Resistance measurements of a high-velocity oxy-fuel powered MHD channel

NETL – Research and Innovation Center

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Motivation: Oxy-Fuel Carbon Capture

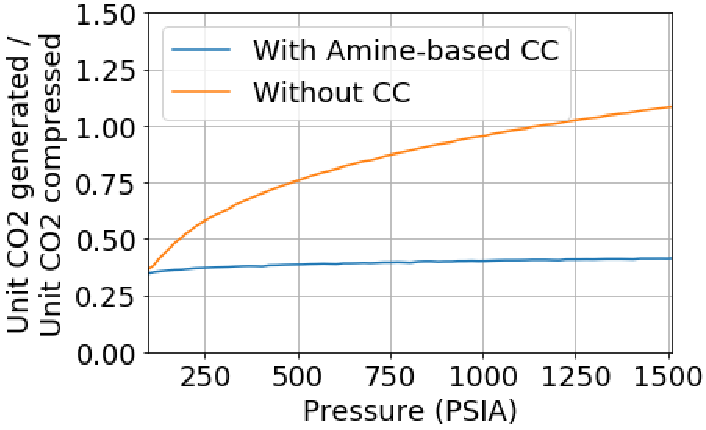
Air Combustion

~10% ~10% ~80%

Hydro***C***arbon + Air (O_2 + N_2) → H_20 + CO_2 + N_2

- Need to separate nitrogen to compress for carbon storage

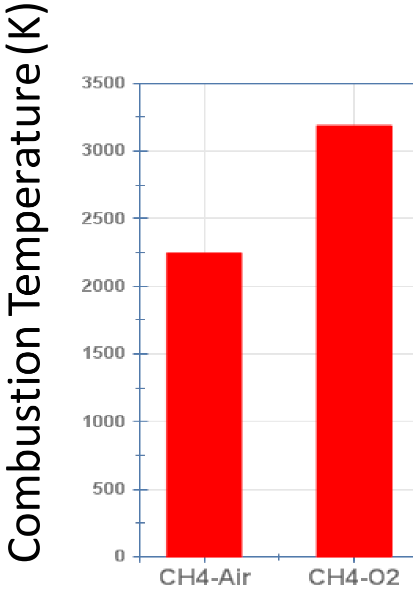
S K Chakravarti et. al 2001

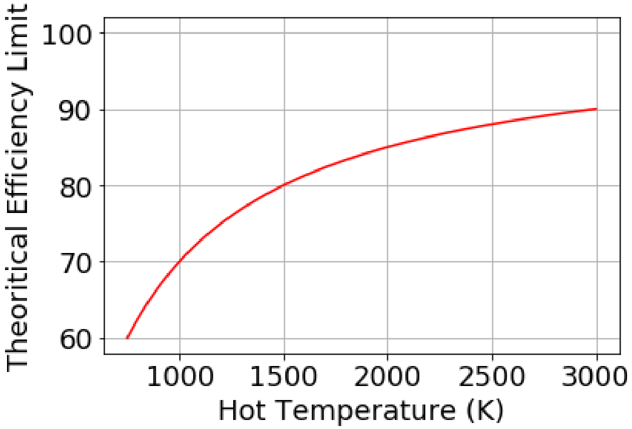


Oxy-fuel Combustion

Hydro***C***arbon + O_2 → H_20 + CO_2

- Pay upfront for oxygen separation
- Carbon Already captured
- Higher temperatures



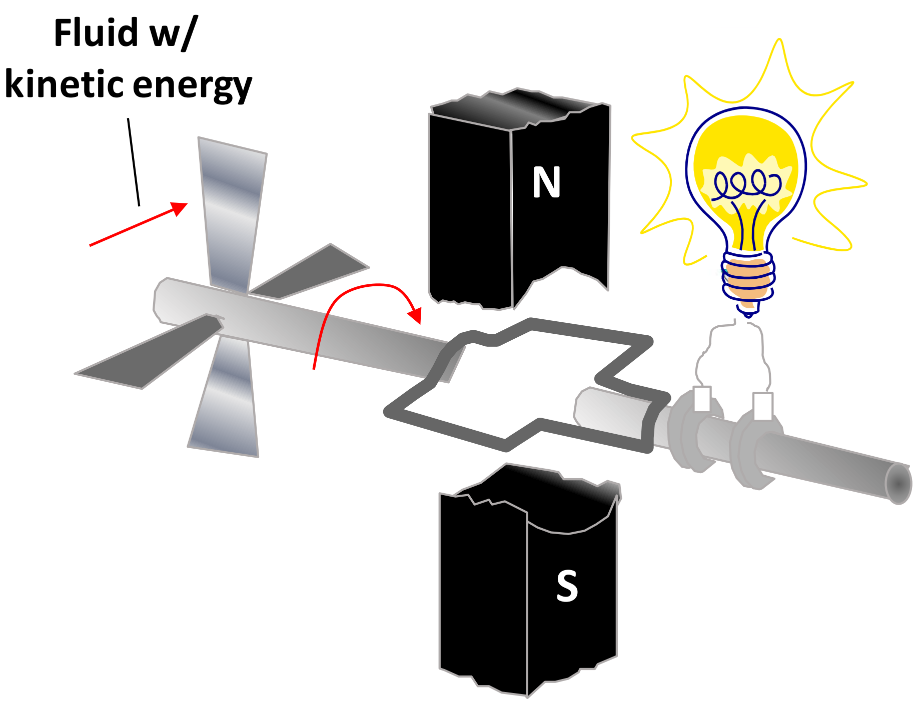


Why don't we use oxy-fuel in power generation?

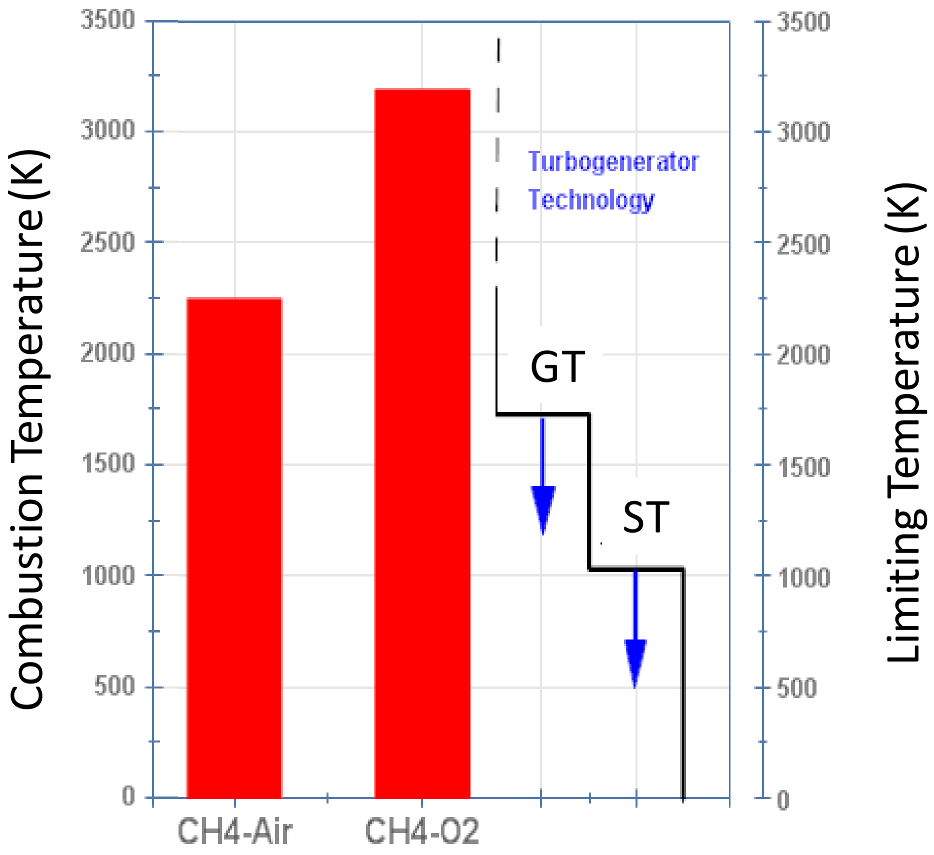
Moving parts make oxy-fuel difficult

Turbogenerator

How most modern power is generated:
Move metallic conductor near magnetic field



Moving parts limit temperature:
Oxygen separation energy not recovered



GT - Gas Turbine

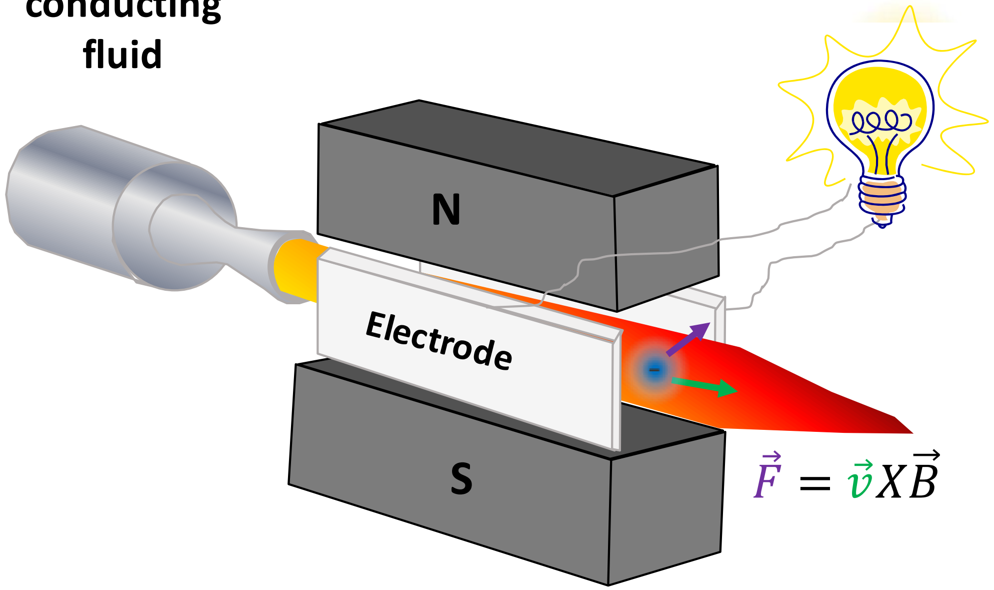
ST - Steam Turbine

Magnetohydrodynamic (MHD) Power Generation

MHD Generator

Electrons **directly extracted** from working fluid itself

Electrically conducting fluid



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

P: Generated Power

σ: Fluid conductivity

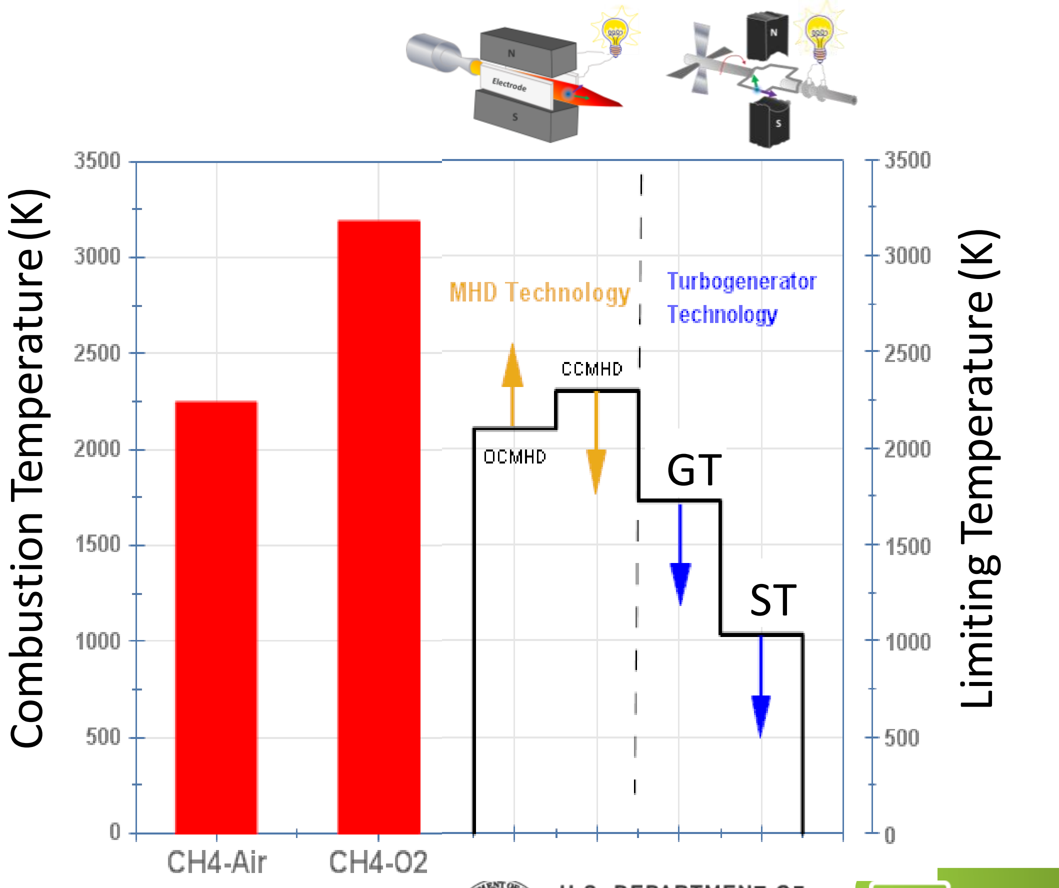
u: Fluid velocity

B: Magnetic field

OCMHD – Open Cycle MHD

CCMHD – Closed Cycle MHD

No moving parts -> Higher temperatures



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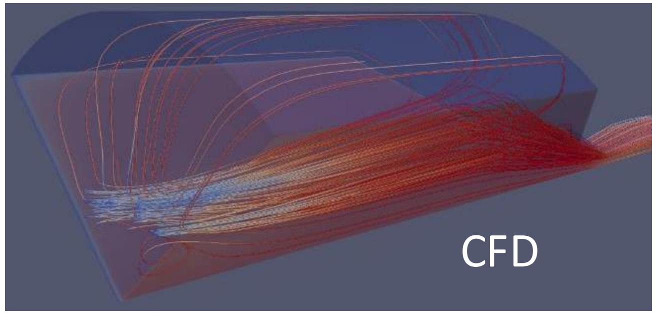
NETL MHD Lab

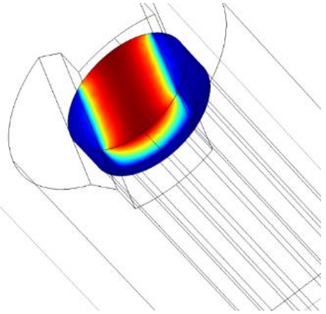
<u>MHD Lab goal:</u> Safely conduct MHD experiments in order to enable future MHD engineering applications.

<u>Theme:</u> <u>Development and experimental validation of simulation tools</u>

Simulation Tools



COMSOL



Experimental Validation 'Magic' Test booth

Control Room

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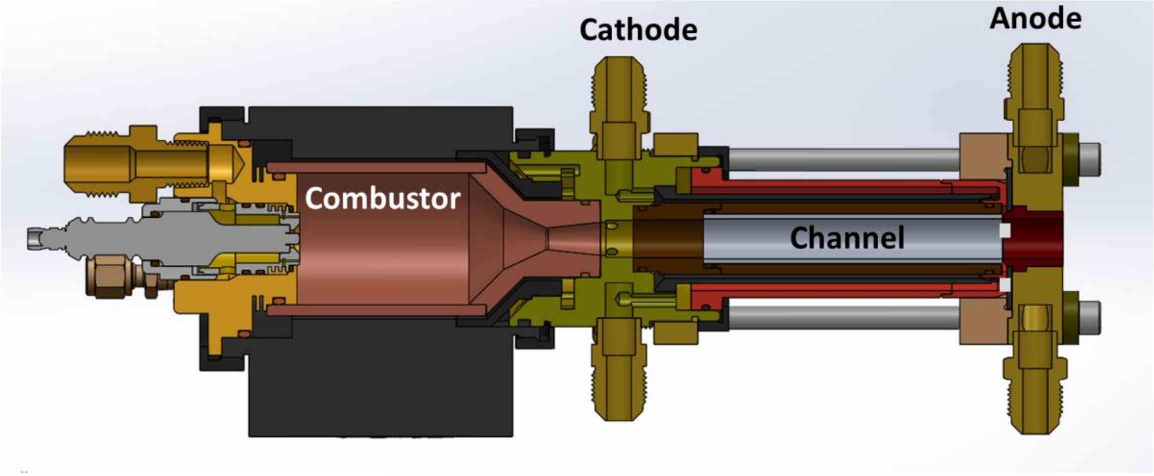
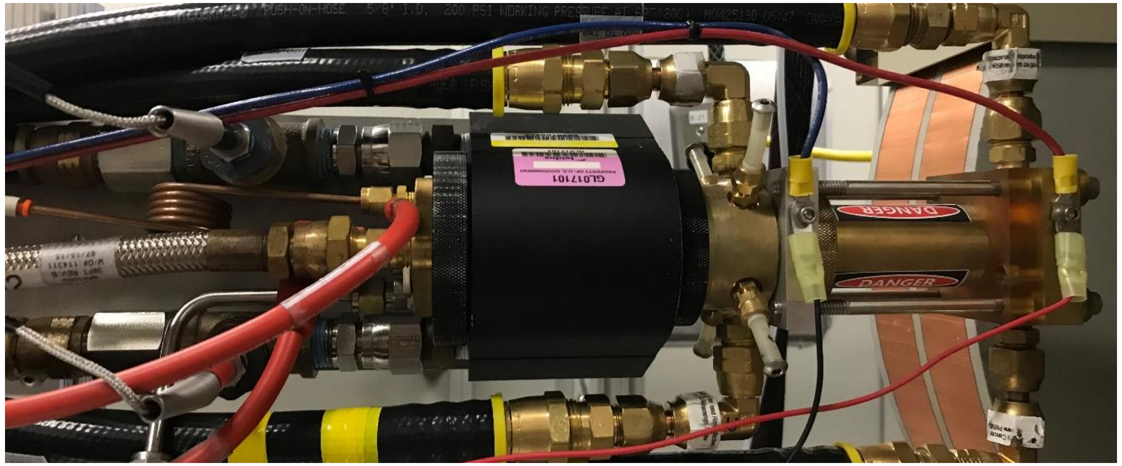
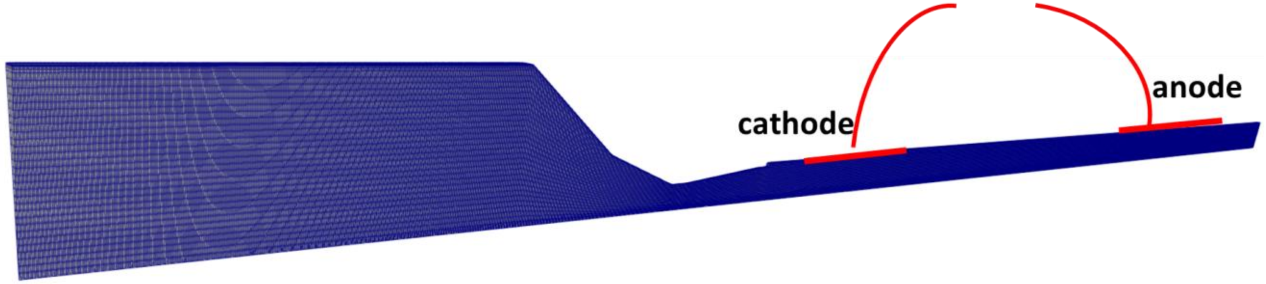
Project Goal: Validated Modeling approach for MHD generator electrical resistance

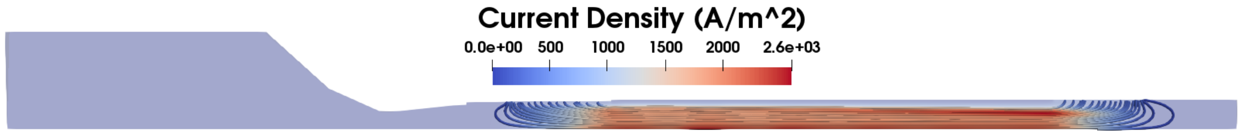
MHDGEN 1.0 Back Power Channel





CFD Simulations



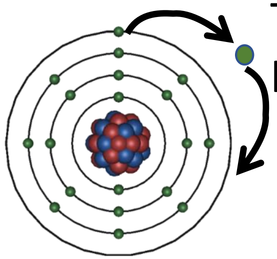


Also augment with 0D Chemical equilibrium

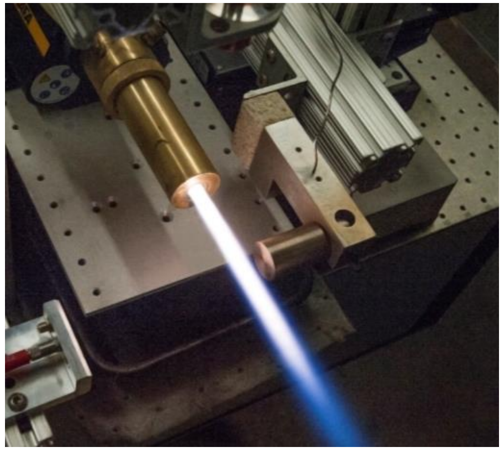
MHD Generator Resistance Background

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

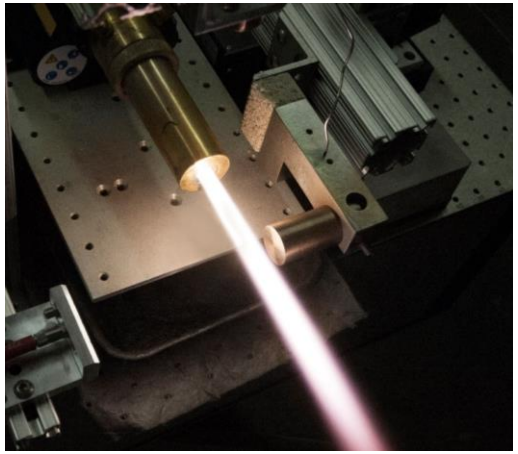
- Combustion products CO_2 and H_2O are not electrically conductive
- Potassium seed (K_2CO_3) is needed



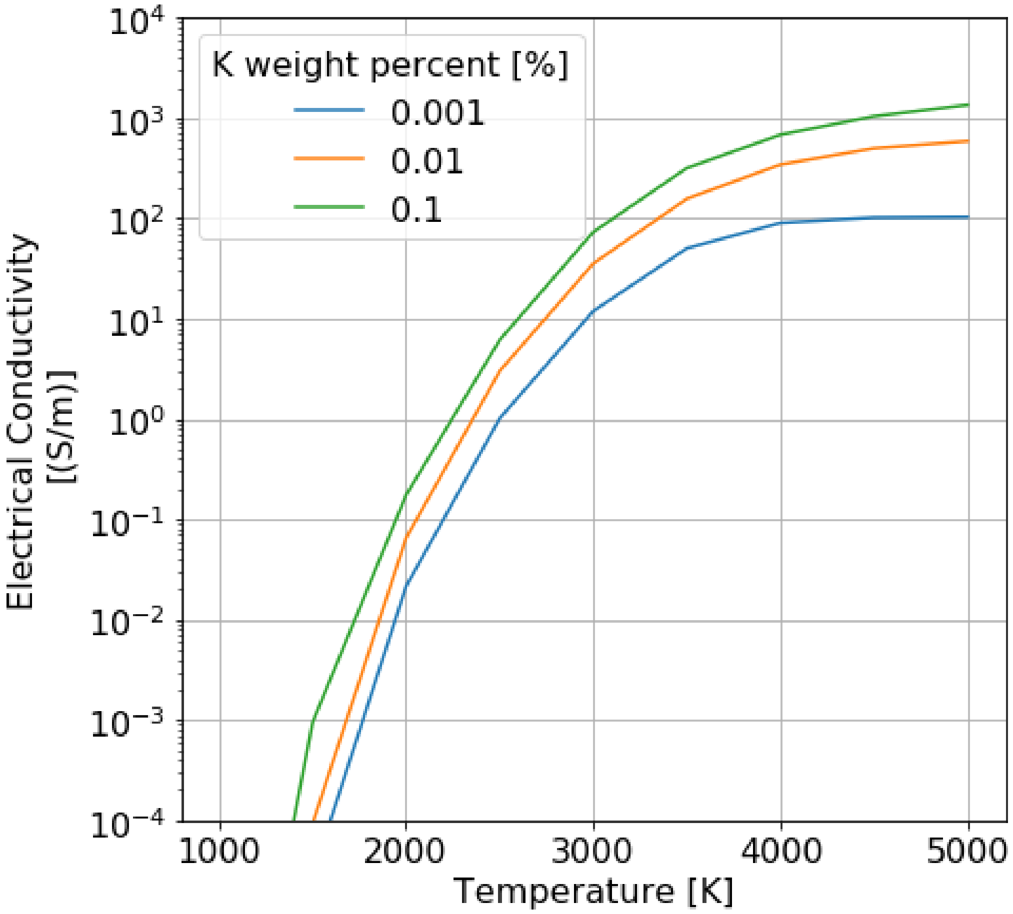
Potassium



Free Jet



With seed injection



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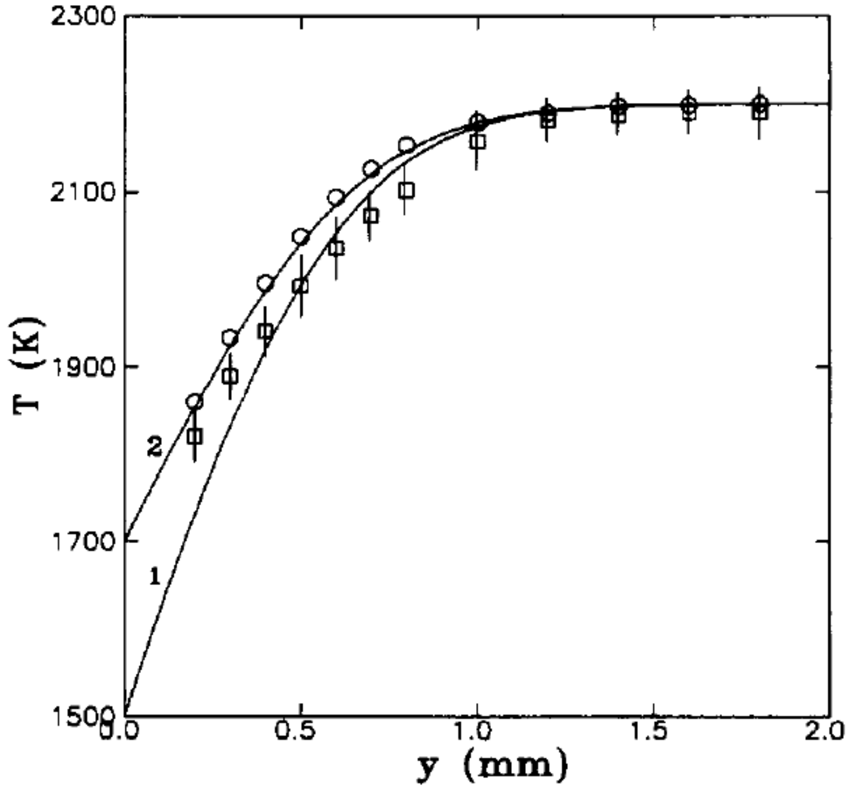
Boundary Layer Resistance

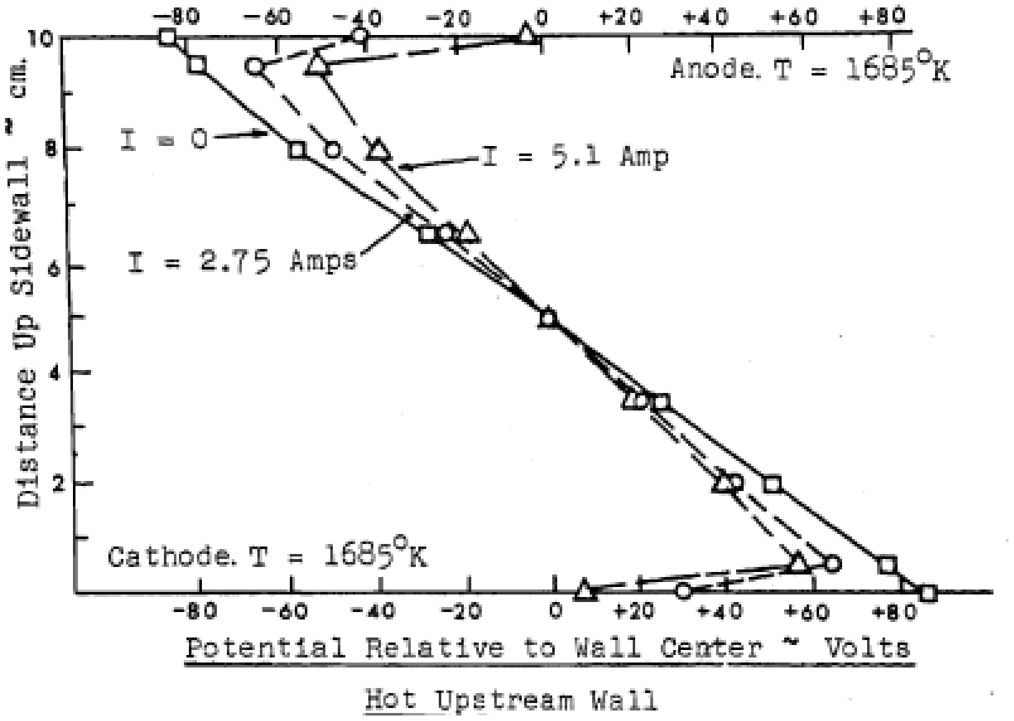
Temperature and conductivity reduced at electrodes

Electrode	Channel



***Nonequilibrium Boundary Layer of Potassium-Seeded Combustion Products*- Benilov 1994**

Boundary Layer Voltage Drop



Electrode

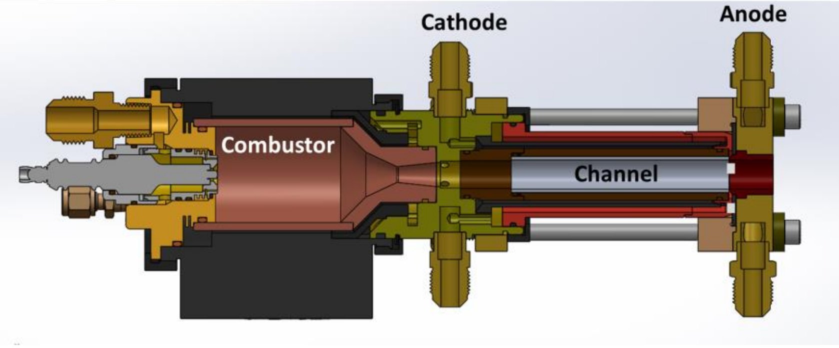
Channel

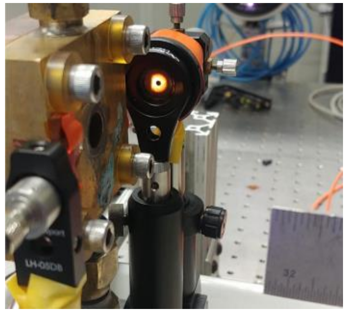
Electrode

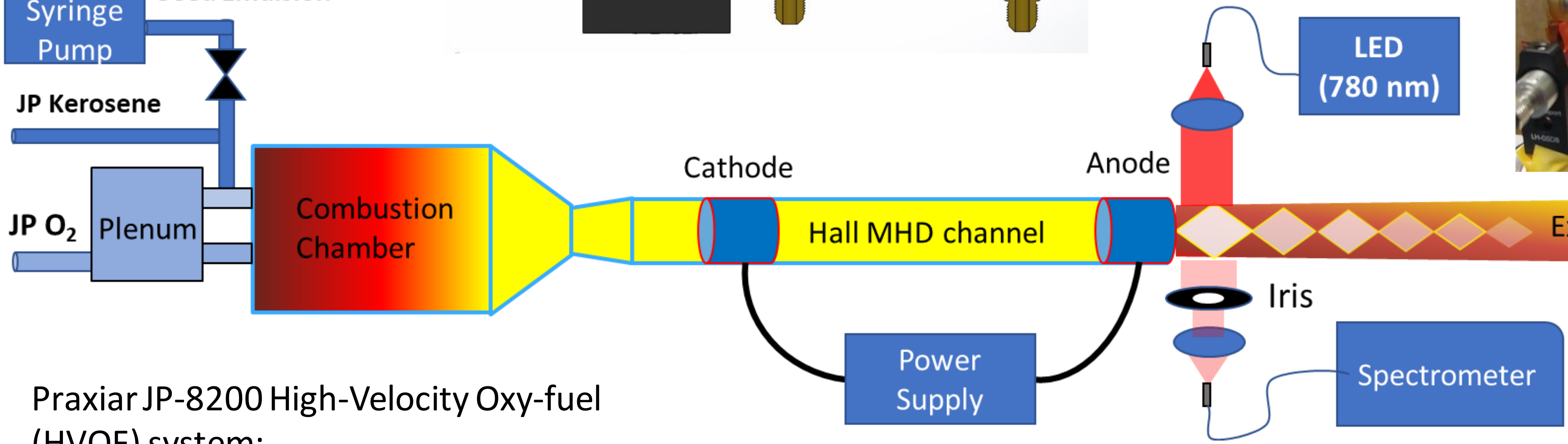
EFFECTS OF ELECTRODE AND BOUNDARY-LAYER TEMPERATURES ON MHD GENERATOR PFRFORMANCE
R. Kessler and R. H. Eustis Symposium on Engineering Aspects of Magnetohydrodynamics 9

MHD Gen 1.0: Back power channel

Experiment: Measure device electrical resistance and potassium number density







Praxiar JP-8200 High-Velocity Oxy-fuel (HVOF) system:

- 160 kW_t Nominal rating
- 6-8 bar oxy-kerosene combustion
- Syringe Pump Seeding Modification

NHR 9200 Power supply: Electrical Resistance (R)

Absorption-Emission Setup: Potassium Number density (n_K)

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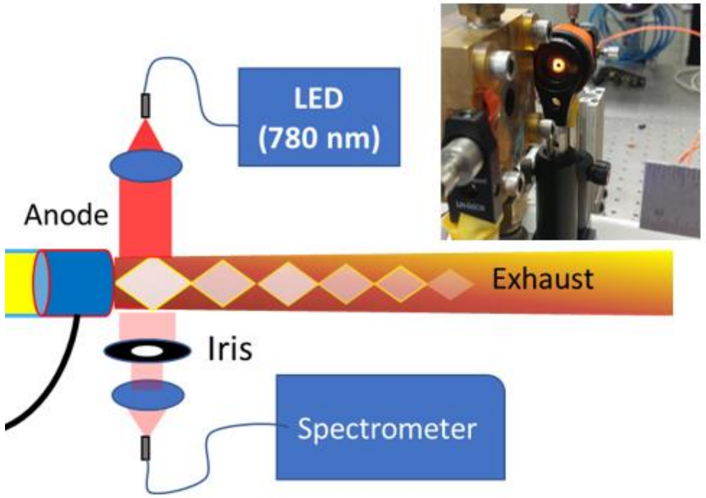
Measurement of Potassum number density (n_K)

Absorption (α) Measurement

Bedick et al. doi.org/10.1016/j.combustflame.2019.11.003



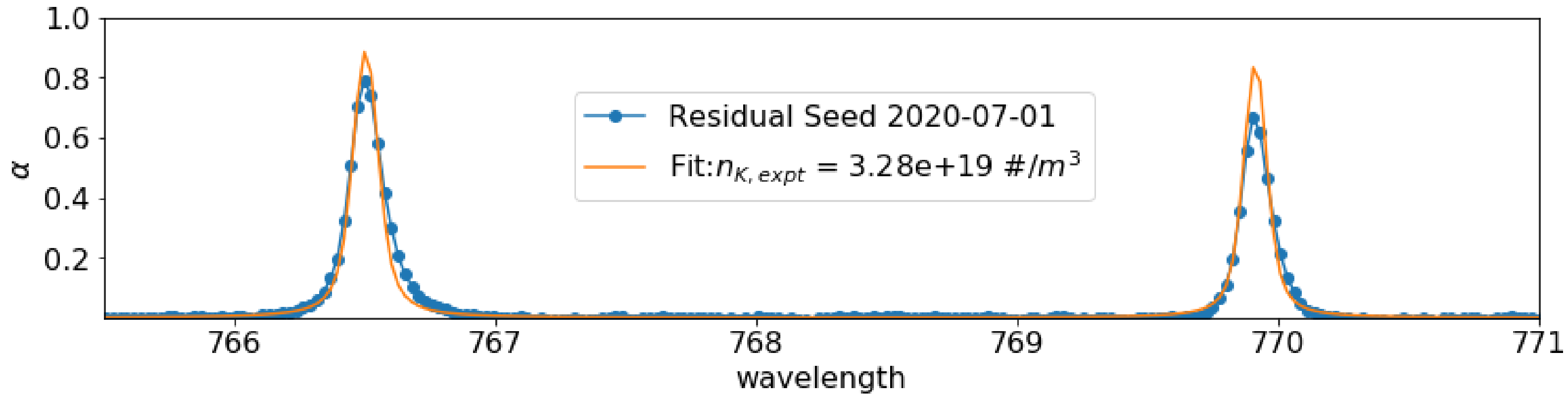
Model α with Beers law: $\alpha(\lambda) = 1 - \exp[-\kappa(\lambda) n_K D]$

$D = Flame\ Width\ (1cm)$

$\kappa =$ optical absorption cross section

Two Voigt lineshapes

$$\kappa(\lambda) = \frac{e^2}{4\epsilon_0 m_e c^2} * \left[\frac{4}{6} f_1 \lambda_{0,1}^2 V(\lambda_{0,1}, \sigma, \gamma_1) + f_2 \lambda_{0,2}^2 V(\lambda_{0,2}, \sigma, \gamma_2)\right]$$



- n_K is only fitting parameter
- Lineshape parameters from air-fired combustion
- Finite spectral resolution of spectrometer accounted for with gaussian convolution

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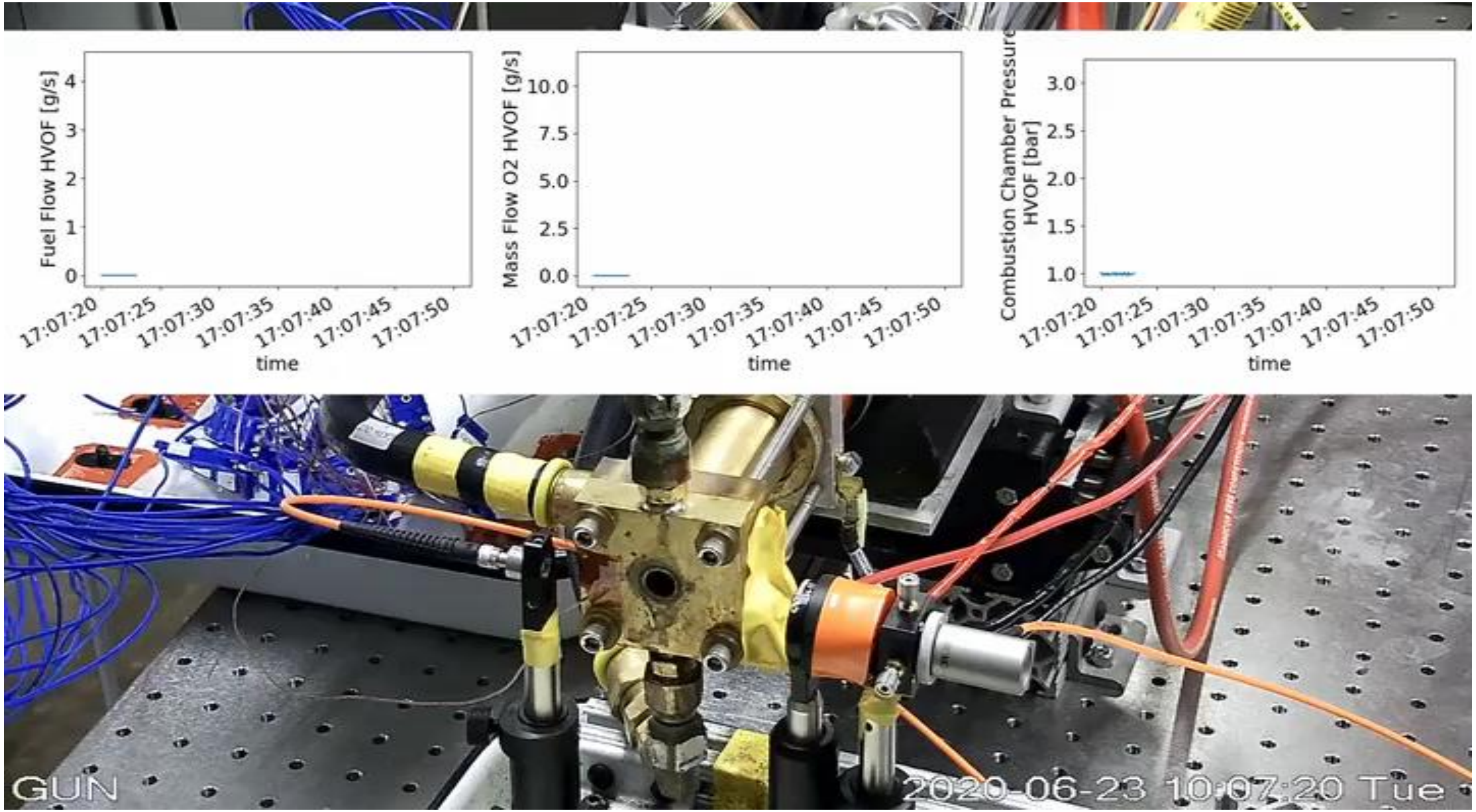
Ignition!

Over 50 sensors continuously logged with National Instruments PXI system

>100 dB sound inside booth!



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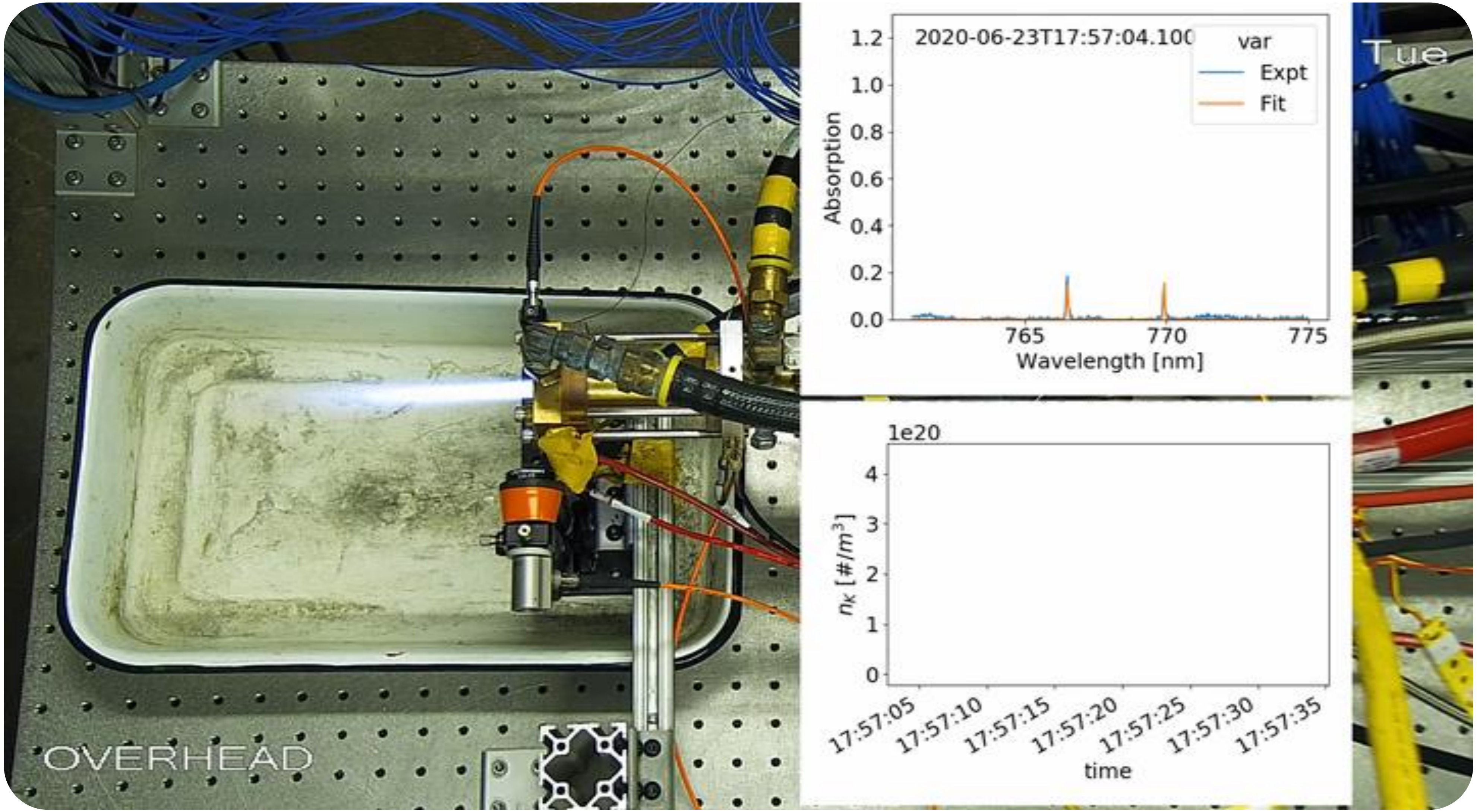
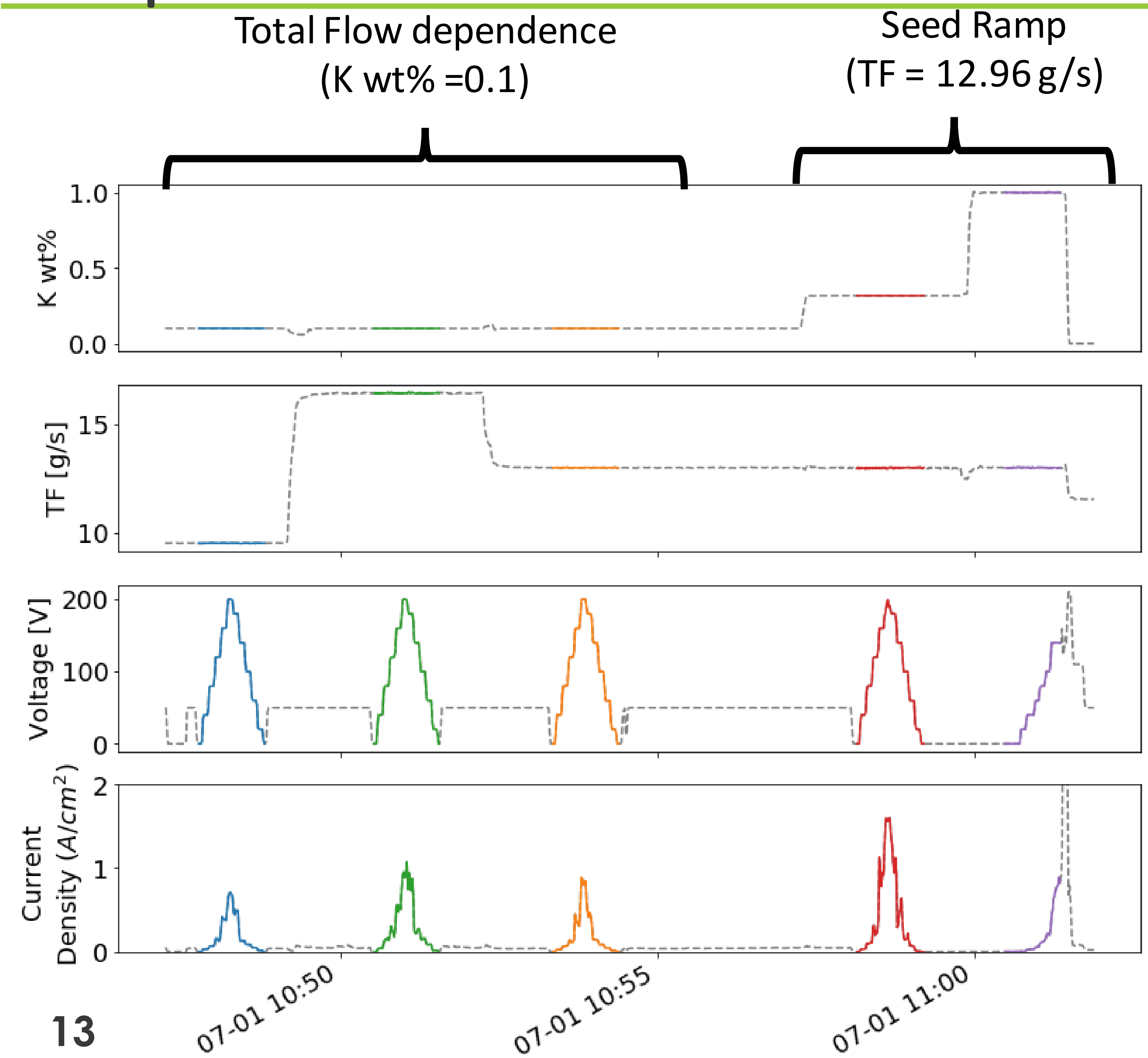
Seed Addition and potassium number density (n_K) measurement

- Potassium Carbonate emulsion added with syringe pump
- Note the 'residual seed' from adsorbed K2CO3 on walls



Experimental Test Matrix Overview: Example from 2020-07-01



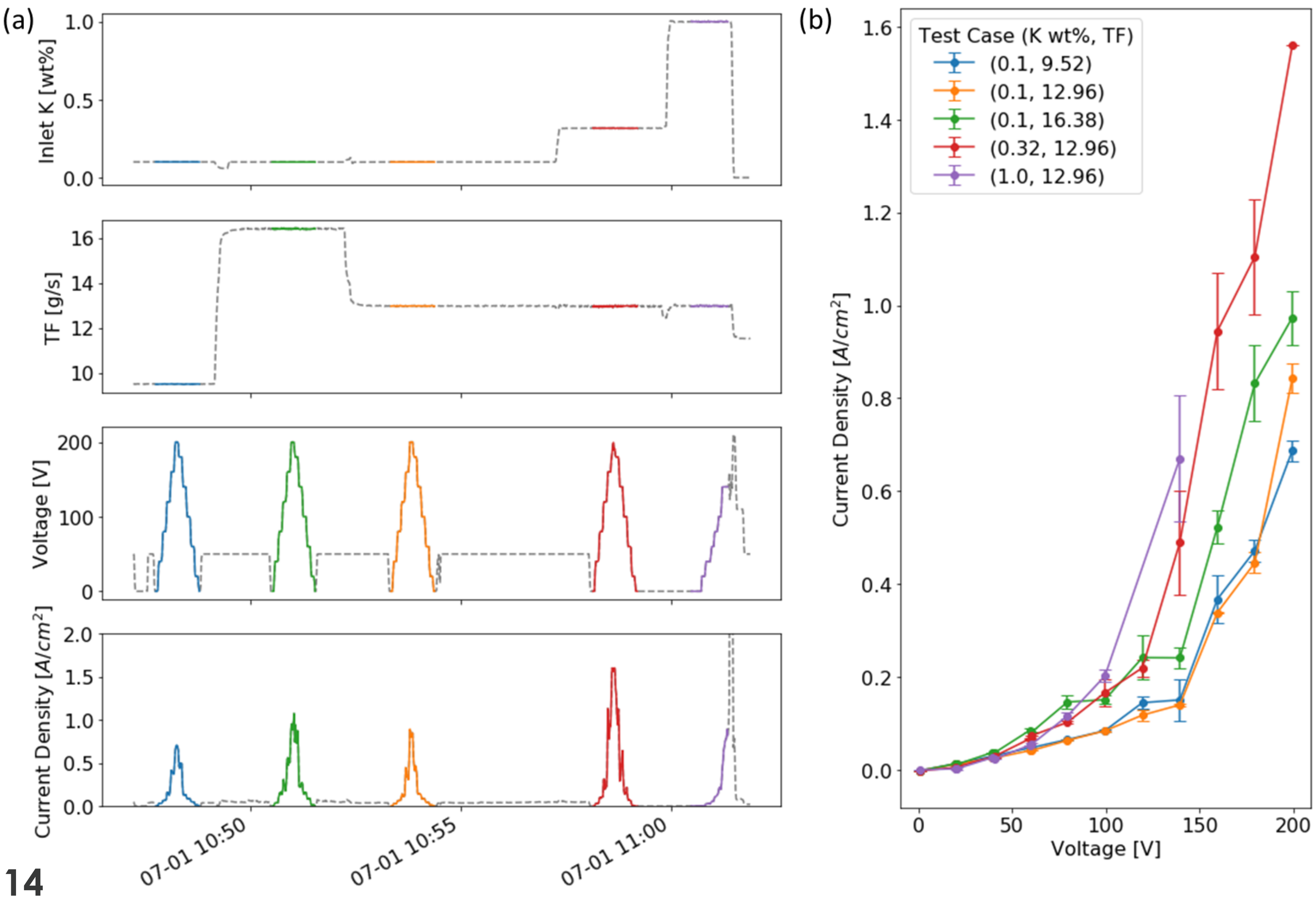
Determine the resistance and potassium number density for various

- Total mass flow rates (TF)
- Inlet Potassium mass fraction (K wt%)
- Applied voltage (V)

K wt%	TF [g/s]
0.1	9.52
0.1	12.96
0.1	16.38
0.32	12.96
1	12.96

Limited syringe pump capacity motivates limited test cases

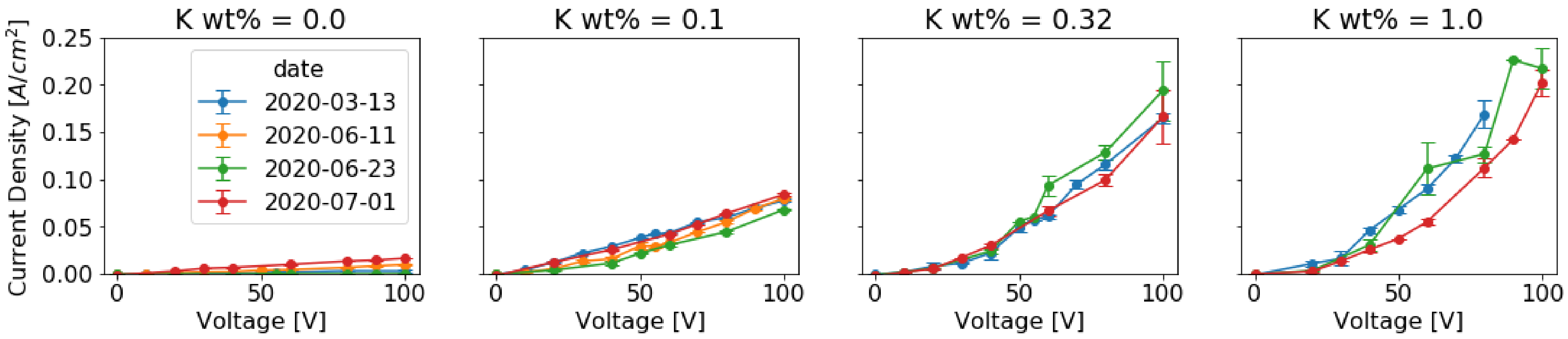
Experimental Overview



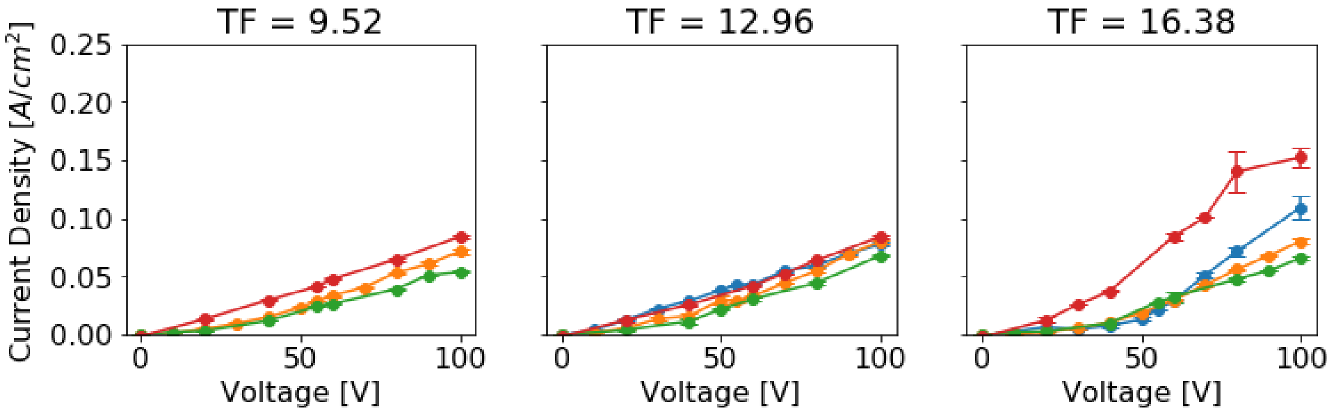
- Determine J-V curve by averaging current at each voltage
- Electrode area 1.5 cm^2
- Transient voltages not included.

Resistance measurements over multiple experiments

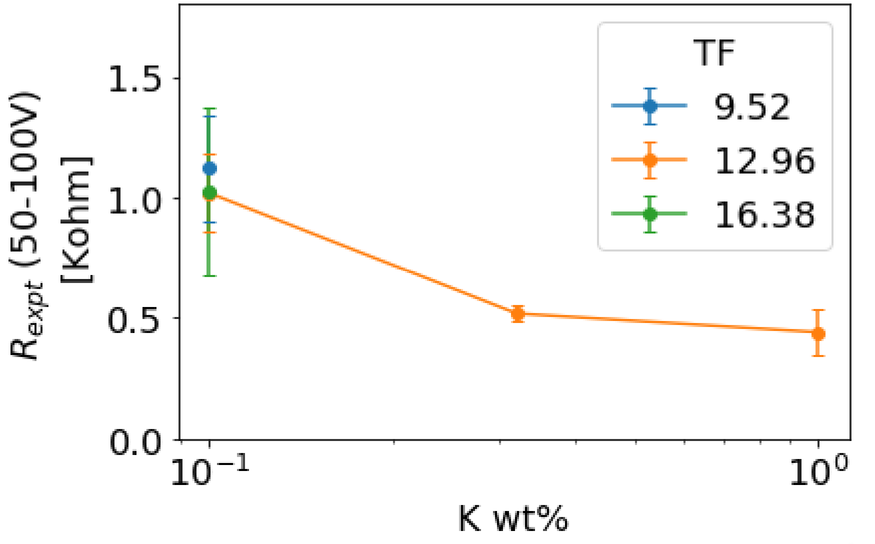
Seed Ramp
TF = 12.96 g/s



Total Flow
Ramp
(Kwt = 0.1%)



Average and Standard Dev. Over all dates
(no error propagation)

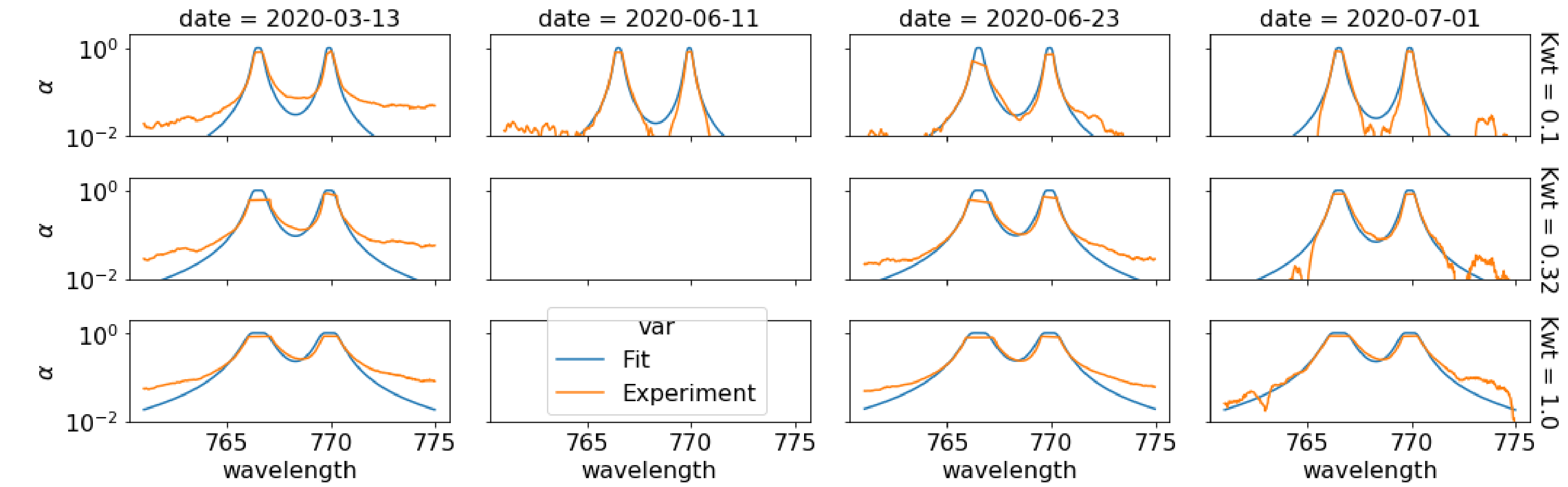


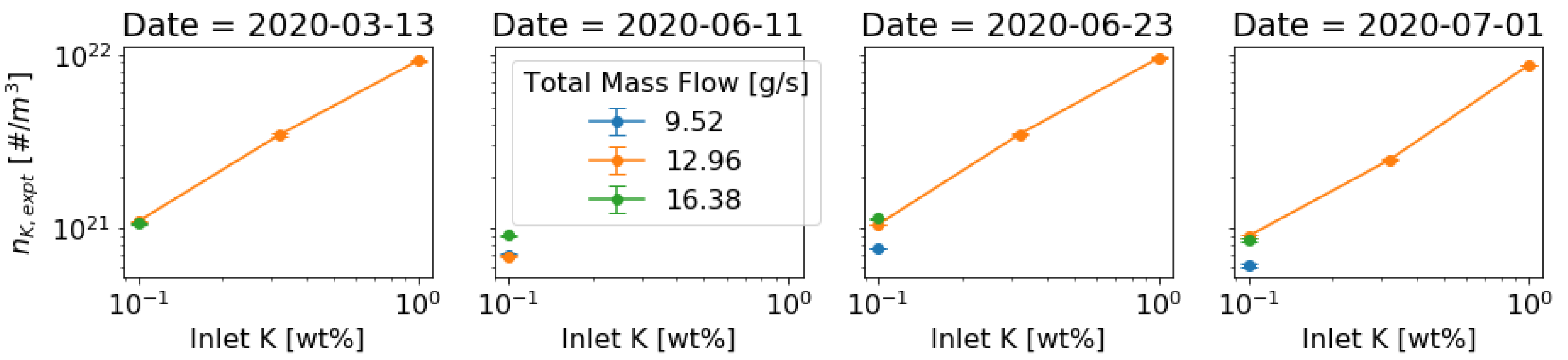
For now on we concentrate on average resistance in range 50-100V for consistency between all dates

$$R_{expt} = \frac{V}{I(V)}$$

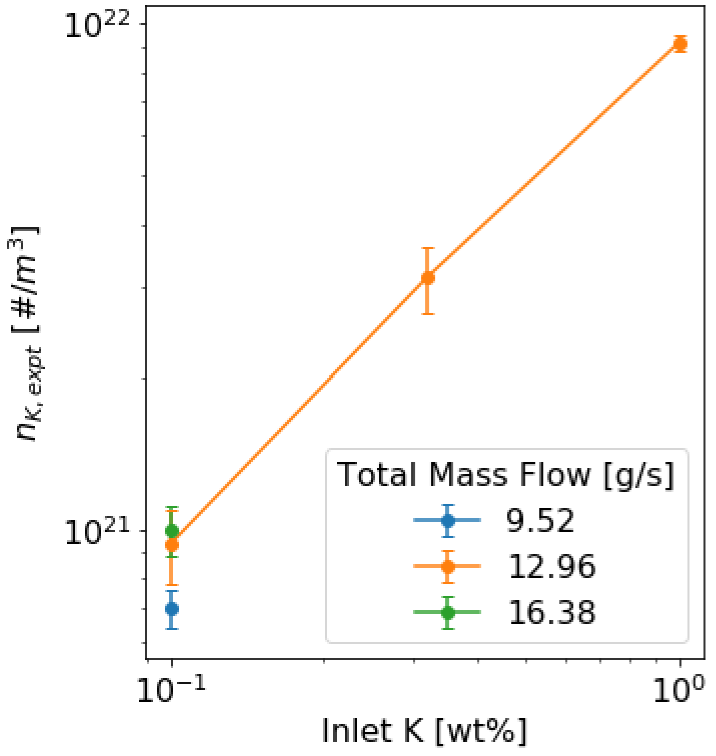
n_K measurements over multiple experiments

Shown for TF = 12.96 g/s





Average and Standard Dev.
Over all dates



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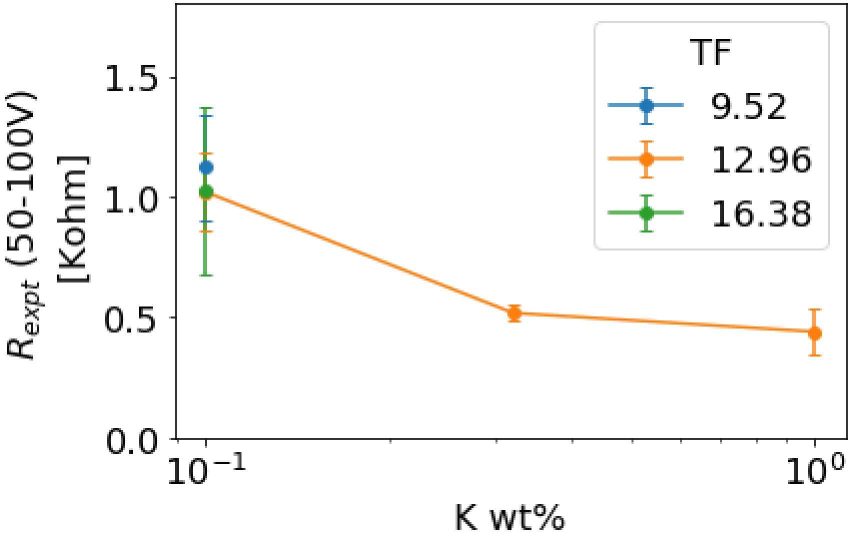
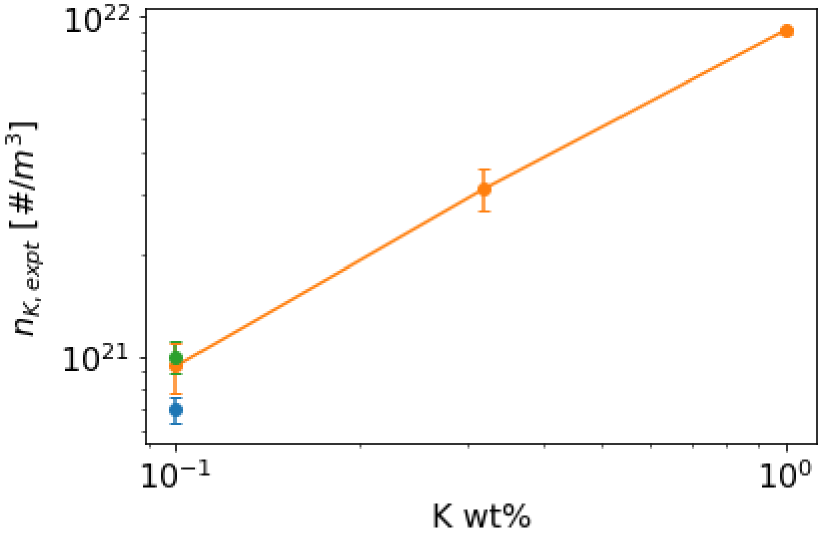
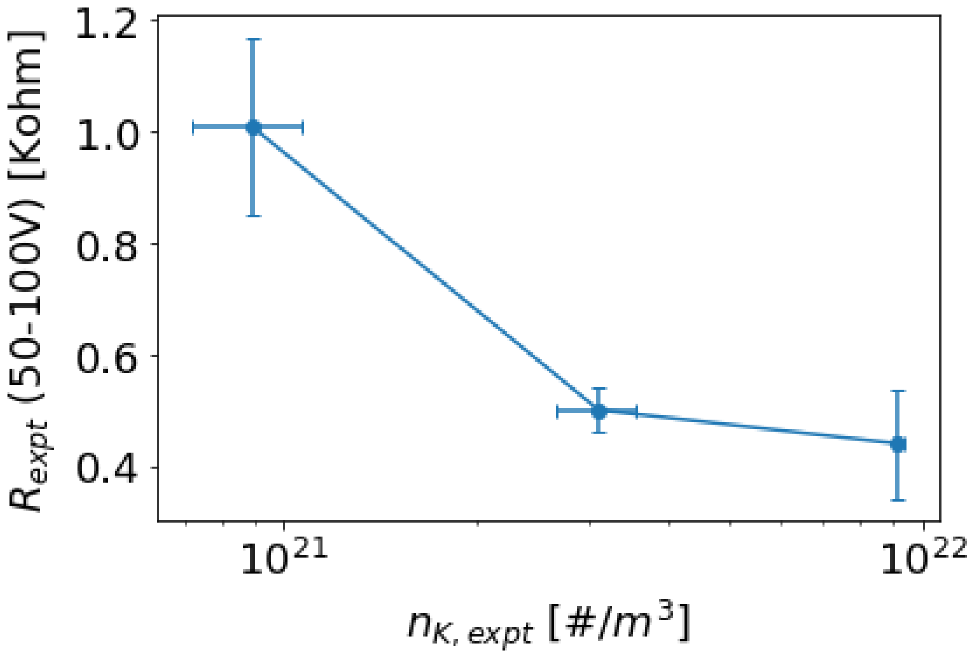
Final Experimental Results: Comparison of Resistance and n_K





For remainder of talk, focus on TF = 12.96 g/s seed ramp



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First pass at modeling: Cantera

2.5.0a3. Cantera: An Object-Oriented Software Toolkit for Chemical Kinetics, Thermodynamics, and Transport Processes.

Augment CFD with simple Cantera-based model (0D chemical equilibrium solution)

Seeded oxy-kerosene combustion, then
Enthalpy removal in three stages

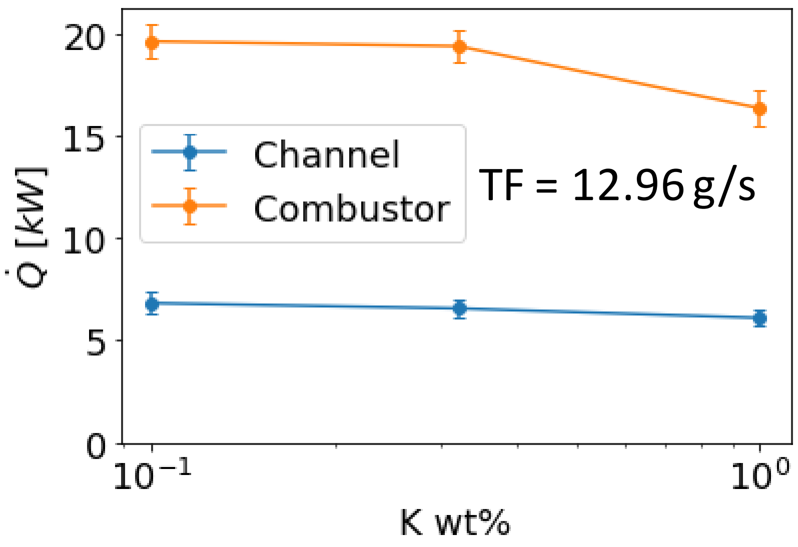
1. Combustor wall heat transfer
2. Work done on gasses (Kinetic energy)
3. Barrel wall heat transfer

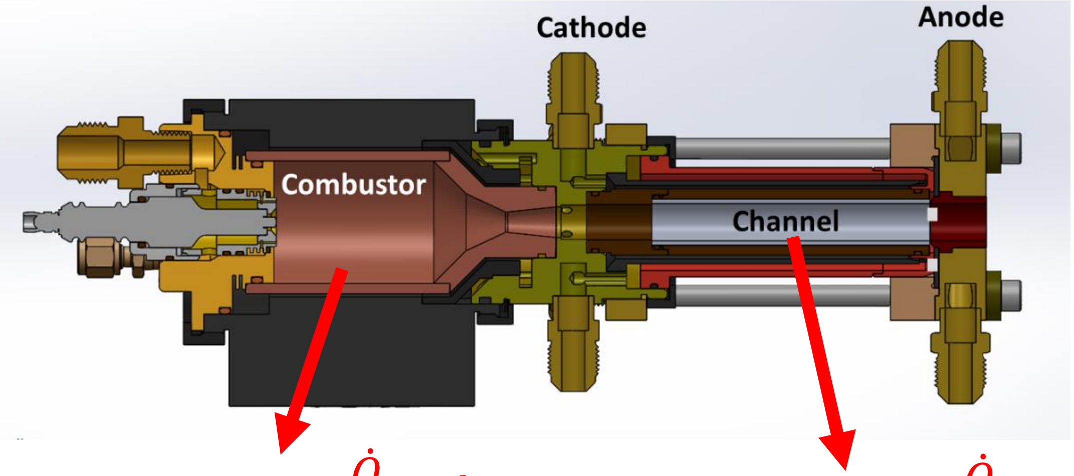
$v_{exit} \cong 1.5\ 10^3 \frac{m}{s}$ from CFD

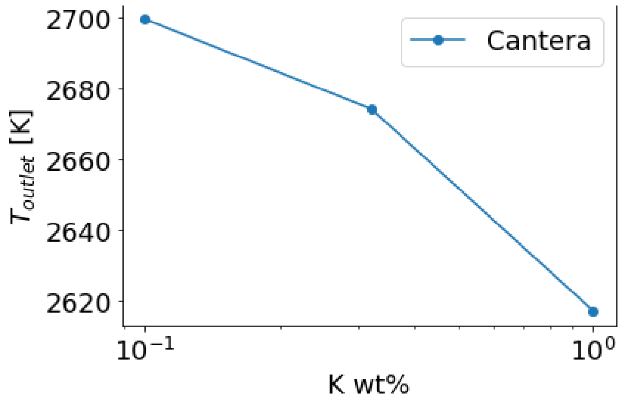
$\dot{Q}$ = Wall Heat Transfer

$\Delta H_{K.E.} = \frac{1}{2}\dot{m}v_{exit}$

T_{outet} = Outlet Temperature







$\Delta H_{Combustor} = \frac{\dot{Q}_{Combustor}}{TF}$

$\Delta H_{Channel} = \frac{\dot{Q}_{Channel}}{TF}$

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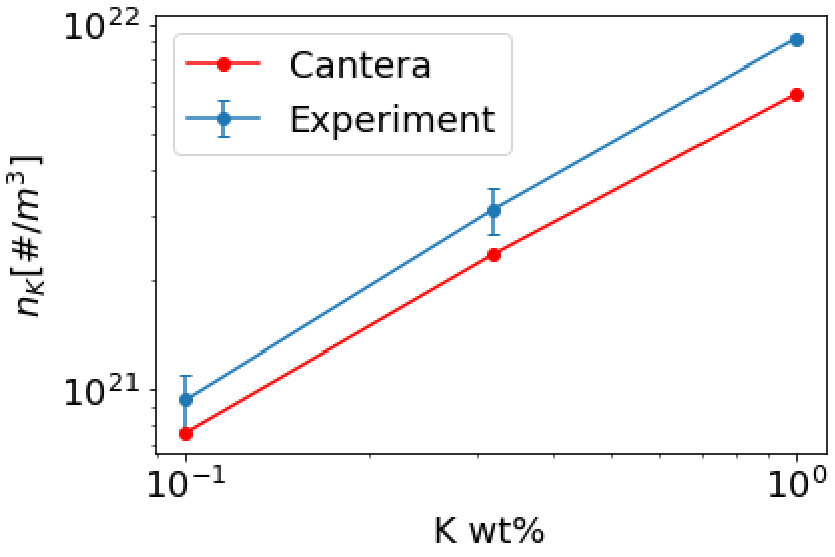
Cantera Modeling Results

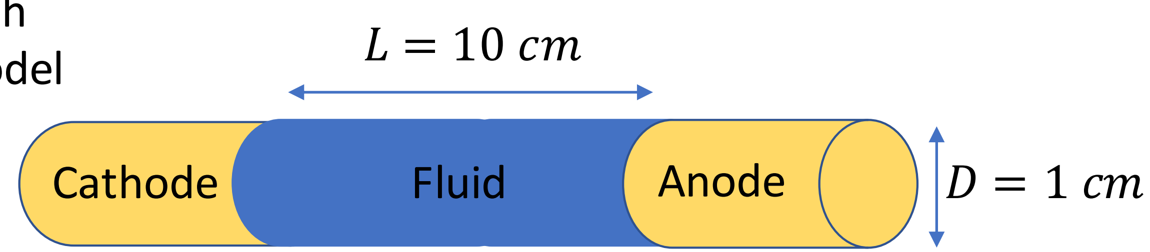


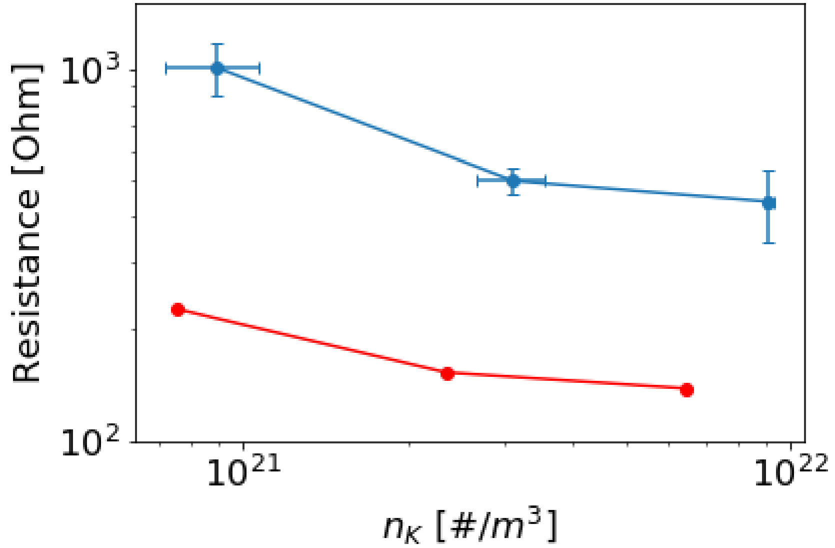
n_K results agree relatively well, but Systematic errors in absorption emission setup/fitting shift experimental results beyond fitting error. Historical spectral lineshape widths used may not be accurate in oxy-fuel conditions.

Calculate Fluid Conductivity (σ) Bedick et al. doi.org/10.1016/j.combustflame.2019.11.003

Model resistance with simple cylindrical model

$$R = \frac{4}{\sigma}\frac{L}{\pi D^2}$$



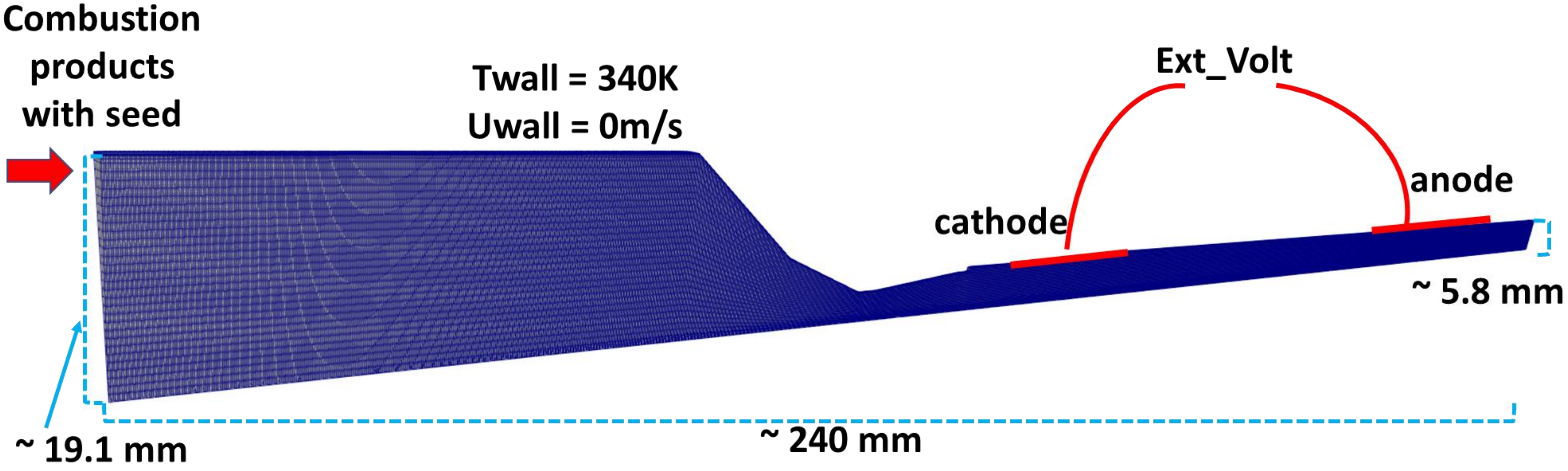


- Model should underestimate resistance
  - Calculated n_K is lower than experiment
  - Using cold outlet gasses for all fluid
- Conclusion: Simple fluid conductivity cannot explain high measured resistance

CFD Modeling Overview

Implement CFD modeling presented at AIAA 2019

Kim, H., et al. A numerical model of a back powered channel for MHD generator application. AIAA Propulsion and Energy 2019 Forum. https://doi.org/doi:10.2514/6.2019-4316



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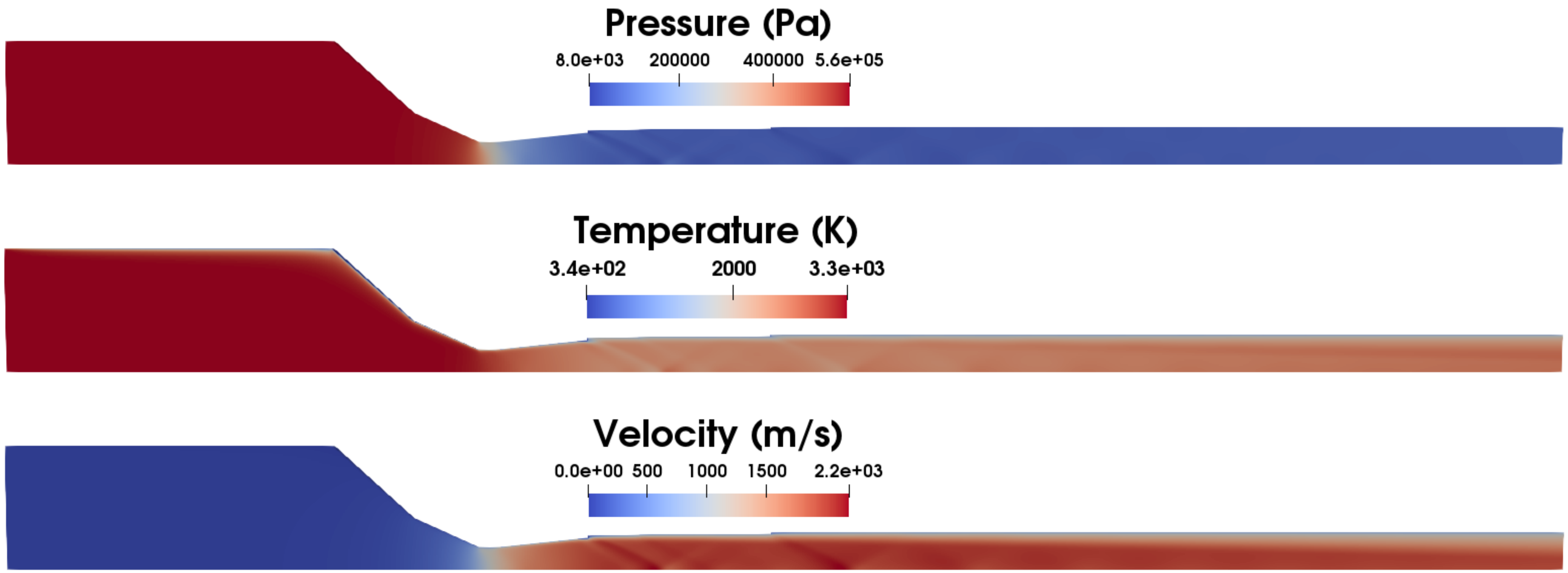
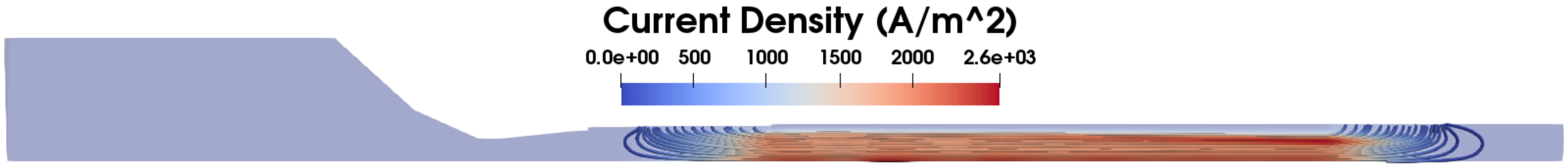
CFD Modeling Overview

Step 1: Solve Fluid flow with simplifications for quick scanning of test cases.

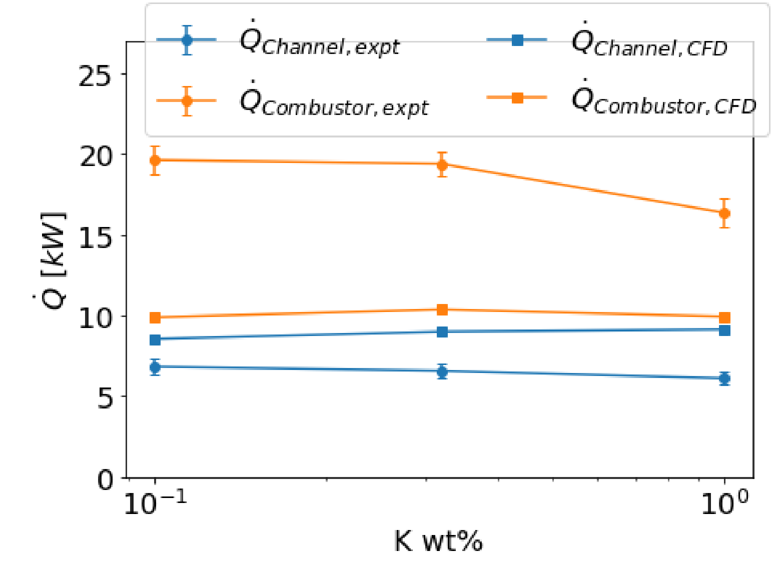
- uniform mixture of fuel, oxygen and seed combustion products injected at combustor back section.
- 2D axi-symmetric geometry

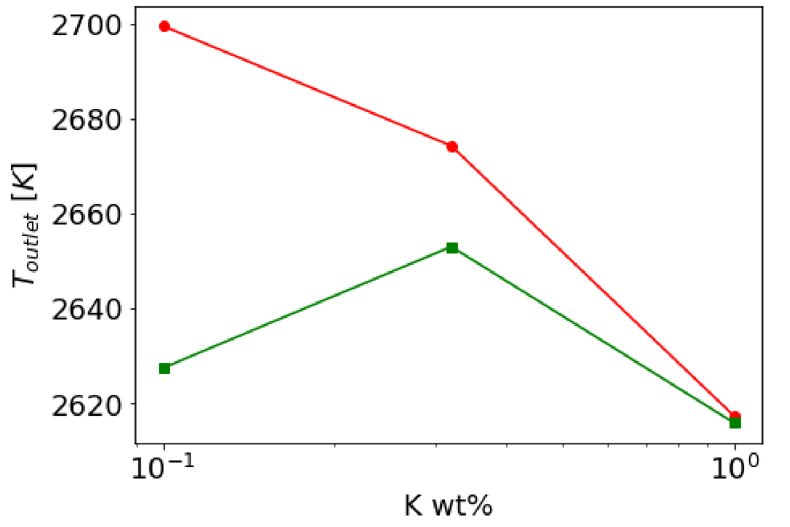


Step 2: Electrostatic model is solved decoupled from the flow using a converged flow field



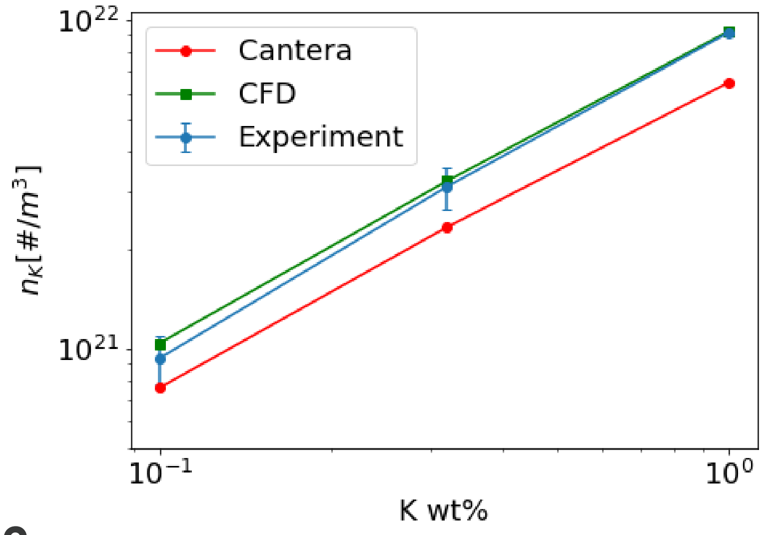
CFD Modeling Results

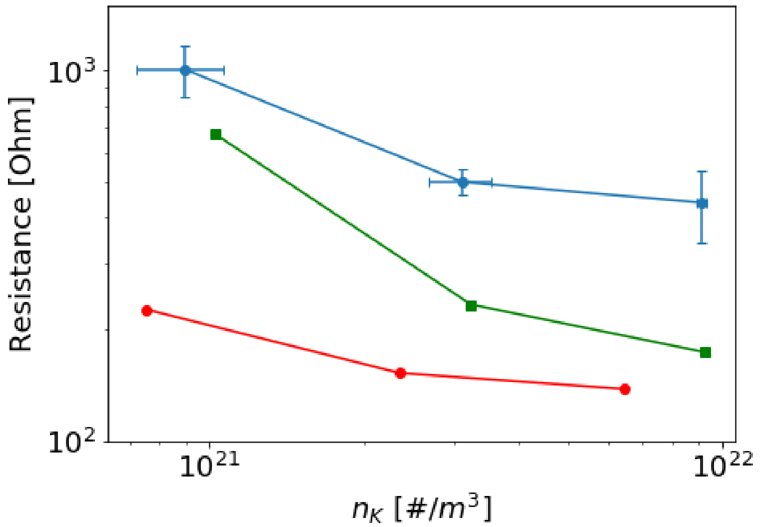




CFD underestimates wall heat transfer, likely due to model simplifications

- injecting pre-combusted gases into the combustion chamber
- neglecting radiation heat transfer





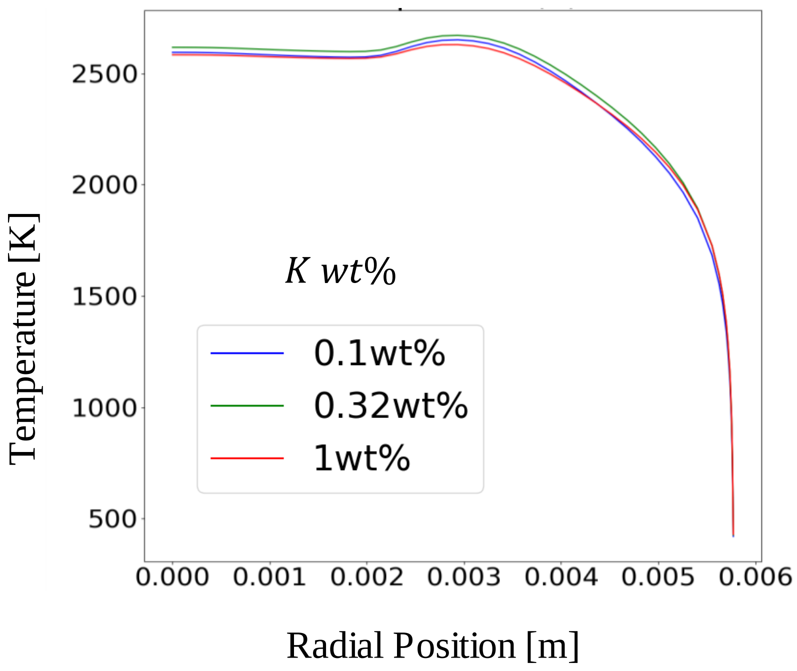
Regardless, CFD predicts closer resistance than Cantera: Boundary layer effects.

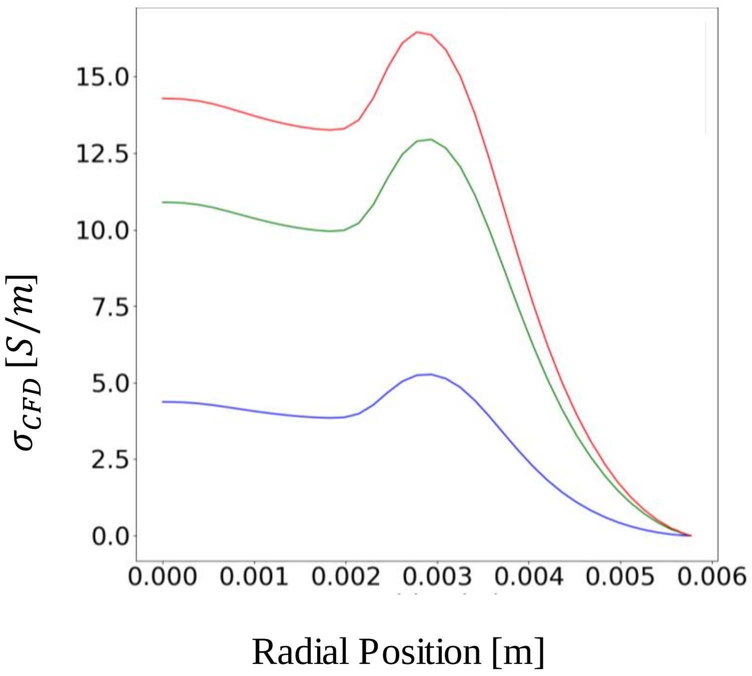
Remaining resistance may be better predicted with inclusion of multiphase effects

Boundary Layer CFD

CFD predicts boundary layer resistance

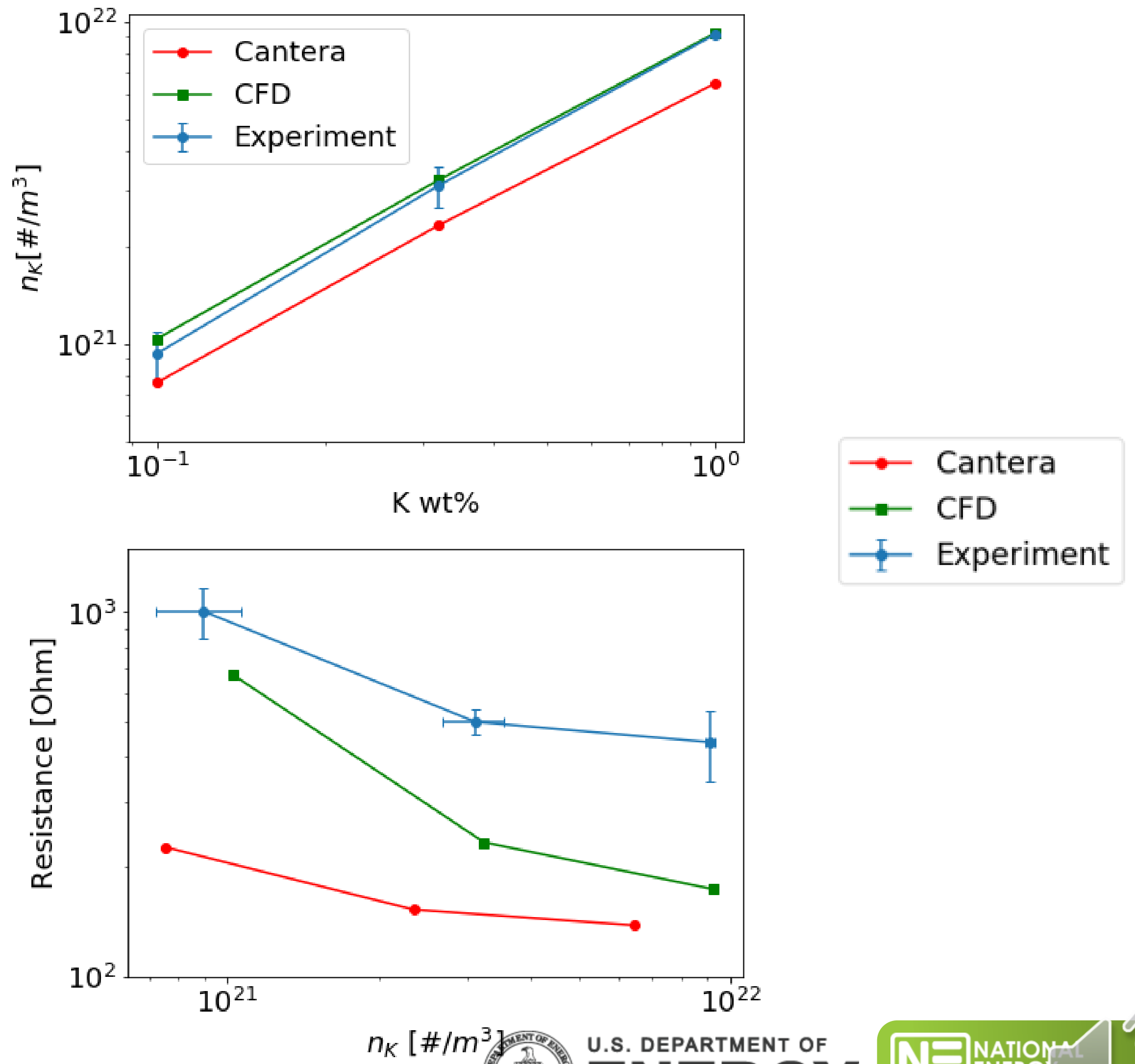
Cross section of gasses at anode





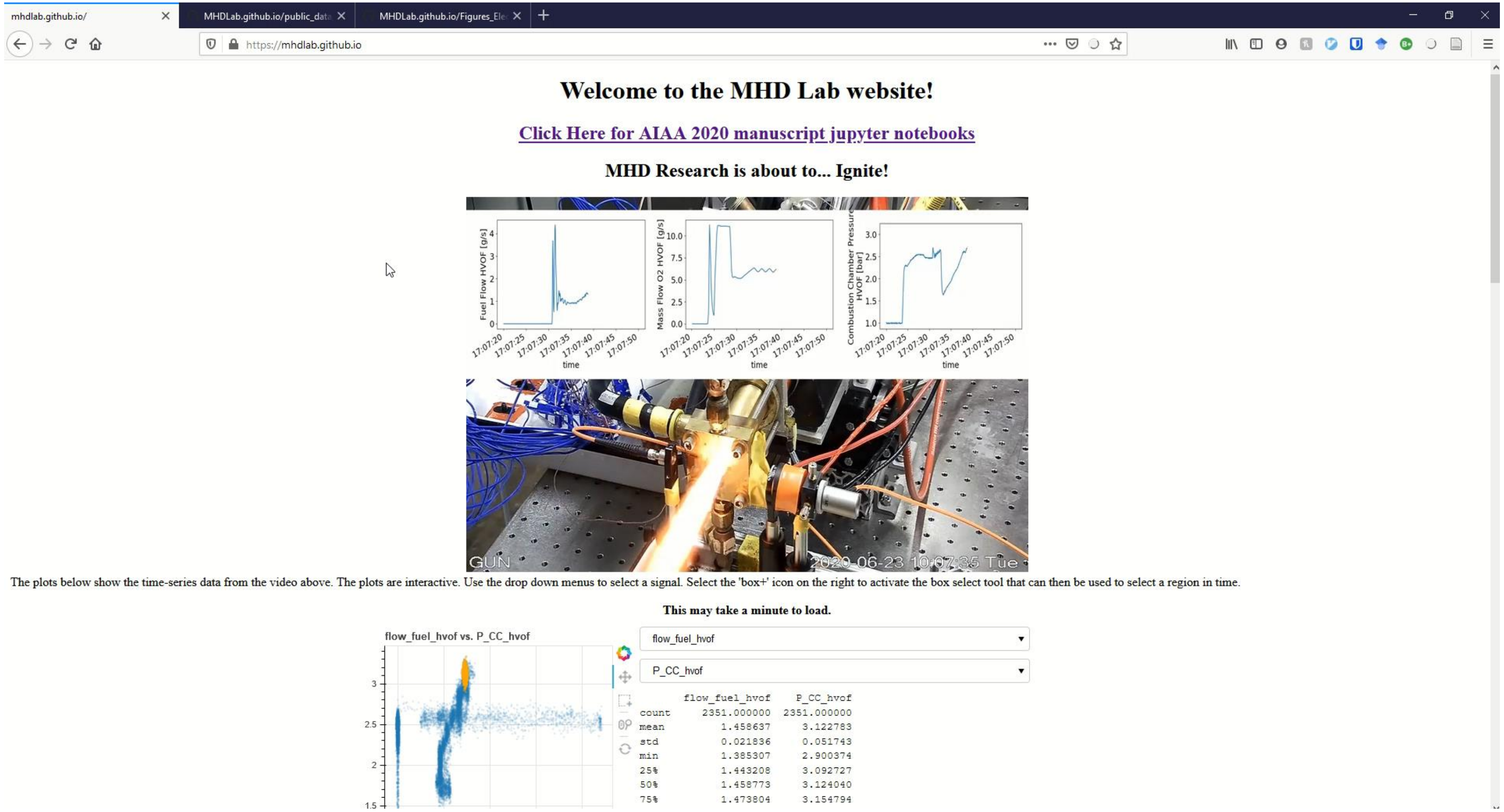
Conclusions

- Measured and Simulated the Electrical resistance and potassium number density of a back-powered MHD channel
- Minimal dependence on total mass flow and significant dependence on inlet Kwt %
- $n_{K,expt}$ agrees relatively well with both simulation results.
- R_{expt} is significantly higher than the resistance predicted in a simple cylindrical resistor model using fluid conductivity calculated in Cantera-based chemical equilibrium calculations.
- CFD simulations predict resistances closer to R_{expt}, which we attribute in part to modeling the cold boundary layer near the electrodes.
- Improved simulations underway with more detailed modeling of fuel emulsion injection, mixing and combustion to reduce the remaining discrepancy



MHD website

MHDLab.github.io



- Datasets and Juptyer notebooks use to generate the figures in the manuscript and this talk.
- Experiments in interactive web-based data visualization
- Work in progress!

Thank you!

I look forward to the QA session

Feel free to contact me at: lee.aspitarte@netl.doe.gov

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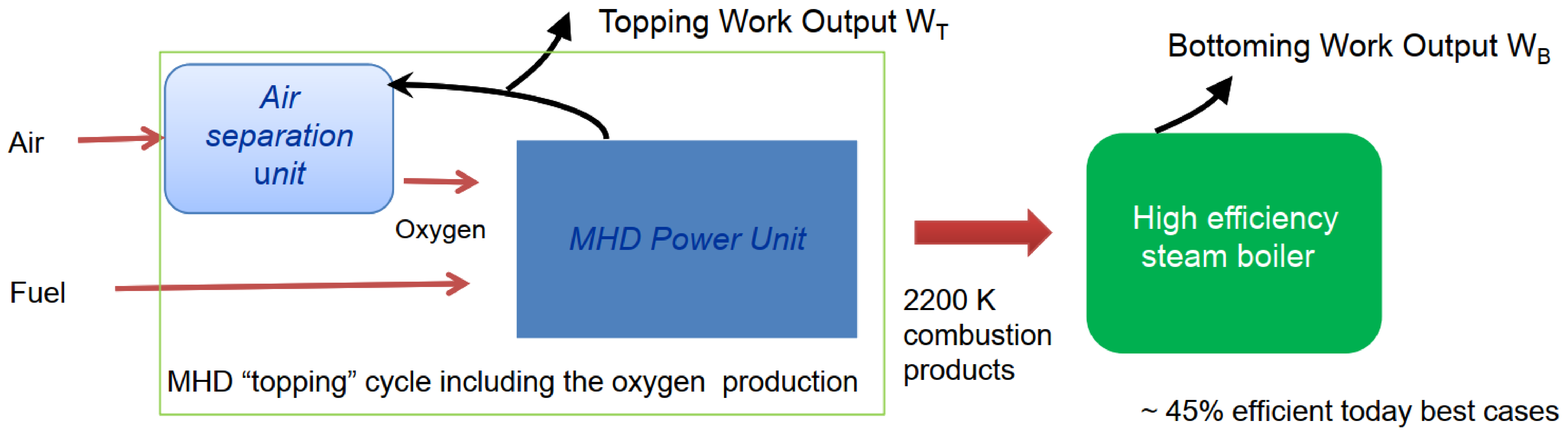
Extra Slides

Oxy-Fuel based MHD Topping cycle



- MHD generator extracts work from high temperature gasses
- Passes lower temperature to conventional steam turbine
- Retrofit potential