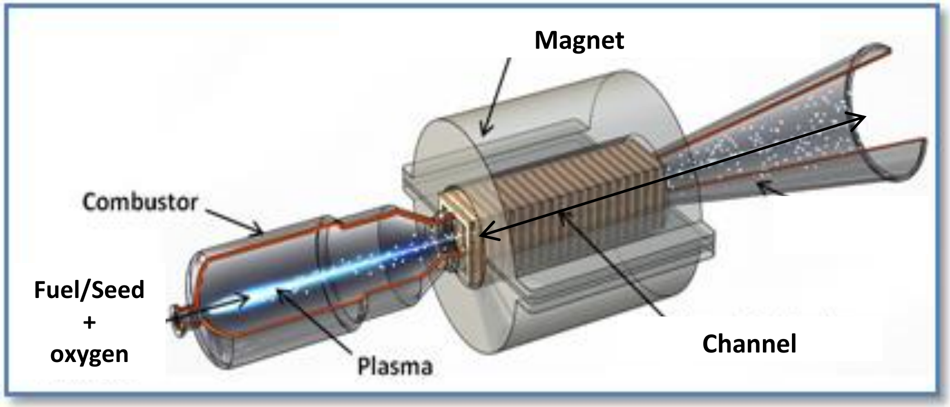
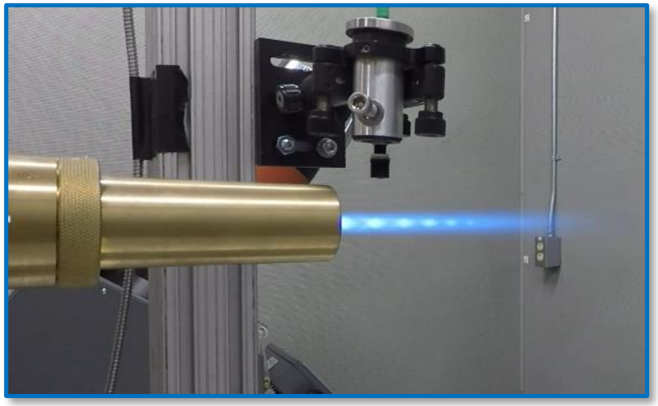
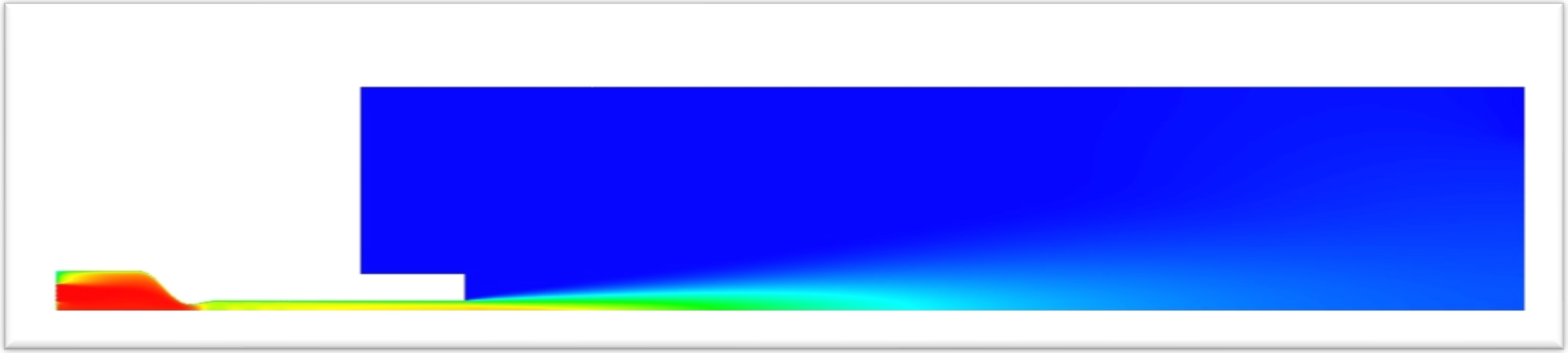
Driving Innovation ◆ Delivering Results







A computational and experimental study of a high velocity oxy-fuel system for MHD generation system development

Hyoungkeun Kim, David Huckaby,
Rigel Woodside, Eric Zeuthen,
Thomas Ochs

ASME Washington D.C. July 11, 2016

Outline

MHD Power Generation & NETL MHD Experiment

- **Multidimensional Modeling**
  - Discretization and Algorithms
  - Physical Sub-models
  - Boundary Conditions
- **Comparison of Predictions and Measurements**
  - Heat Flux
  - Radiation
  - Shock Chain
- **Conclusions and Future Work**

MHD Energy Conversion

MHD (Magnetohydrodynamics) is a branch of physics which studies the interaction of an electrically conductive fluid with a magnetic field.

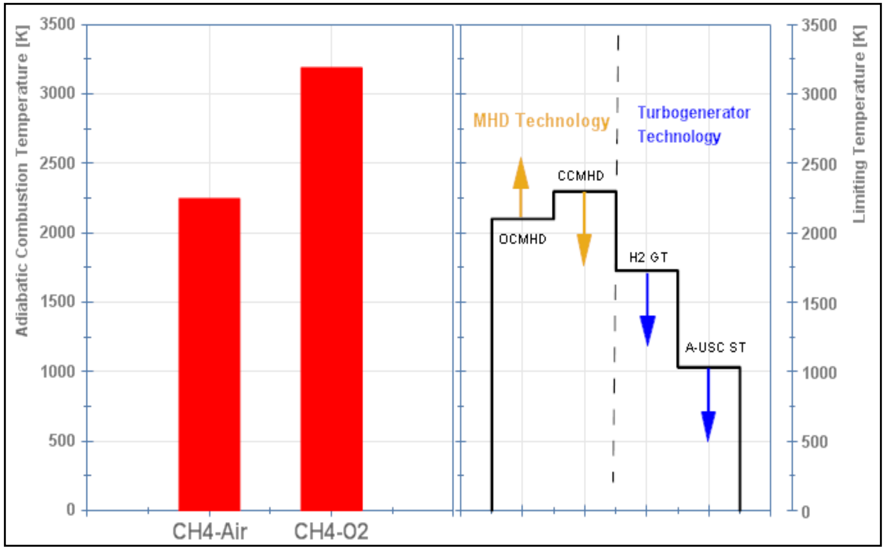
Lorentz Force

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

Carnot Limit

$$n_{th} \leq 1 - \frac{T_C}{T_H}$$

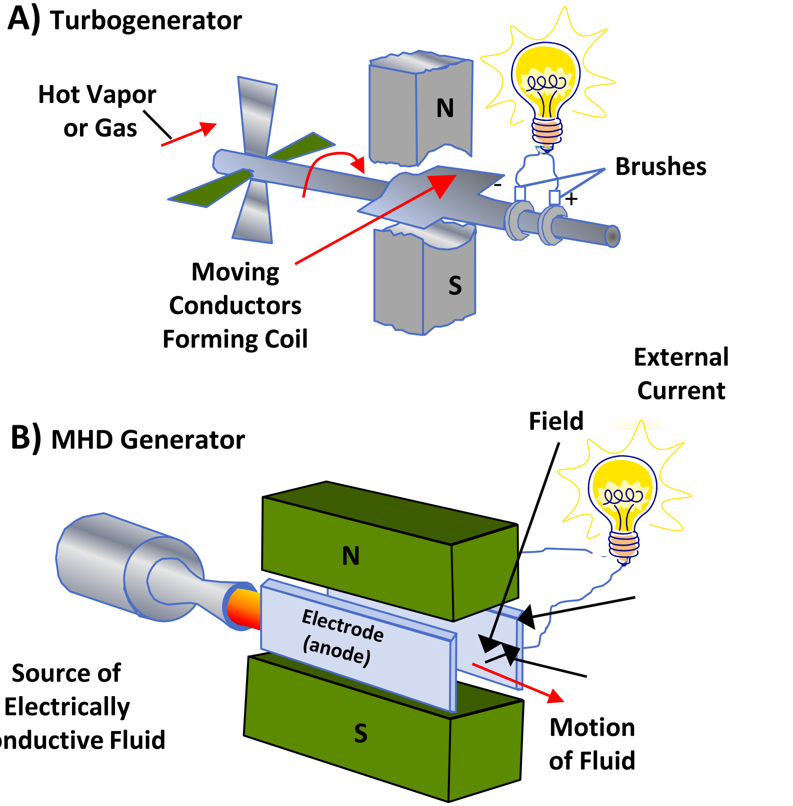
MHD technology better utilizes oxy-fuel (for carbon capture)



This technology does not yet exist commercially; NETL's research is at a TRL level of 2-3.

Today, nearly all of our power plants (coal, natural gas, hydroelectric, wind, concentrated solar, nuclear, bio-mass) use mechanical turbines to generate electrical power.

In the future, if developed, we may use a more efficient generator which operates without moving parts. This is called a MHD generator.

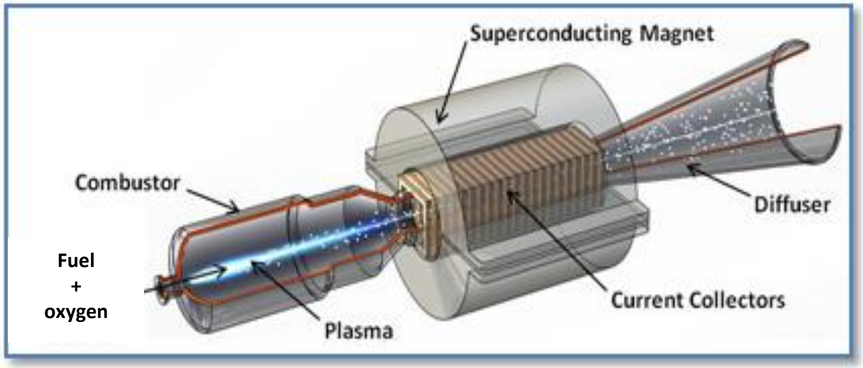


NETL's MHD Laboratory in Albany, Oregon

Lab became operational late Fall 2015

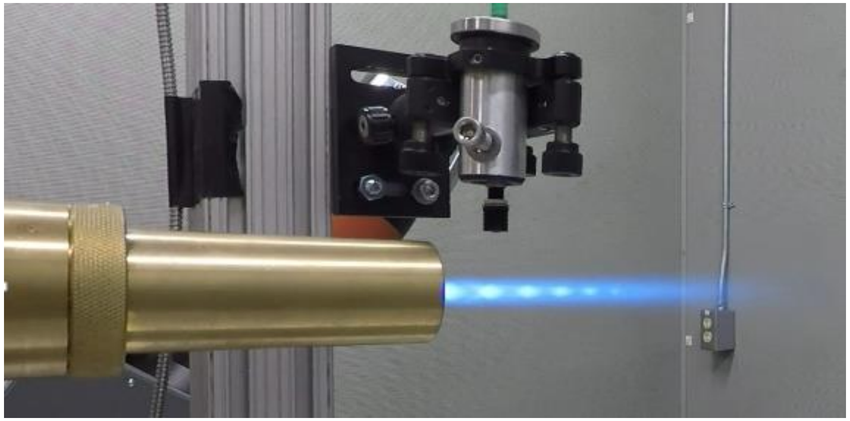
MHD Lab goal: To safely conduct MHD experiments in order to enable future MHD engineering applications which can be beneficial to the public.

- Validate developed simulation tools
- Test materials in realistic service conditions
- Proof of concept testing



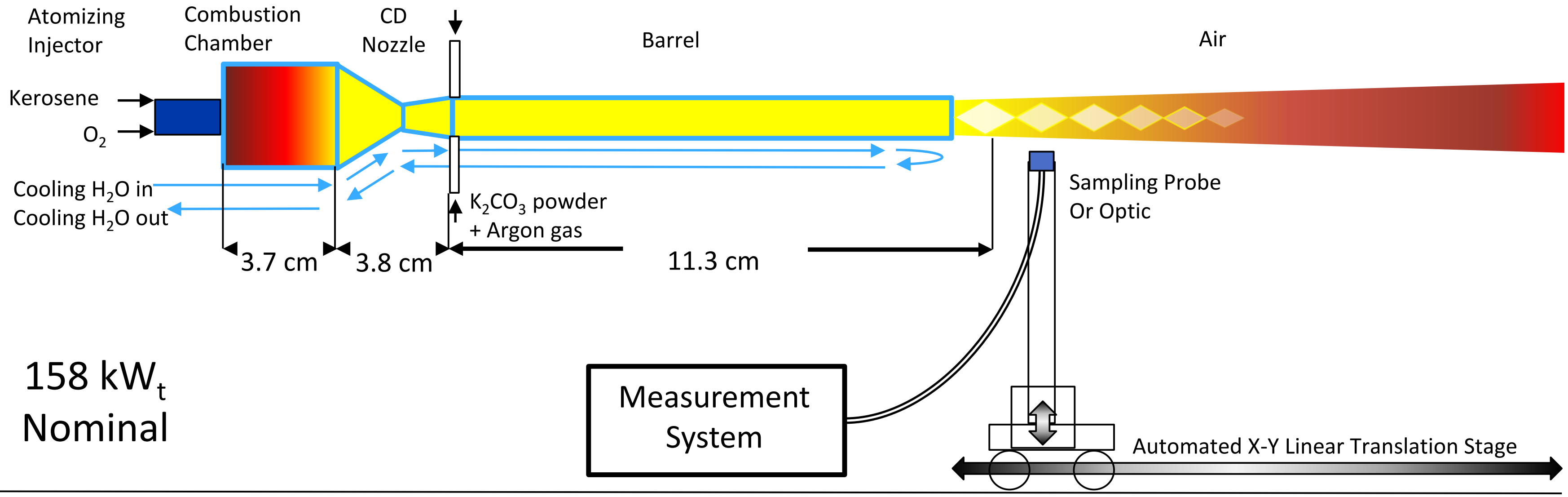
Cartoon of Open Cycle MHD topping Unit

"remote" MHD testing inside a 20' x 12' booth



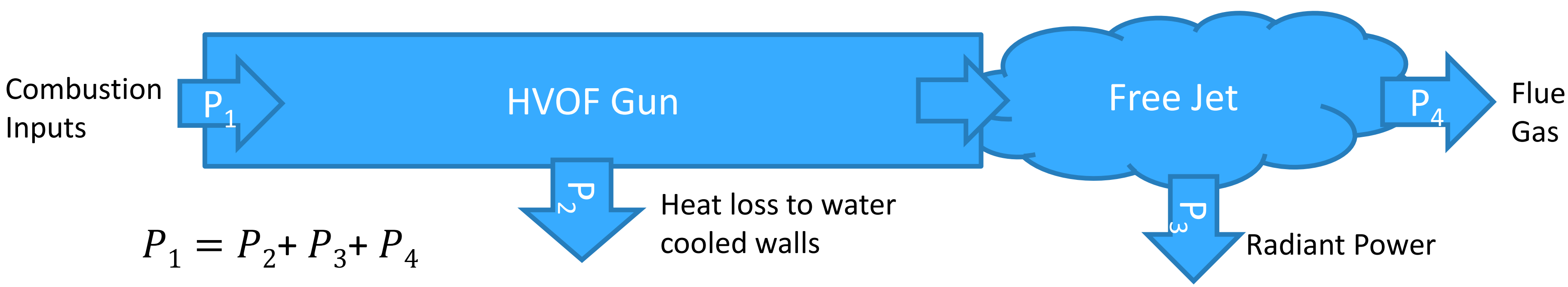
Oxy-fuel combustor testing is underway. The gasses exit the nozzle at near Mach 2, resulting in shock diamond formation.

High Velocity Oxy-fuel (HVOF) Set-up



158 kW_t
Nominal

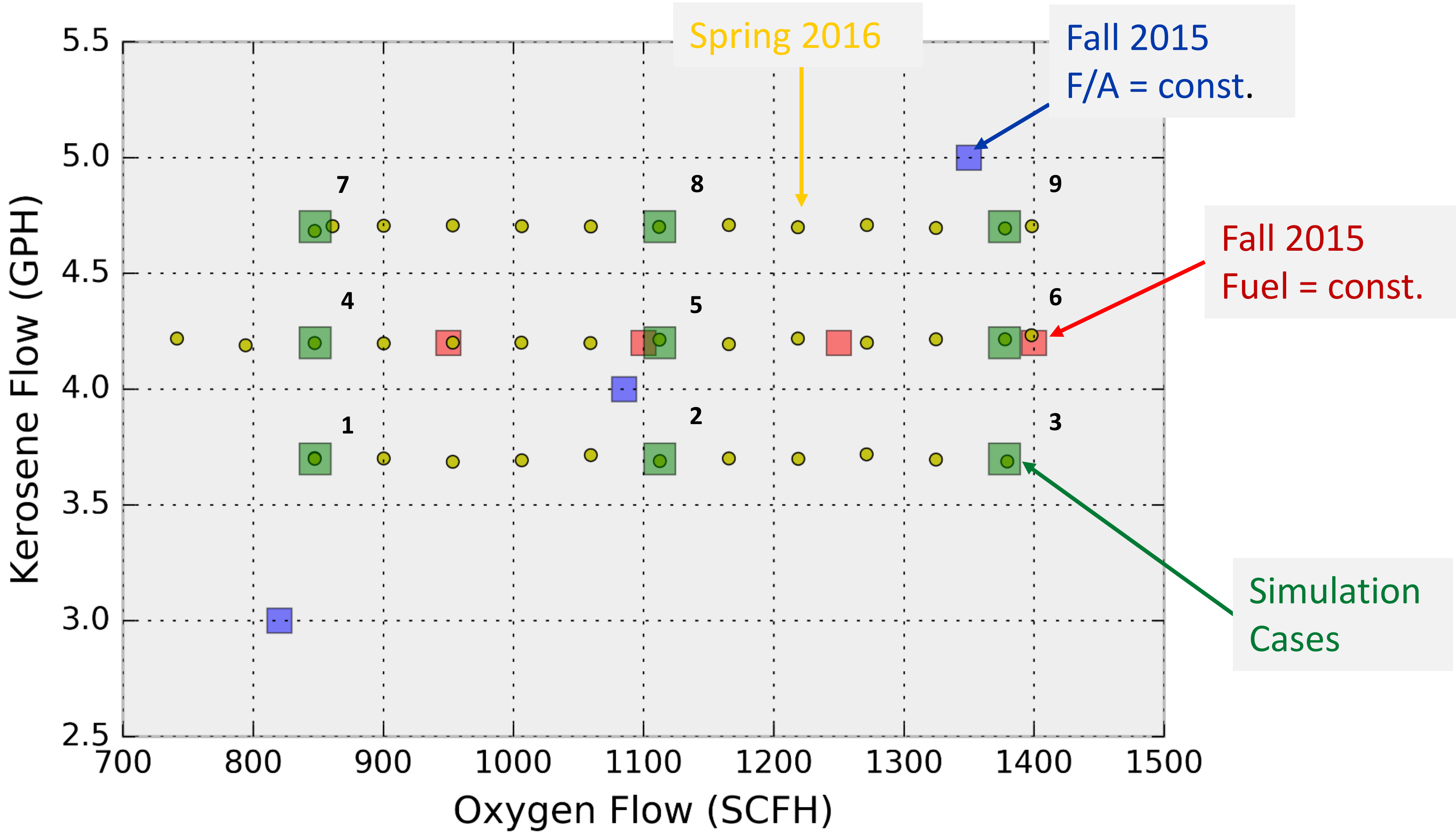
- Initial test campaign focuses on establishing steady-state "global" heat balance



$$P_1 = P_2 + P_3 + P_4$$

- Obtain test data varying fuel & oxygen inputs within an envelop of stable operation

HVOF Operating Conditions



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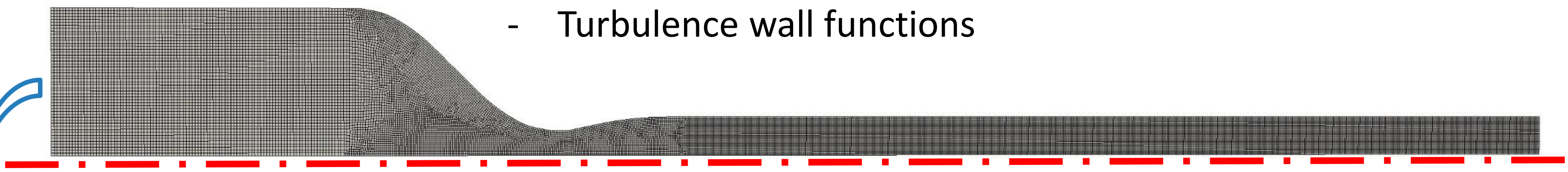
Discretization and Algorithm

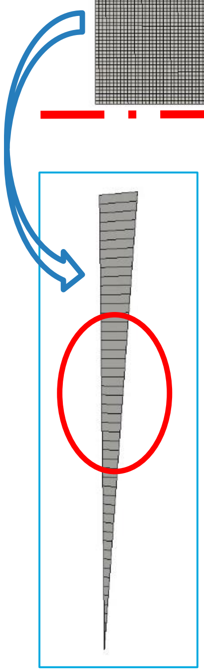
- **Customized version of `reactingFoam` in OpenFOAM**
- **Equations**
  - conservation of mass, momentum, energy and species
  - Multicomponent calorically perfect ideal gas
  - k-ω-SST turbulence model w/ Mach correction
  - Radiative transfer equation
- **Discretization**
  - Unstructured Polyhedral
  - 1^{st}-order upwind and 2-order flux-limited
  - "Rhie-Chow" pressure dissipation
- **Algorithm**
  - Segregated solver
  - PIMPLE pressure correction algorithm with chemical reactions
  - Operating splitting for stiff chemical reaction
  - P1 grey-gas

Combustor + CD Nozzle + Channel Boundary Conditions

Wall conditions
- Fixed wall T
- $\nabla P = 0$ along the wall
- Turbulence wall functions

Outlet condition
- Wave transmissive with $P = 0.5\ bar$





5° slice

Inlet condition - small hole for gas injection

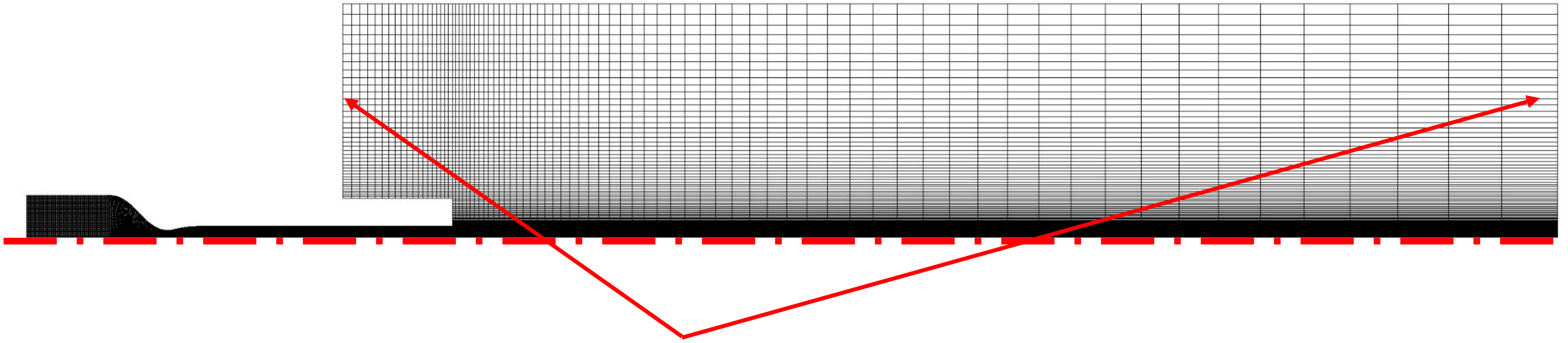
Mass flow inlet with fixed composition, T and ∇P=0

- Combustion(comb) :
  - Inject low temperature premixed fuel (Kerosene, C12H26) & oxygen
  - Combustion occurs inside of combustor
- Combustion Product(combProd) :
  - Inject hot (~3000K) equilibrium products {CO,CO2,H2O, O2, …}
  - More stable simulation

Exhaust Boundary Conditions

Exhaust Wall conditions

- inletOutlet T ~ 300 K
- $\nabla P = 0$
- U ~ (0,0,0)

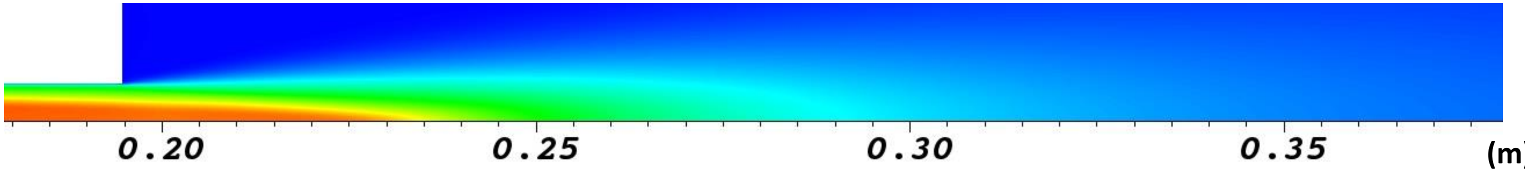


Outlet condition

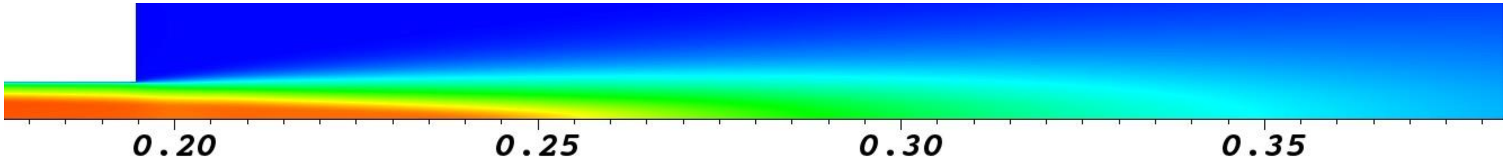
- inletOutlet T ~ 300 K
- Wave transmissive with $P \sim 1\ atm$
- U <- pressureInletOutletVelocity

Sensitivity to Turbulence Model

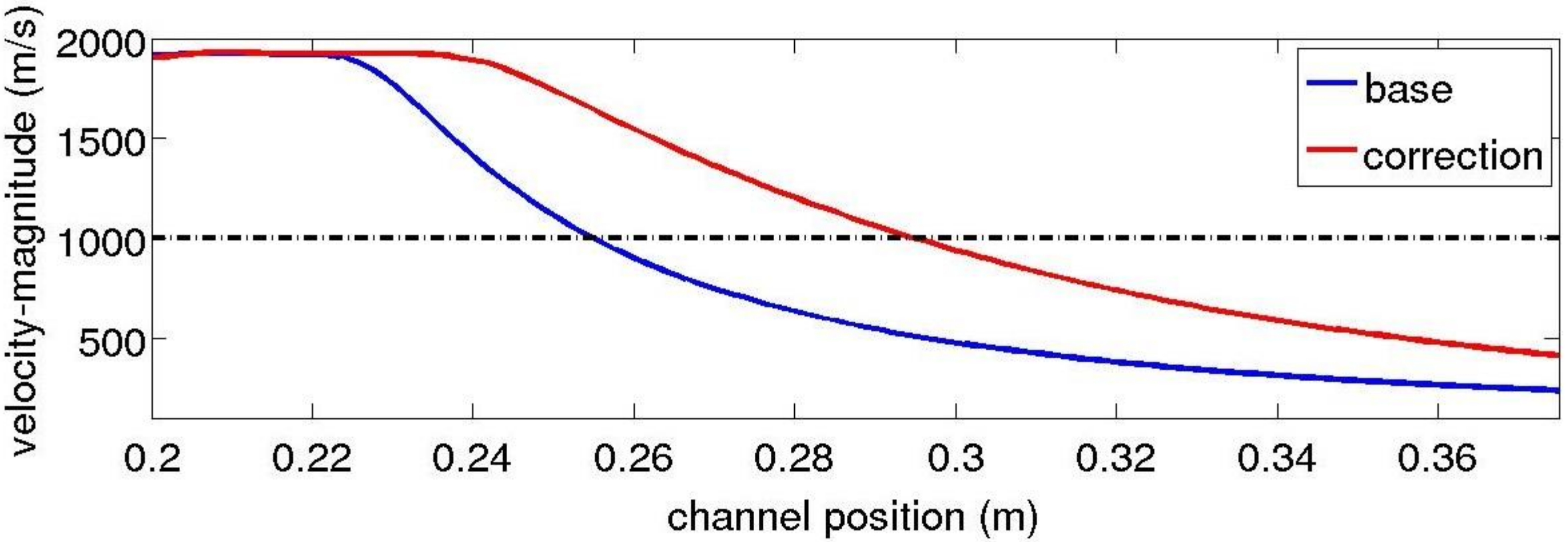
k-ω-SST



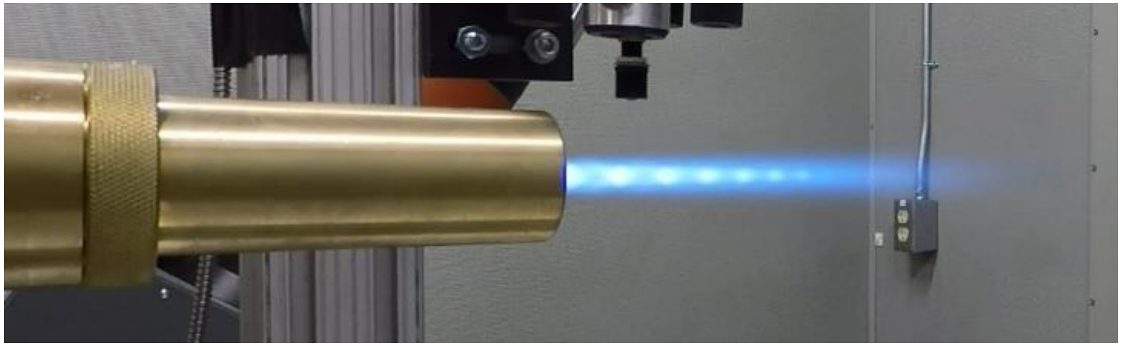
k-ω-SST compressibility correction



Velocity comparison at centerline



Turbulence models with compressibility correction



- Compressible turbulent kinetic energy equation with compressibility correction for shear layers
  - $\frac{\partial \rho k}{\partial t} + \frac{\partial \rho U_i k}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + \rho P_k - \rho(\varepsilon + \varepsilon_c) + \overline{p"d"}$
- Turbulent dissipation correction $\varepsilon_c = f(M_t)\varepsilon$ with $M_t = \sqrt{2k/\gamma RT}$
  - ***Sarkar*** $f(M_t) = 0.5M_t^2$
  - ***Zeman*** $f(M_t) = 0.75\left(1 - e^{-((M_t-0.1)/0.6)^2}\right)H(M_t - 0.1)$
  - ***Wilcox*** $f(M_t) = 1.5(M_t^2 - 0.25^2)H(M_t - 0.25)$
- Pressure dilatation with recommended constant values
  - $\overline{p"d"} = -\alpha_2 \rho P_k M_t^2 + \alpha_3 \rho \varepsilon M_t^2$ where $\alpha_1 = 1.0,\ \alpha_2 = 0.4,\ \alpha_3 = 0.2$

R. H. Nichols, Turbulence Models and Their Application to Complex Flows, Revision 4.01
D. Guézengar et al., Variations on a k-ε turbulence model for supersonic boundary layer computation, 1999

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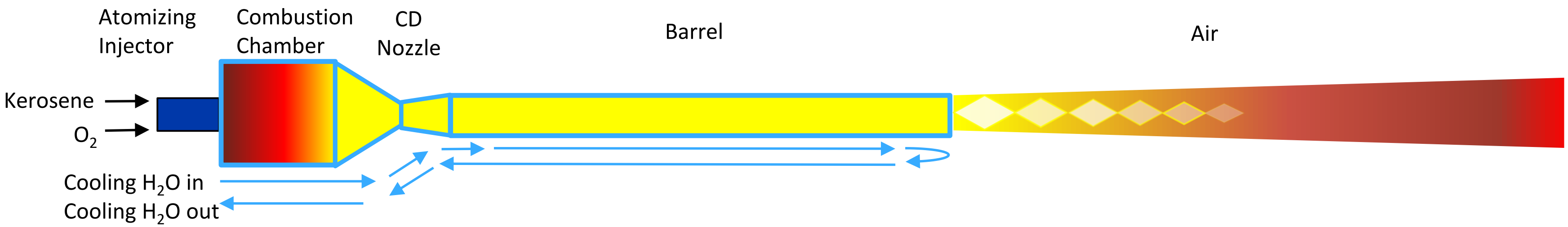
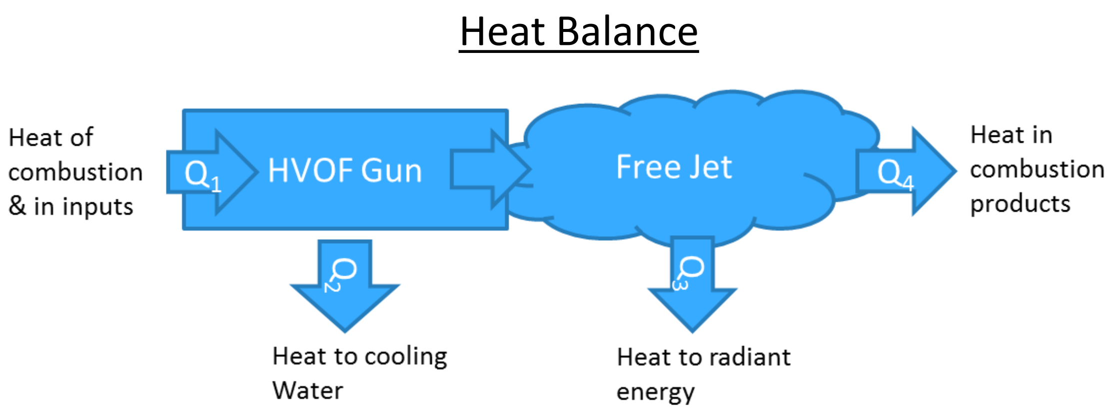
Heat Balance: Measurements





- **Q1: From Inputs: T, P, mdot + off-line HHV test on fuel**
- **Q2: From cooling water: mdot*C_p*dT where dT = T_{out}-T_{in}**
- **Q3: Use a Total Radiometer**
- **Q4: From the balance**

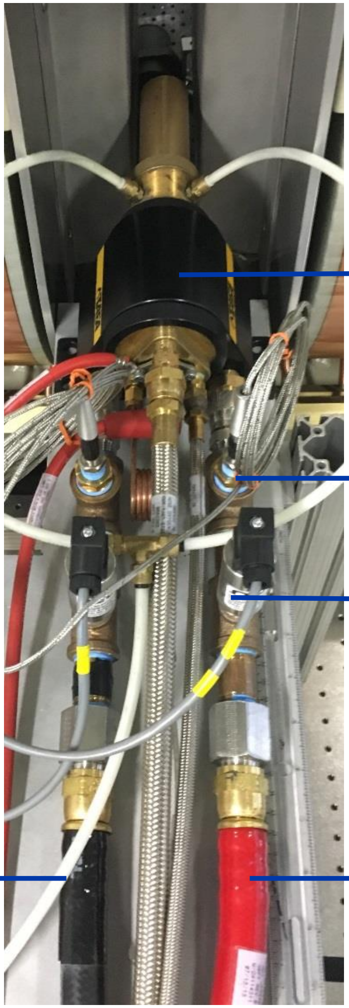
Wall heat loss methodology

- Water volume flow, temperature, and pressure are measured
- Temperature and water flow used to measure thermal power absorbed by water

$$Q_{Therm,Water} = \Delta T \cdot \dot{\mathrm{m}} \cdot C_p$$

- Surface area (SA) inside the combustor, C/D nozzle, and barrel measured
- Heat flux is computed from power transfer into water across all internal SA

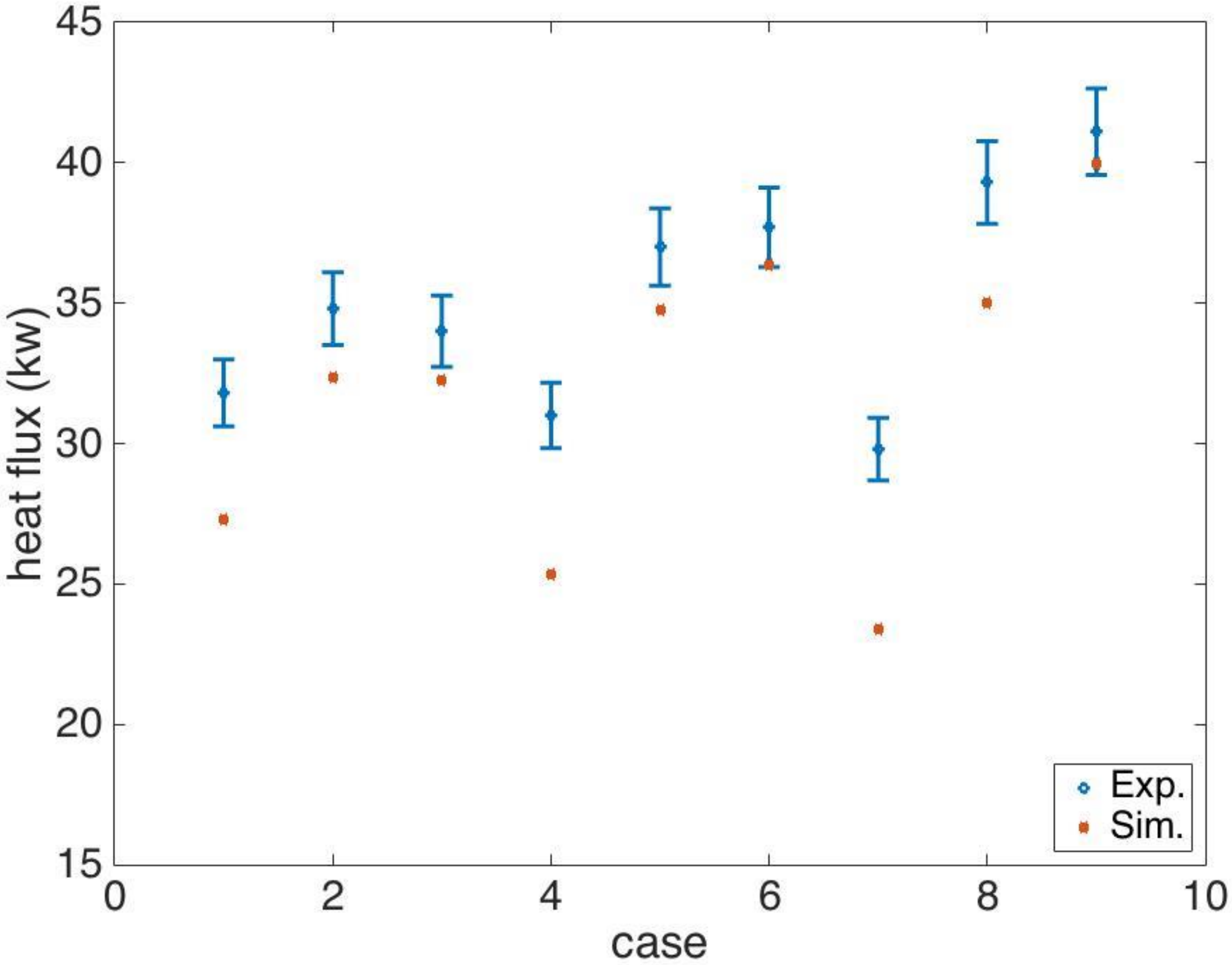
- Uncertainties:
  - TC differential 3.5%
  - flow meter 1%
  - Cp_water 1%



Heat Flux Distribution (kW)

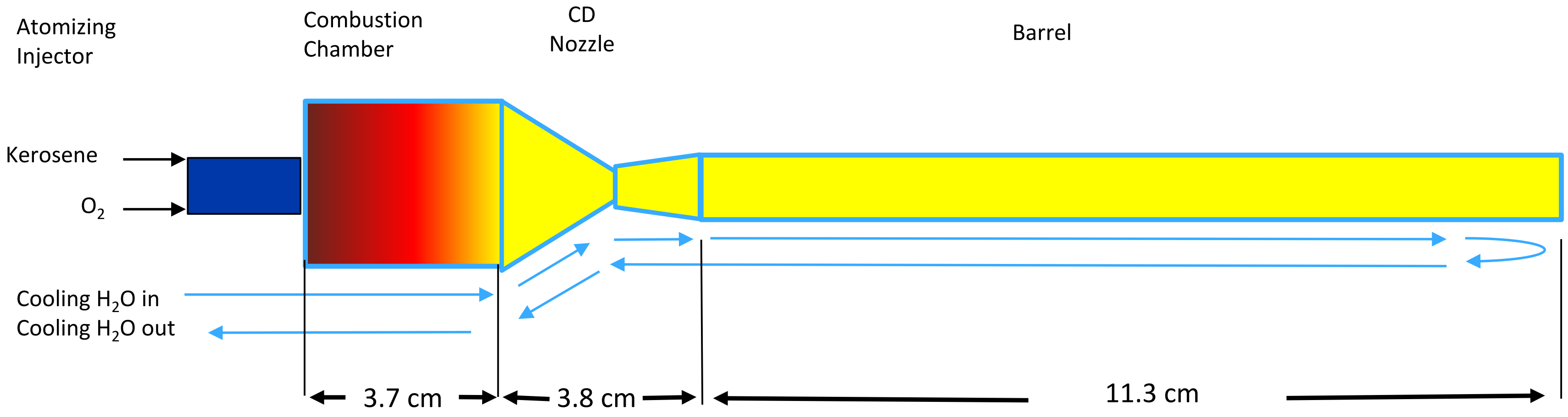
Case	Combustor	Nozzle	Barrel	Slice total	Total	Experiment
1	0.016	0.103	0.259	0.379	27.29	31.8
2	0.018	0.127	0.304	0.449	32.33	34.8
3	0.016	0.139	0.293	0.448	32.26	34.0
4	0.016	0.096	0.240	0.352	25.34	31.0
5	0.019	0.131	0.333	0.483	34.78	37.0
6	0.018	0.147	0.340	0.505	36.36	37.7
7	0.014	0.091	0.220	0.325	23.40	29.8
8	0.020	0.131	0.335	0.486	34.99	39.3
9	0.019	0.163	0.373	0.555	39.96	41.1

Heat Flux Comparison



- T_{wall} ~ 340K
- T_{inlet} ~ 400K
- Simulation didn't include
  1. Phase change of liquid fuel
  2. Injection kinetic energy of liquid fuel and gas oxygen

Wall temperature estimate



Surface area $\approx (3.811cm)\pi(3.703cm) + (2\text{cm})\pi(14cm) = 1.323 \times 10^{-2} m^2$

Total heat flux experiment $\approx 40 \times 10^3 W$

$$\dot{q} \approx \frac{total\ heat\ flux}{total\ surface\ area} = \frac{40 \times 10^3 W}{1.323 \times 10^{-2} m^2} = 3.023 \times 10^6 W/m^2$$

$$3.023 \times 10^6 W/m^2 \approx \dot{q} = \frac{k(T_{w,g} - T_{w,c})}{t_w} \approx \frac{(400\,W/mK)(T_{w,g} - 300K)}{0.005m}$$

$$T_{W,g} \approx 337.79\ K$$

Heat flux sensitivity with T_{wall}

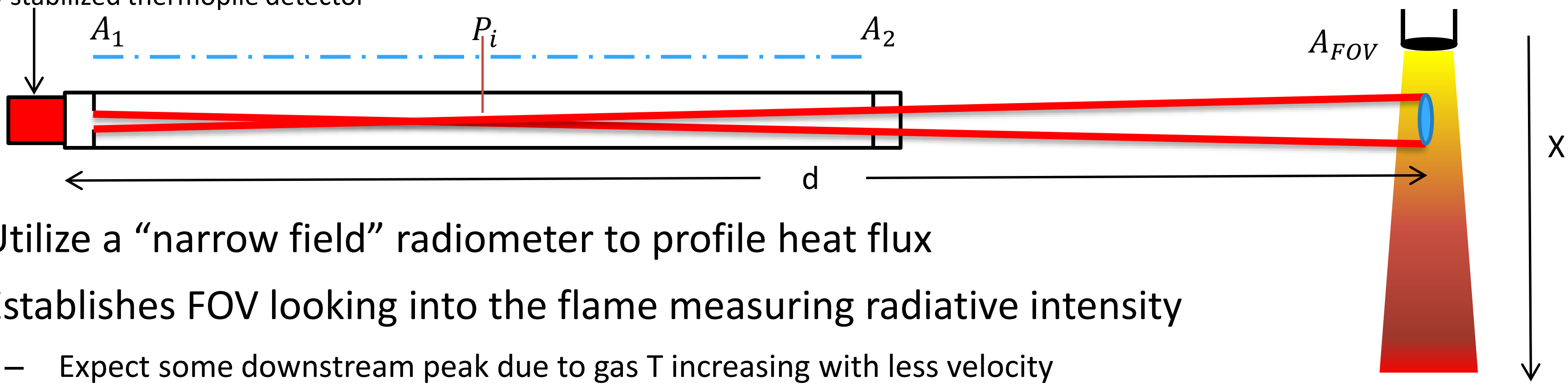
Combustion with T_inlet = 400K and T_wall variation

T_wall	Combustor	Nozzle	Barrel	Slice total	Total (kW)
340K	0.021	0.133	0.333	0.487	35.06
320K	0.053	0.131	0.316	0.500	36.00
300K	0.047	0.134	0.337	0.518	37.30

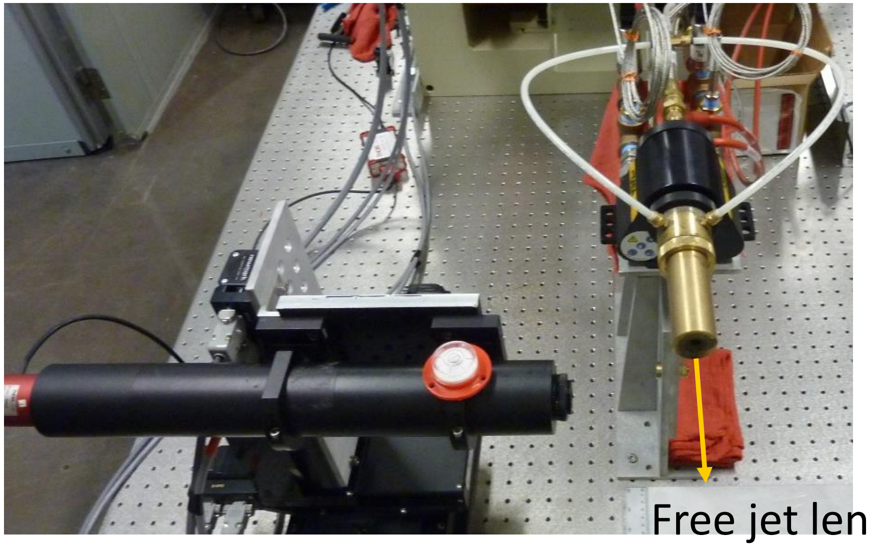
Combustion with T_inlet variation and T_wall = 340K

T_inlet	Combustor	Nozzle	Barrel	Slice total	Total (kW)
400K	0.021	0.133	0.333	0.487	35.06
350K	0.047	0.096	0.320	0.463	33.34
300K	0.046	0.083	0.316	0.445	32.04

Radiant Flux Measurement methodology



- Utilize a "narrow field" radiometer to profile heat flux
- Establishes FOV looking into the flame measuring radiative intensity
  - Expect some downstream peak due to gas T increasing with less velocity
  - Expect radiance to taper off when ambient air is entrained into exhaust plume



Free jet length

Two aperture narrow field radiometer

$$\Phi = \frac{L_S \cdot A_1 \cdot A_2}{d^2} \quad [Watts]^*$$

Extended source radiance, L_s

$$L_s = \frac{A_1 \cdot A_2}{\Phi \cdot d^2} \quad \left[\frac{Watts}{m^2 \cdot sr}\right]$$

* From Art of Radiometry by Palmer and Grant

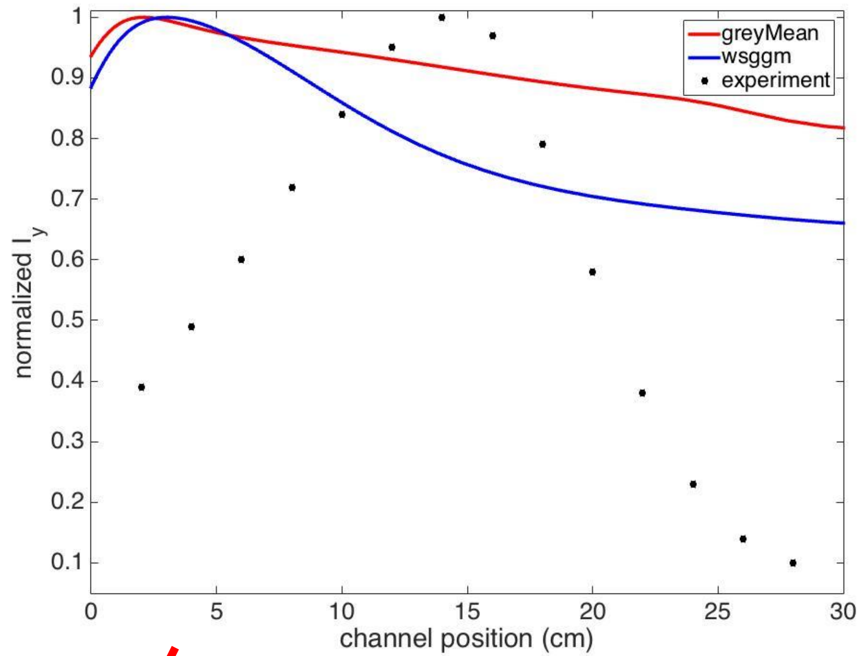
Radiant Flux Results – case 5.5 (Exp.) & 5 (Sim)

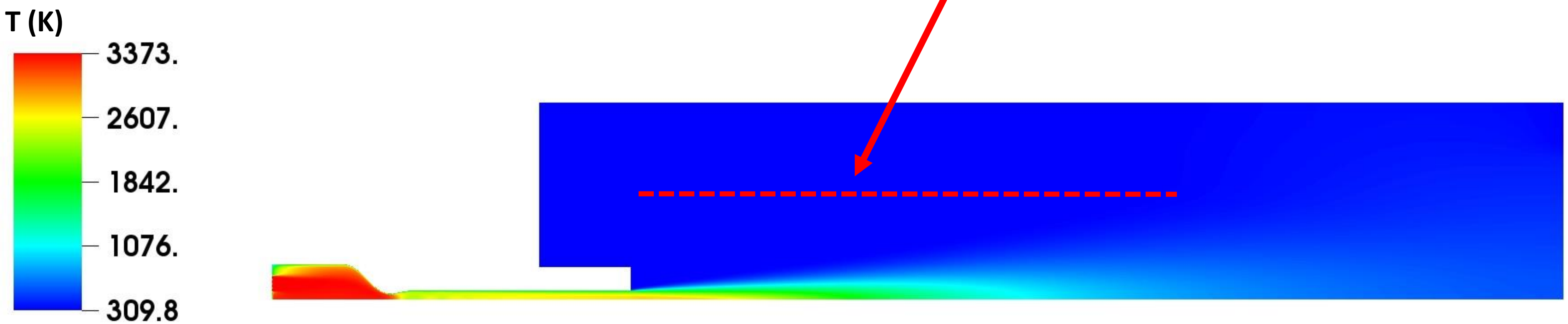
$$I(x, \hat{s}) = \frac{1}{4\pi}(G(x) + 3q_r \cdot \hat{s})$$

where $\hat{s}$ - propagation direction
x - position vector
q_r - radiant energy flux

$$q_r = \frac{1}{3(a + \sigma)} \nabla G$$

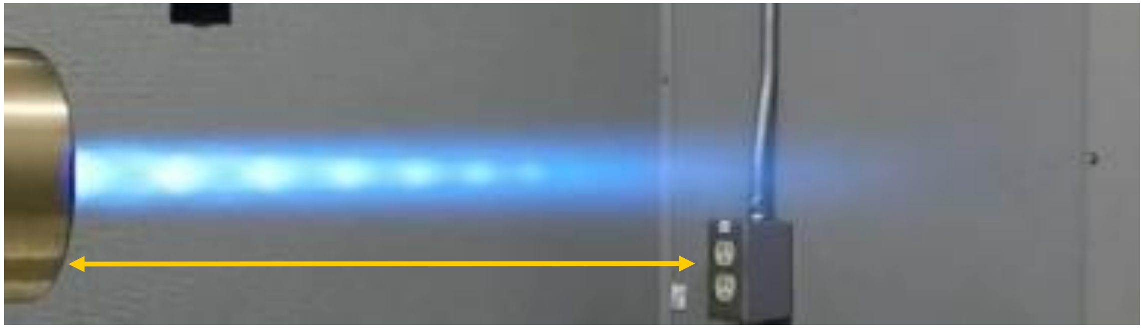
where a (1/m) - absorption coeff.
σ (1/m) - scattering coeff.





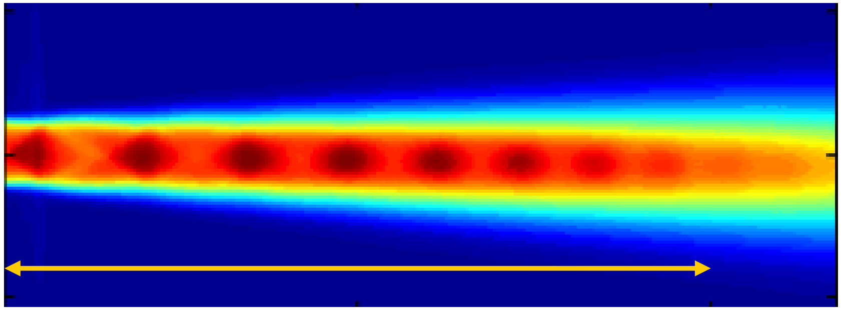
Shock Chain at Exhaust (1)

Experiment HD Camera

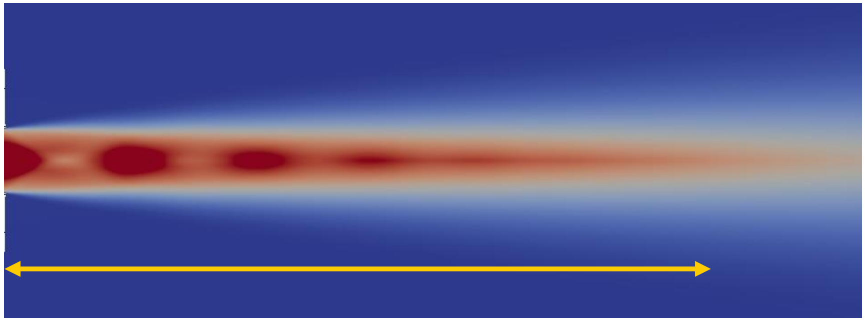


100 mm

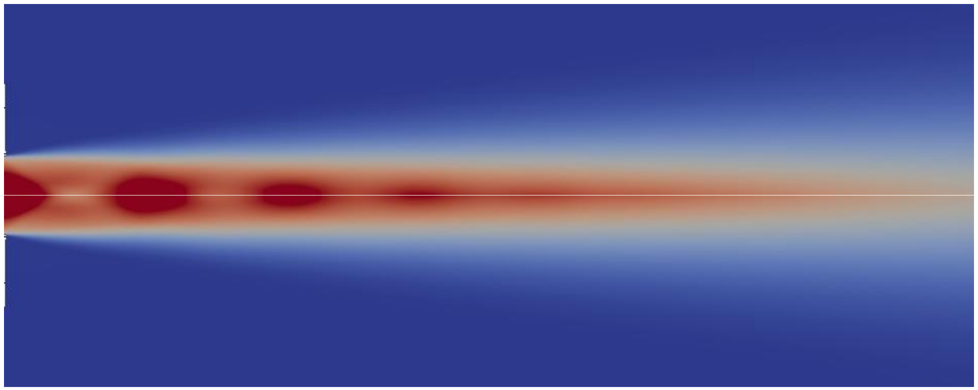
Experiment
IR (infrared) image (P, T, CO2, …)



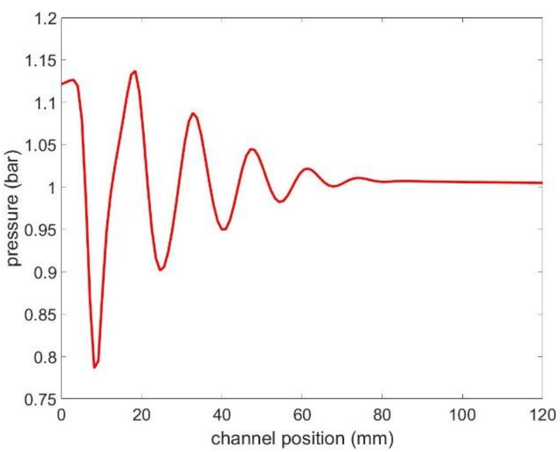
Simulation
ρPTM

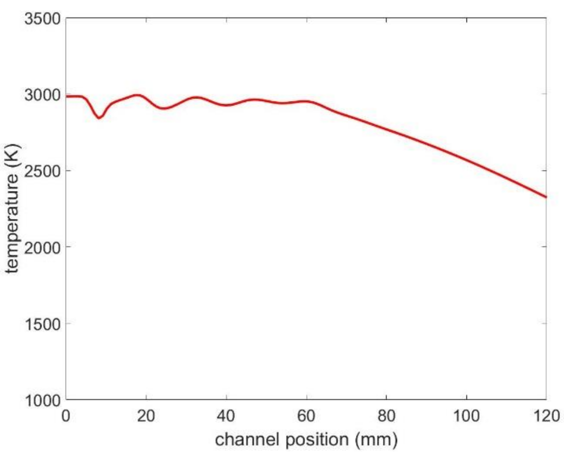


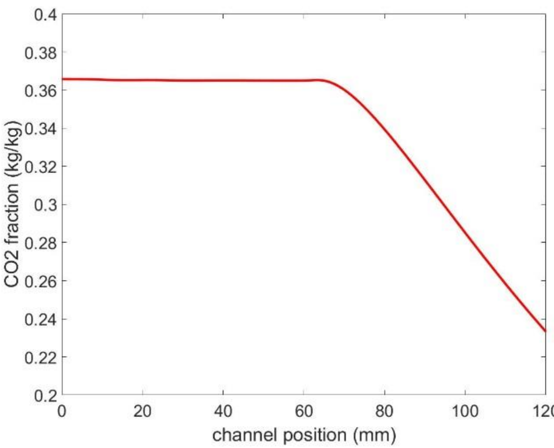
Shock Chain at Exhaust (2)



- P, T, CO2 variation along centerline
- These values will be used in post-processing to mimic IR image.







Conclusions and Future Work

- **MHD Power generation Laboratory is operational**
  - Several datasets have been produced of the HVOF oxy-fuel combustor
- **Completed an initial comparisons of model with experimental data**
  - Simulation over-predict the dissipation of the exhaust waves
  - Prediction of the spreading rate appear to be much better radiation predictions
- **In the Future,**
  - More quantitative comparison of predictions and measurements
    - Further analysis and processing of experimental data
    - Improvements to computational model
  - Add "MHD channel" to experiment and simulations

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- **Travis Haima, AECOM – MHD Lab technician**
- **Brian Lovich, ORISE Intern**

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Reference for picture on slide 4

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