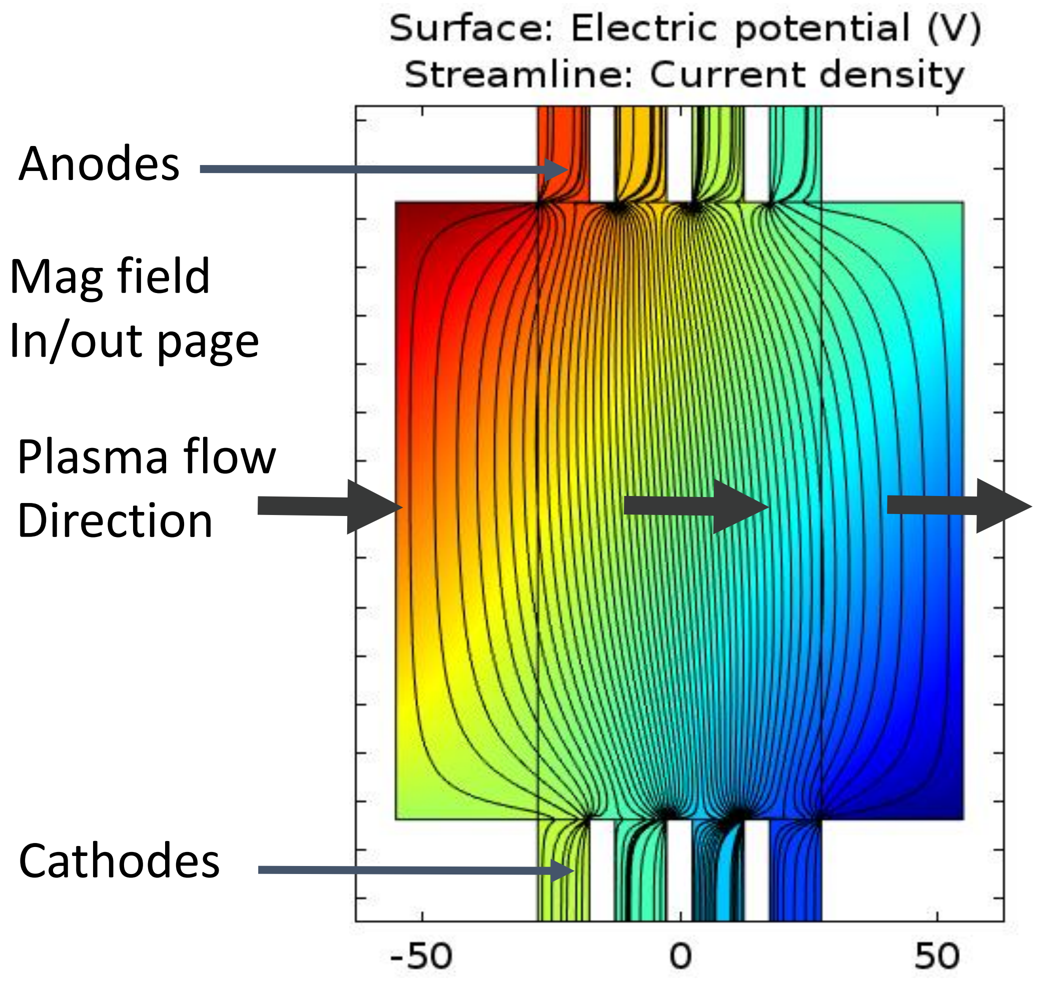




Design for Current Density

What is "J_y" in 3D?

- **Segmented Faraday Background**
  - J_y limits practical MHD power densities
  - Channel width : Electrode width ~ 75:1
  - Electrode width : Insulator width ~ 2:1
- **3D Approach**
  - Comsol Multi-Physics AC/DC platform
  - Neglect Lorentz Force on flow
    - OK for short channel section evaluation
  - Virtual resistors as generator loads
  - Electrical conductivity considered as a tensor
- **Results**
  - Jy non-linearly distributed on surface
  - With β_H on, J does not follow voltage gradient
  - Peak currents at electrode-insulator corners
    - Different for anode versus cathode

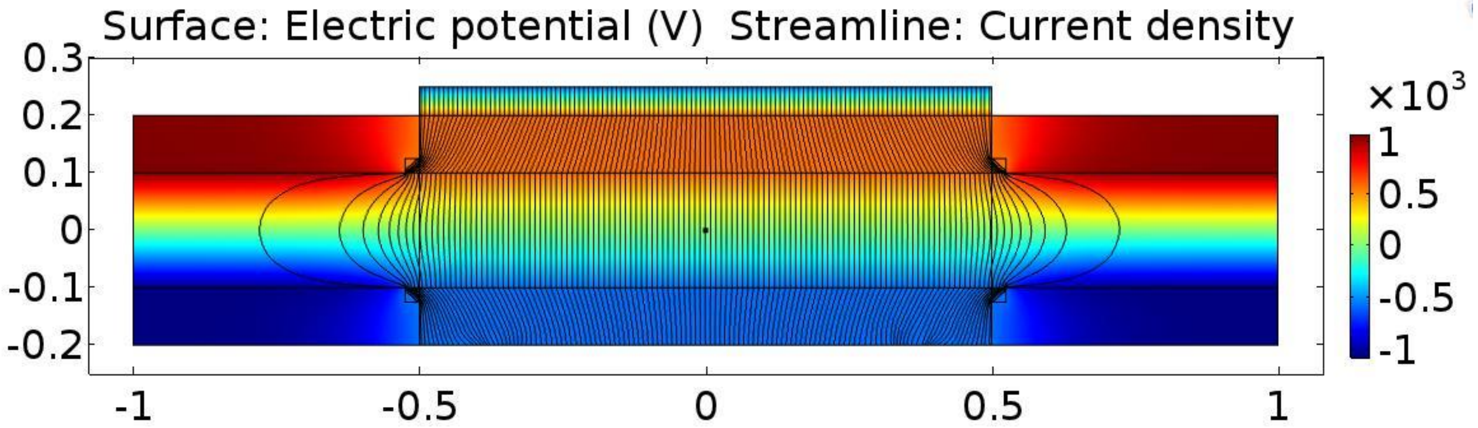


Note: Dimensions exaggerated for illustration purposes

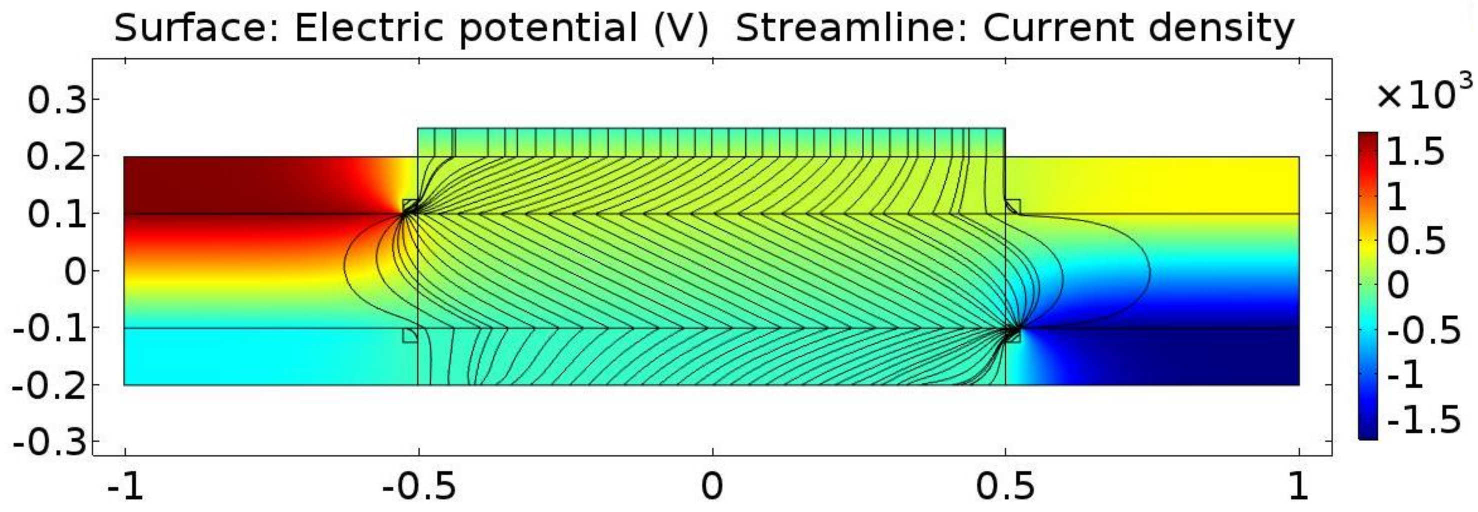
Current Density Results

Results shown are for a “Continuous” Linear Faraday Generator

- B & u profiles off
- Heat transfer off
- Fixed plasma properties
- No arcing or boundary layers
- Corners filleted w/ conductivity profile
  - Reduces numerical instability & error to achieve verification (next slide)
  - Real system likely different (b/c arc behavior)



β = 0

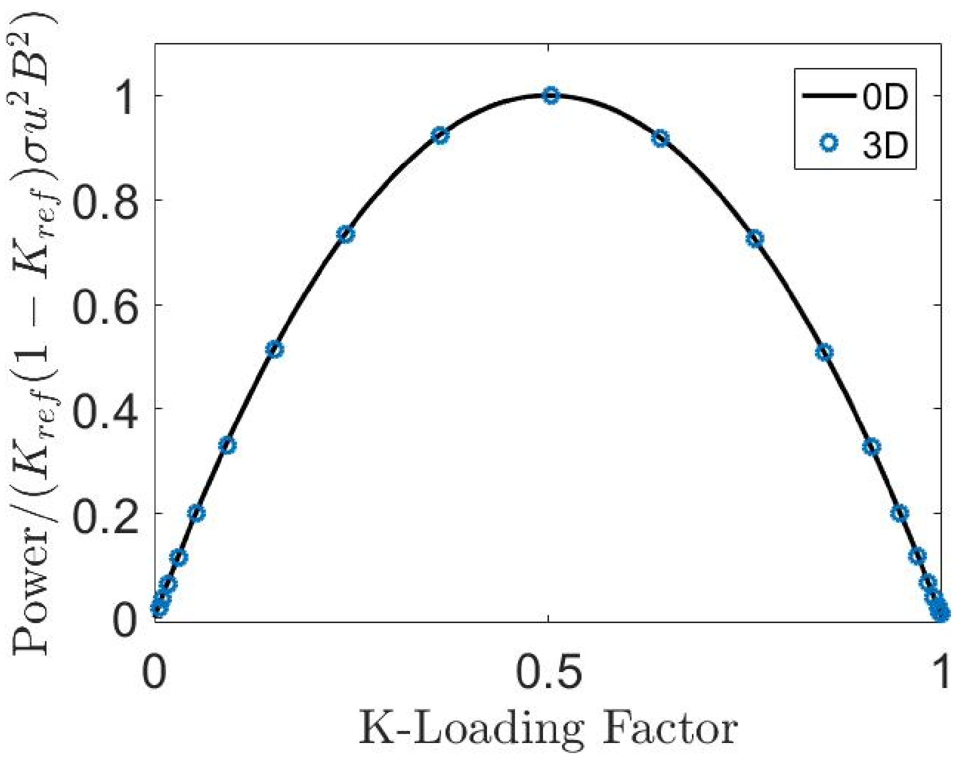


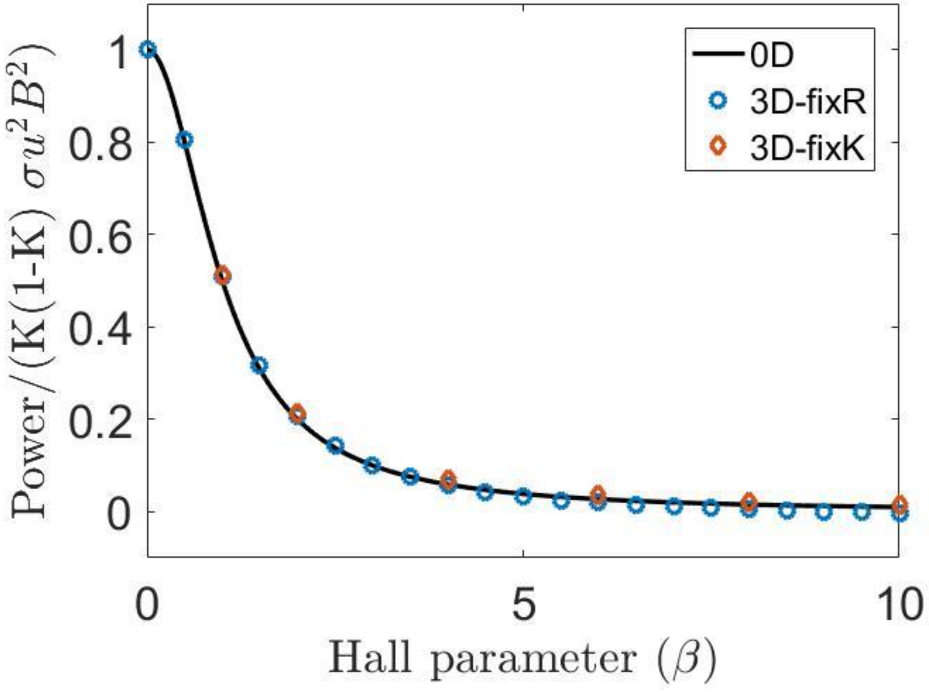
β = 2

Current Density Results

Computational verification with a “Continuous” Linear Faraday Generator

Normalized power output versus generator Hall Parameter (β= 0) with $K_{ref} = 0.5$





- 3D results verified vs. analytical solution for simple generator
- Tool useful to optimize electrode & insulator geometry
- Design for complexities
  - B, u, sigma profiles
  - Non-standard loading and geometries
  - MHD edge effects near channel ends

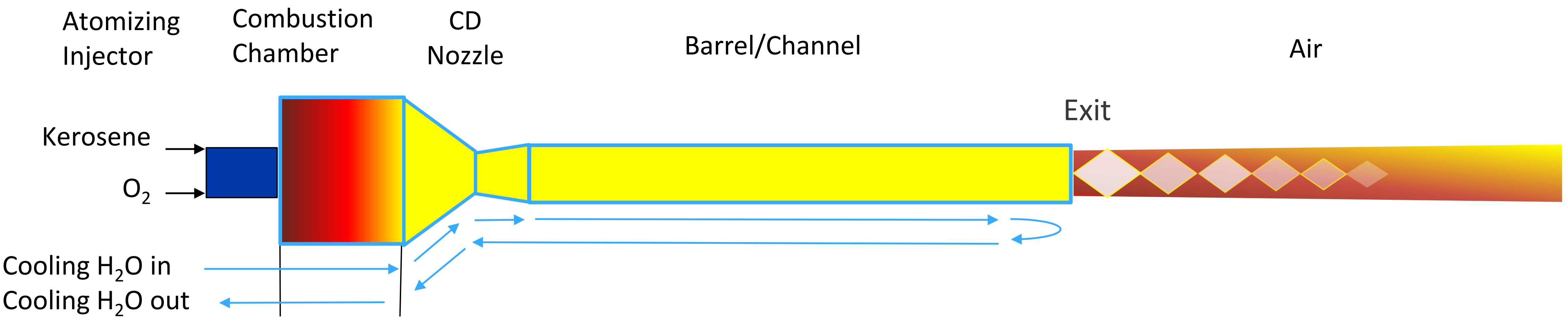
High Velocity Oxy-Fuel (HVOF) System

Characterizing Heat Balance in HVOF

- Customized Praxair JP 8200 HVOF utilized
- Kerosene-Oxygen Combustion
- 6-8 bar combustion
- ~160 kW_t Input Power
- Cold copper wall heat transfer
  - Use calorimetric method from cooling water temperature and mass flow measurements

Simulation

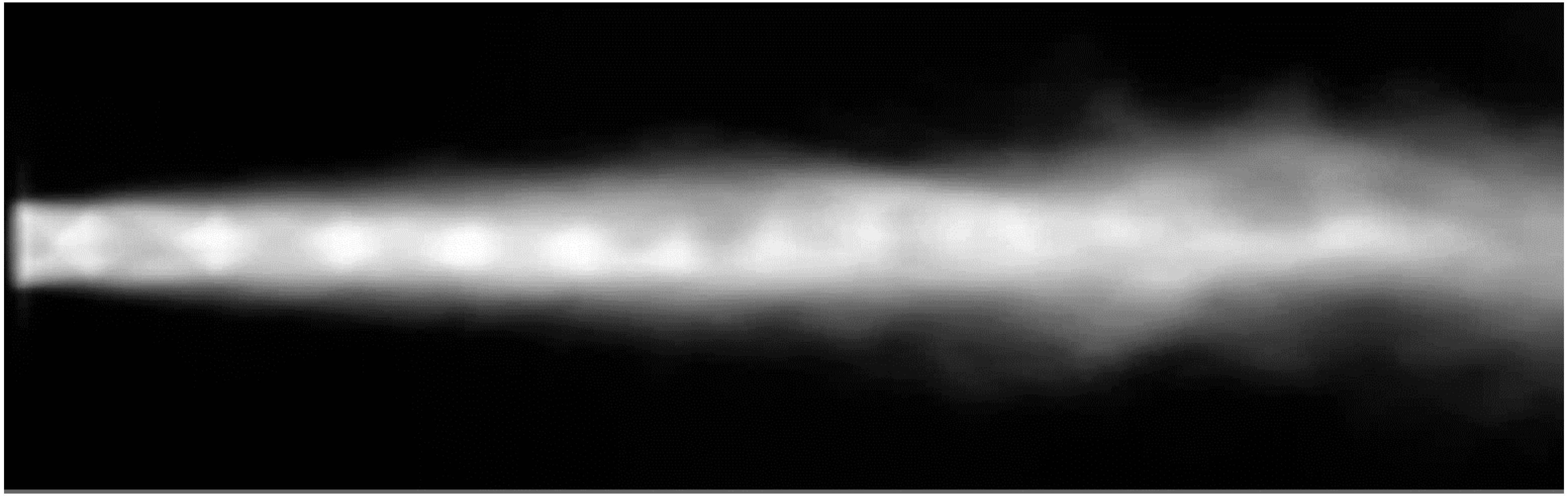
- customized OpenFOAM model
  - "`sonicParcelFoam`"
  - Reaction mechs adapted for dodecane
  - Convective: using wall functions
  - ($y^+ = yu_\tau/\nu \sim 2$) B.L.
    - Sensitivity study on-going
  - Radiative: P1 grey gas



Establish a baseline cold wall heat transfer rate for future supersonic oxy fired MHD channels

HVOF in action

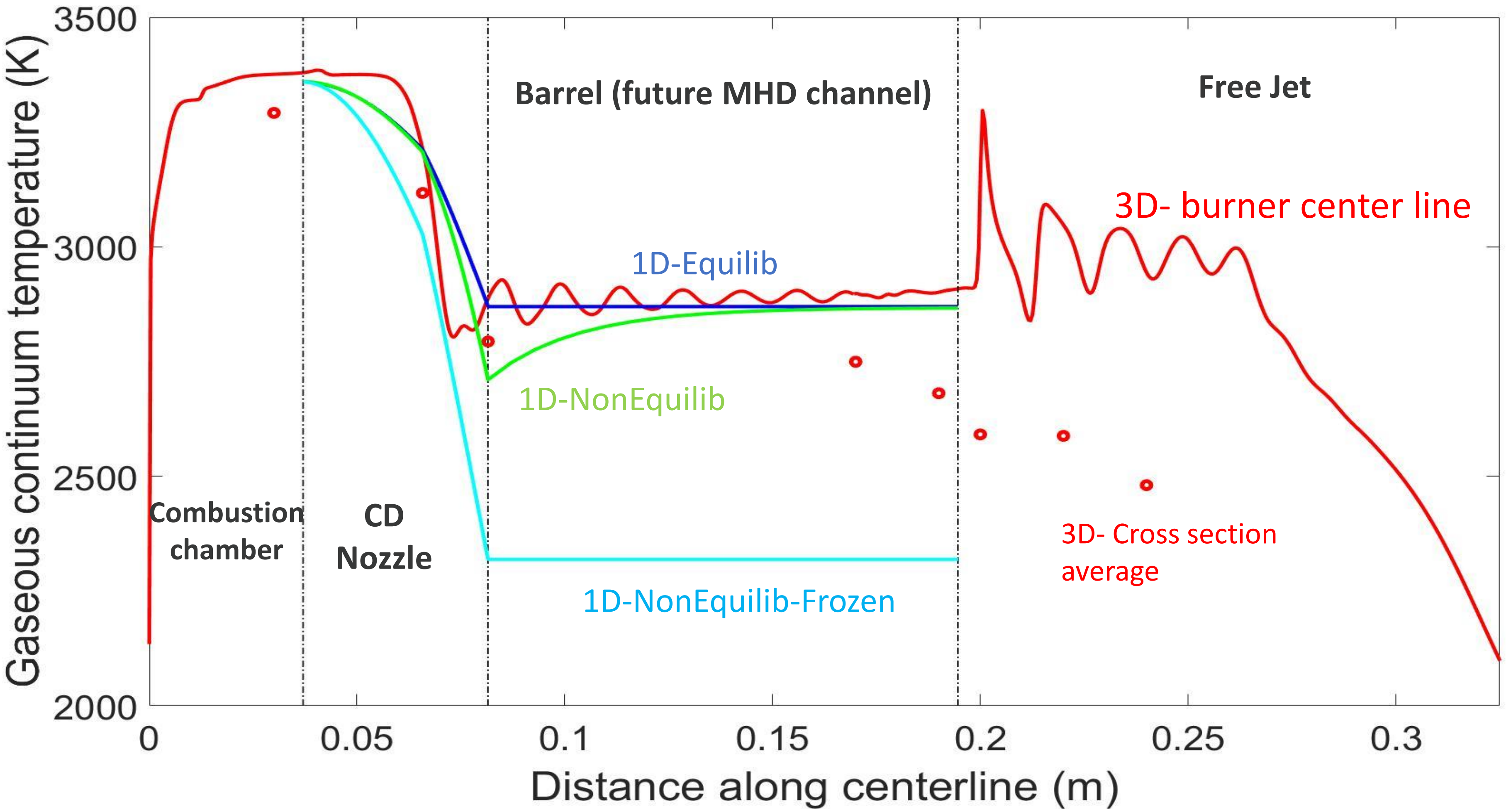
Video from IR camera (See later slide for additional details)



Simulation Results of HVOF

Gas temperatures for Cold wall HVOF

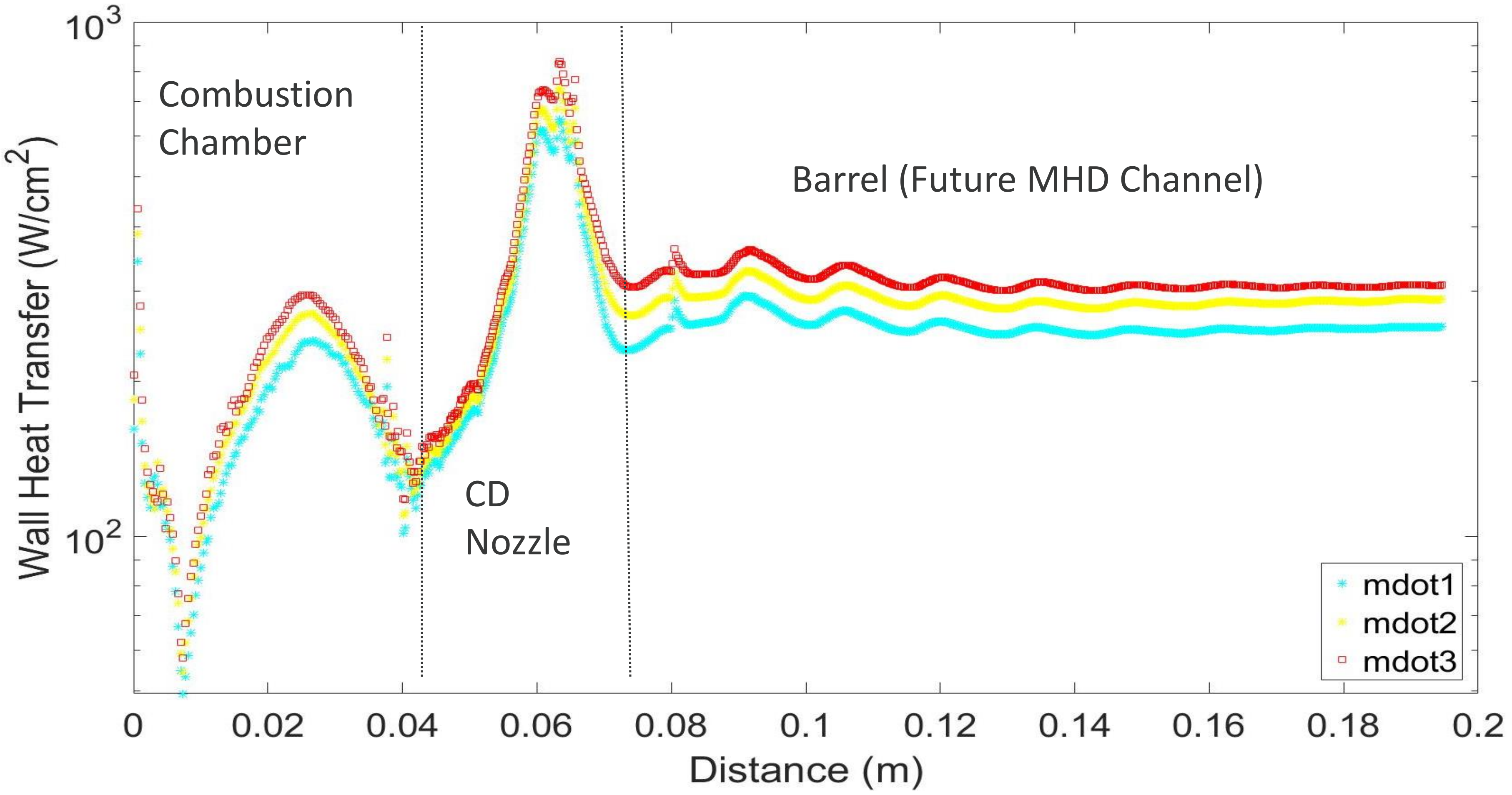
- 1D: 1D NETL MHD code output
- 3D: openFOAM
- Shocks can be seen in 3D Temps
- Maintains very hot core ~3000K
- Cross section T of flow rapidly stratifies near HVOF exit



Simulation Results of HVOF

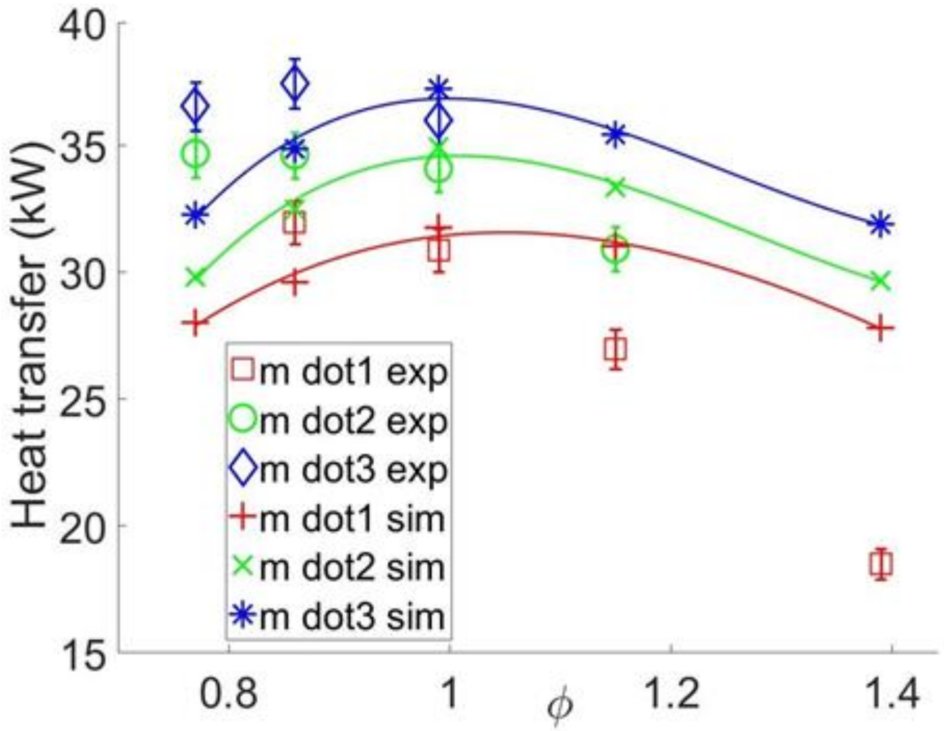
Wall Heat Transfer for Cold wall HVOF

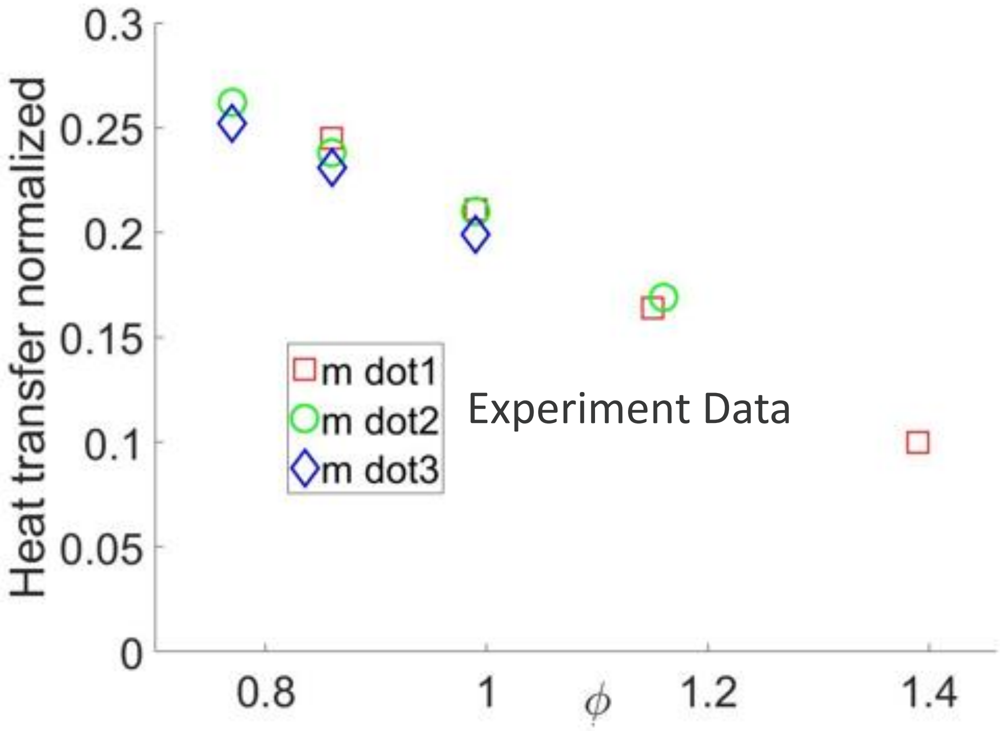
- Peak velocities ~2100 m/s
- Peak heat flux at throat
  - ~700 W/cm^2
- Cold Channel Wall
  - ~300 W/cm^2
- Flux increases with mass flow (thermal input)



HVOF Total Wall Heat Transfer

Experiment versus simulation



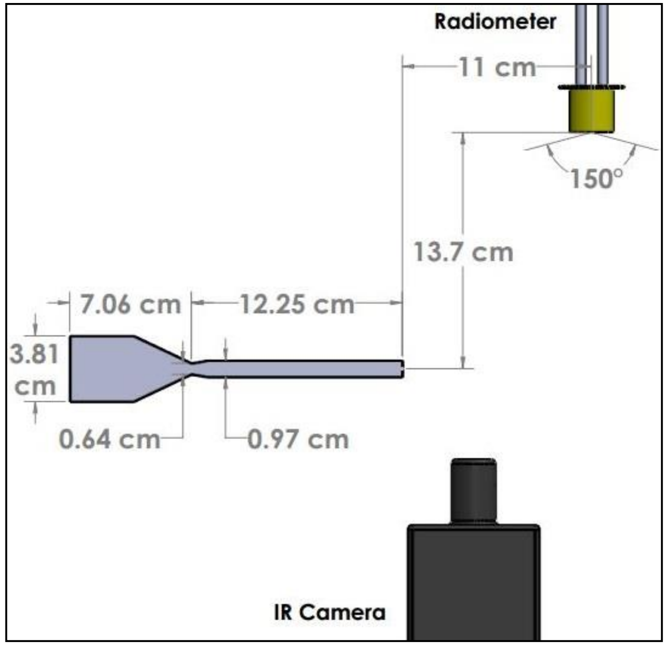


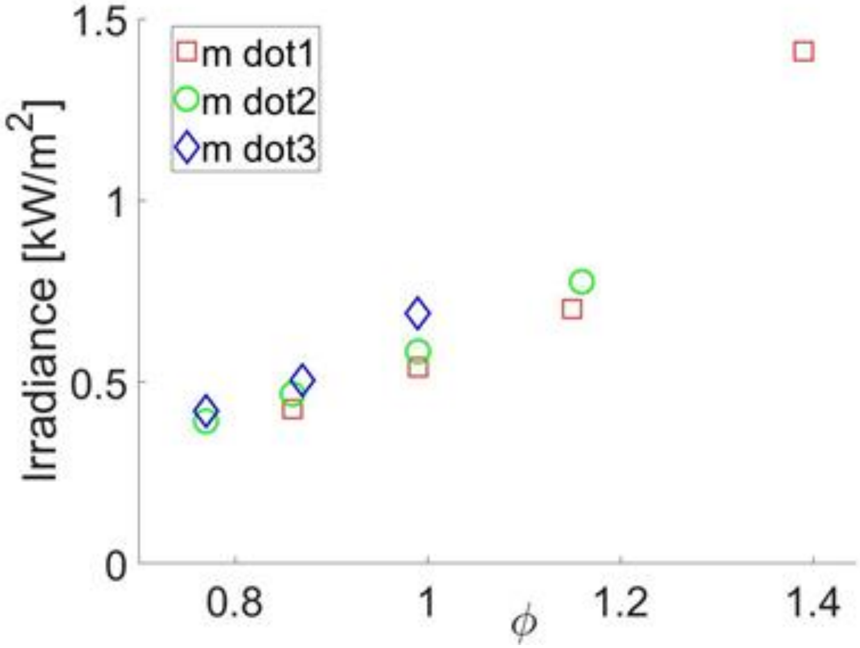
- Simulation and experiment differ on conditions for peak transfer
  - Simulation assumes pre-vaporized fuel & pre-mixed reactants → predicts complete kerosene consumption
  - Experiment results suggests complete combustion may not be fully achieved in these tests

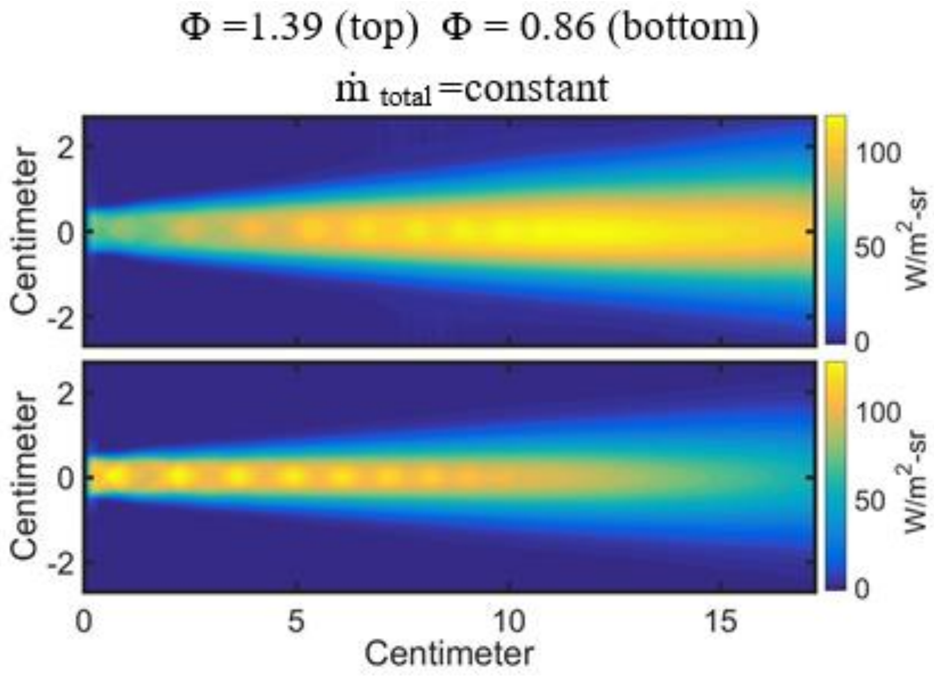
- For expected stochiometric conditions, ~20% of input power went to wall cooling
- Sensitivity to mass flow changes similar for simulation and experiment

Thermal Radiation

Irradiative measurements and shock structure with CO_2 IR imaging







- Infrared camera w/ CO_2 bandpass filter (4370nm ± 10nm)
  - High temperature blackbody for radiance calibration
- Wide angle radiometer measures total irradiance from the plume
  - spectral region of 0.15-10 µm

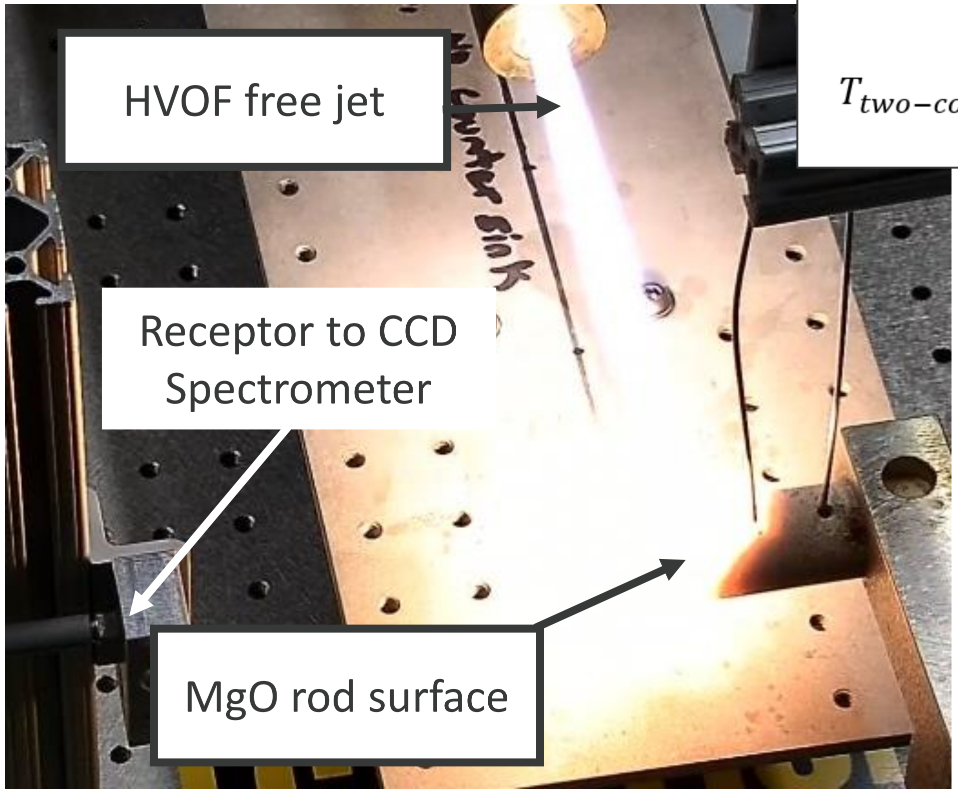
- fuel riches cases have higher radiance
  - Additional combustion/soot in jet
- Shock structure apparent
  - cfd simulation comparisons underway

Further experiments will characterize total radiation fraction. Can fuel rich cases provide advantage?

Magnesia (MgO) Rod Test

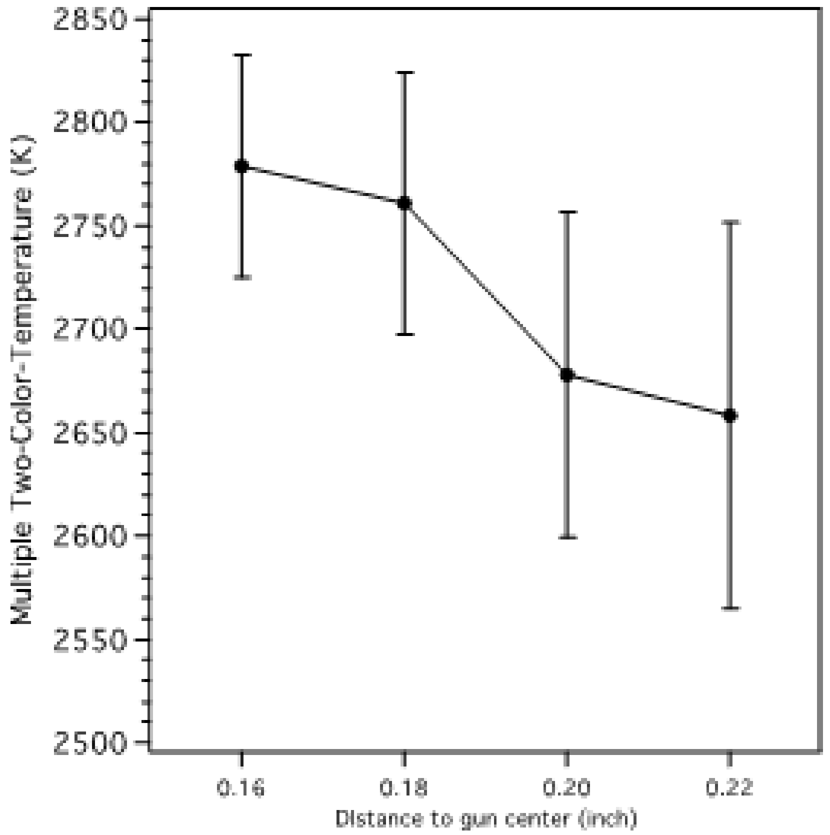
Direct Insertion of high temp refractory into free jet (gross temperature check)

Custom pyrometer constructed using CCD spectrometer; Multi two-color method employed



$$T_{two-color} = \frac{-\frac{hc}{k_B}\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)}{\ln\left(\lambda_1{}^5 B_{\lambda 1} - \lambda_2{}^5 B_{\lambda 2}\right)}$$

Exposed Surface Temperatures



- Measured temperatures consistent with HVOF expectations
- Technique used in materials exposure work
- MgO rod does survive this test

Photoionization

General description and testing

- **Combustion driven MHD plasma is a partially ionized system which rapidly reaches thermal equilibrium**
  - Very little seed introduced thermally ionizes (~1-3% of it)
- **Ionization potential of K is 4.34 eV**
  - So “photoionization” of potassium using UV photons < 285nm
  - UV source must be efficient enough to make sense for bulk ionization > 10% efficiency past gross estimate (Rosa, 1963)
- **Directed energy with lasers = Good spatial & temporal control**
  - Boundary layer arc control and manipulation possible
    - “Help” electrons travel from plasma to cooler electrode
  - Due to arcs the boundary already likely in non-equilibrium
- **Experimental approach**
  - Test set-up: Potassium seeded HVOF fired into a 2T magnet and excite with multiple pass pulsed 248nm Excimer laser.
  - Initially characterize total laser absorption measurement as test conditions change
  - Later apply high speed K1 Spectroscopy (<1ns acquisition times)

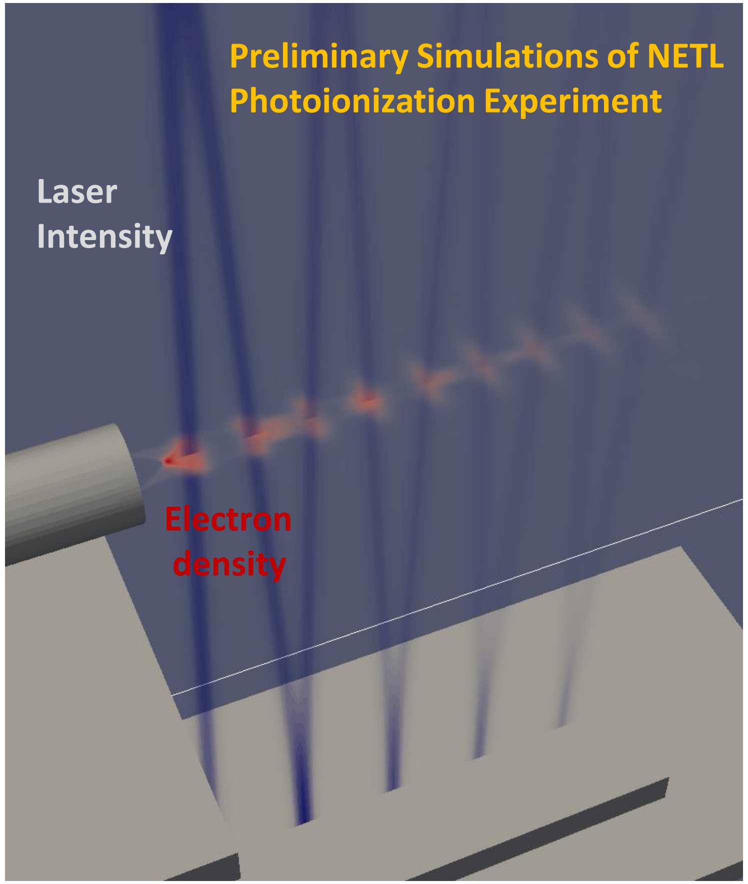
Shake down testing of seeded HVOF in magnet

“Lilac” color is from thermally excited K

Photoionization Simulation

CFD Photoionization Modeling and Simulation

- **Under development (in OpenFOAM)**
- **Customization of radiation and reaction sub-models**
  - Photon as reactant
  - Infinitely Small Weight (ISW) method for calculating laser propagation using the discrete ordinate method (DOM)
  - Generalize boundary conditions for reflection and transmission
  - Photon absorption coefficient is linked to photo-ionization reaction coefficient



Ionization

$$\frac{d[K^+]}{dt} = \frac{d[e]}{dt} = \underbrace{k_{photo}[e][K]}_{\kappa}[hv] - k_{rec}[M][e][K^+]$$

$$K + e + hv \xrightarrow{k_{photo}} K^+ + e + e$$

$$K^+ + e + M \xrightarrow{k_{rec}} K + M$$

Radiation

$$\hat{\mathbf{s}} \cdot \nabla I(\hat{s},\lambda) + \kappa(\lambda) I(\hat{s},\lambda) = \kappa(\lambda) I_B(\lambda) + \boxed{\hat{\eta}(\lambda)} + \frac{1}{4\pi}\int I(\hat{s}_i,\lambda)\Phi(\hat{s}_i,\hat{s})d\Omega$$

Non-equilibrium term

Conclusions

- **Oxy-fuel combustion plasma conductivity predictions highly uncertain**
  - Validation testing very difficult to execute but underway
- **Supersonic combustion driven channels need non-equilibrium considerations**
  - We have added this to NETL's 1D MHD engineering code
- **Hall Parameter, load factor, and optimized channel/electrode/insulator dimensional ratios are need to correctly predict power output performance**
  - We have developed a tool which can correctly assess these complicating factors
- **HVOF heat transfer rates measured are very high but simulations can predict them**
  - Likely need much higher wall temperatures for efficient energy conversion
- **Photoionization provides new options as UV laser technology develops**
  - We are testing to obtain basic properties for this technique

Acknowledgements

NETL Co-Principal Investigators: Dr. Clint Bedick, E. David Huckaby, Danylo Oryshchyn
NETL ORISE fellows: Eric Zeuthen, Dr. Hyoungkeun Kim, Michael Redle
2016 ORISE Summer Interns: Yi Hsun Yang, Brian Lovich, Dr. Duncan McGregor
Technical consultants: Dr. John Lineberry, Dr. Geo Richards, Thomas Ochs, Dr. Nathan Gibson
AECOM Research Technicians & Engineering Staff
NETL Management, ES&H, IT, Multi-media & Site Operations Staff