UTSR 2022 Gas Turbine Industrial Fellowship Program

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Personal Background

UTSR
University Turbine Systems Research

About me:

- Fynn Reinbacher
- **PhD Student ME**
  (Iowa State University, Ames IA)
  Detonations, laser diagnostics, plasma assisted combustion
- **M.Sc. AerE 2018**
  (Iowa State University, Ames IA)
- **B.Sc. ME 2016**
  (RWTH Aachen University, Aachen Germany)

UTSR Summer Fellow:

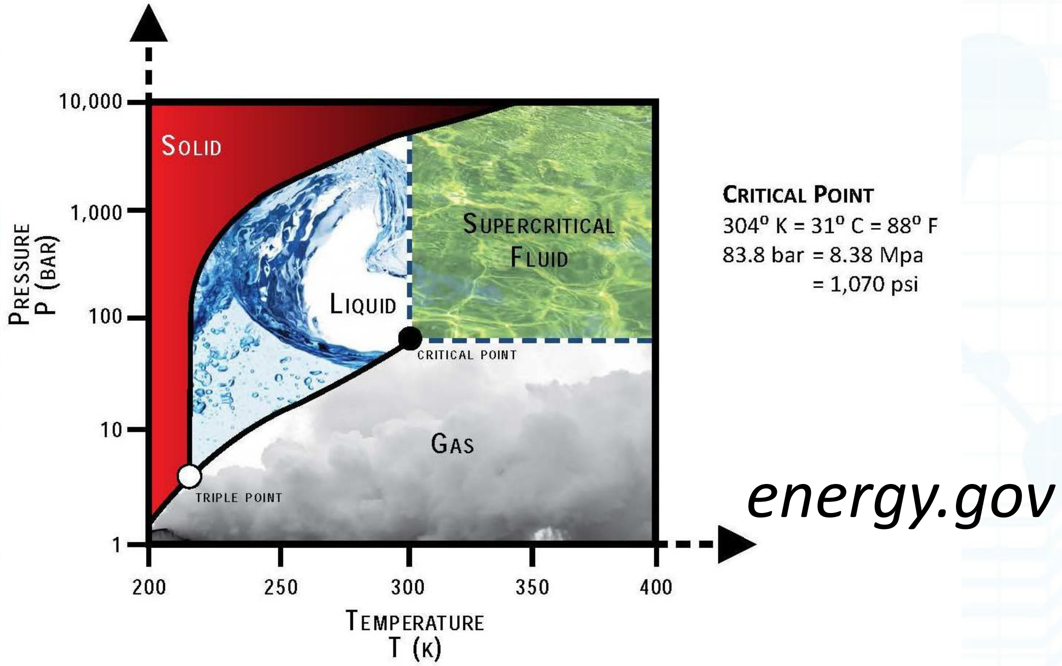
- Hosted by:
  Southwest Research Institute
  (San Antonio, TX)
- Division 18 Mechanical Engineering,
  Machinery Department, Propulsion & Energy Machinery Group

Summer Fellowship Overview

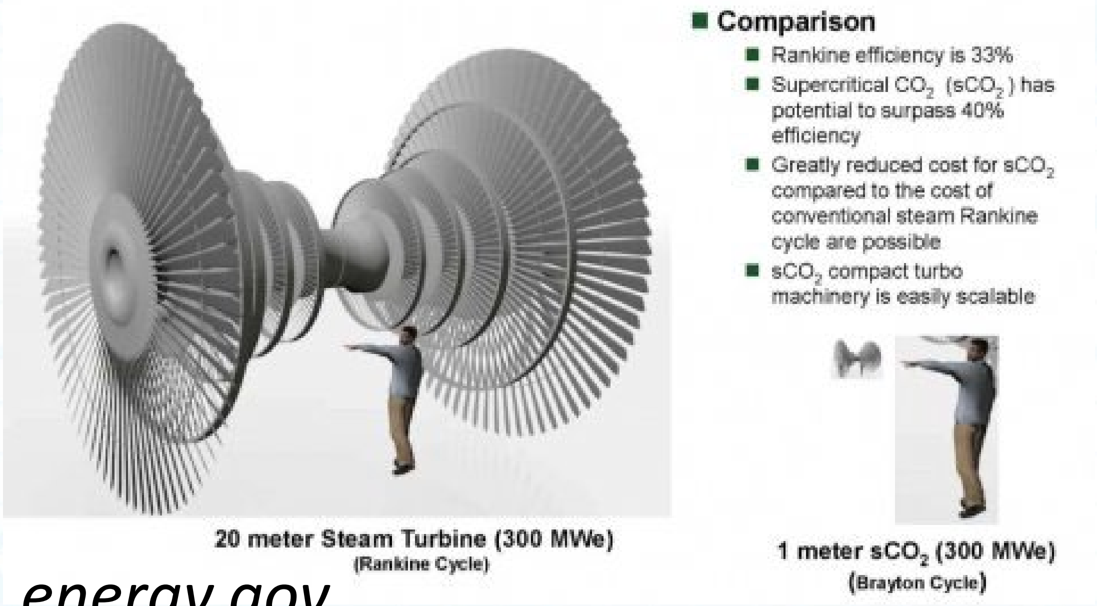
- Background:
  - sCO_2 Power Cycles
  - Allam-Fetvedt Cycle
  - sCO_2 Oxy Fuel Combustion
- Work at SwRI:
  - Benchtop Oxy-Fuel Combustor
  - Laser Spark Ignition for Oxy-Fuel combustion
  - Misc. other projects

Background: sCO_2 power cycles

- sCO_2 as working fluid: "*dense like a liquid, behaves like a gas*"
- Non-toxic, non-flammable
- Smaller, higher efficiency turbines



energy.gov



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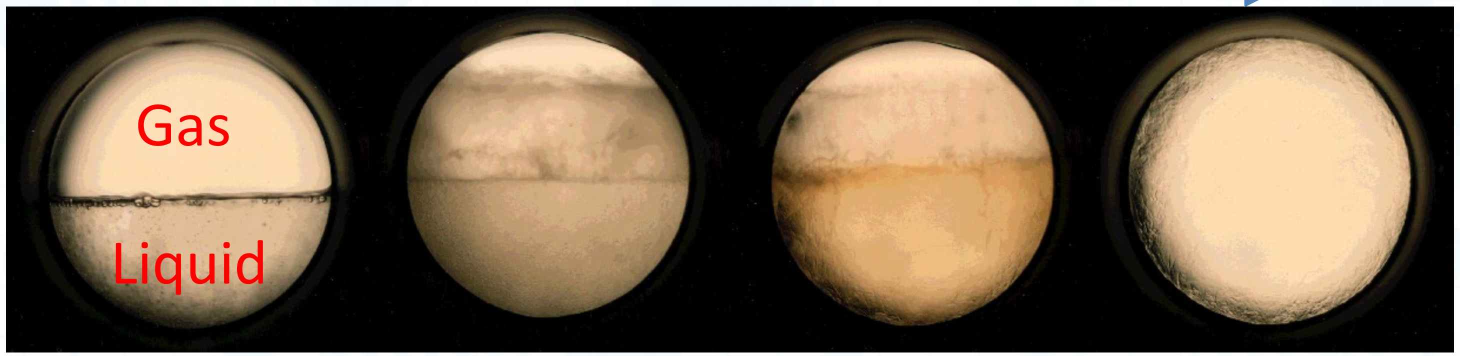
Increase T and p to $T > T_{crit}$ & $p > p_{crit}$

Supercritical fluid



Modified from [1]

Allam-Fetvedt Cycle

- Direct fired sCO_2 Power cycle
  - Oxy-Fuel combustion
- Numerous advantages
  - No N_2 = no NO_x
  - Direct sequestration of liquid CO_2
  - …

<u>However:</u>

- sCO_2 challenging medium to work with
- Combustion environment largely unknown

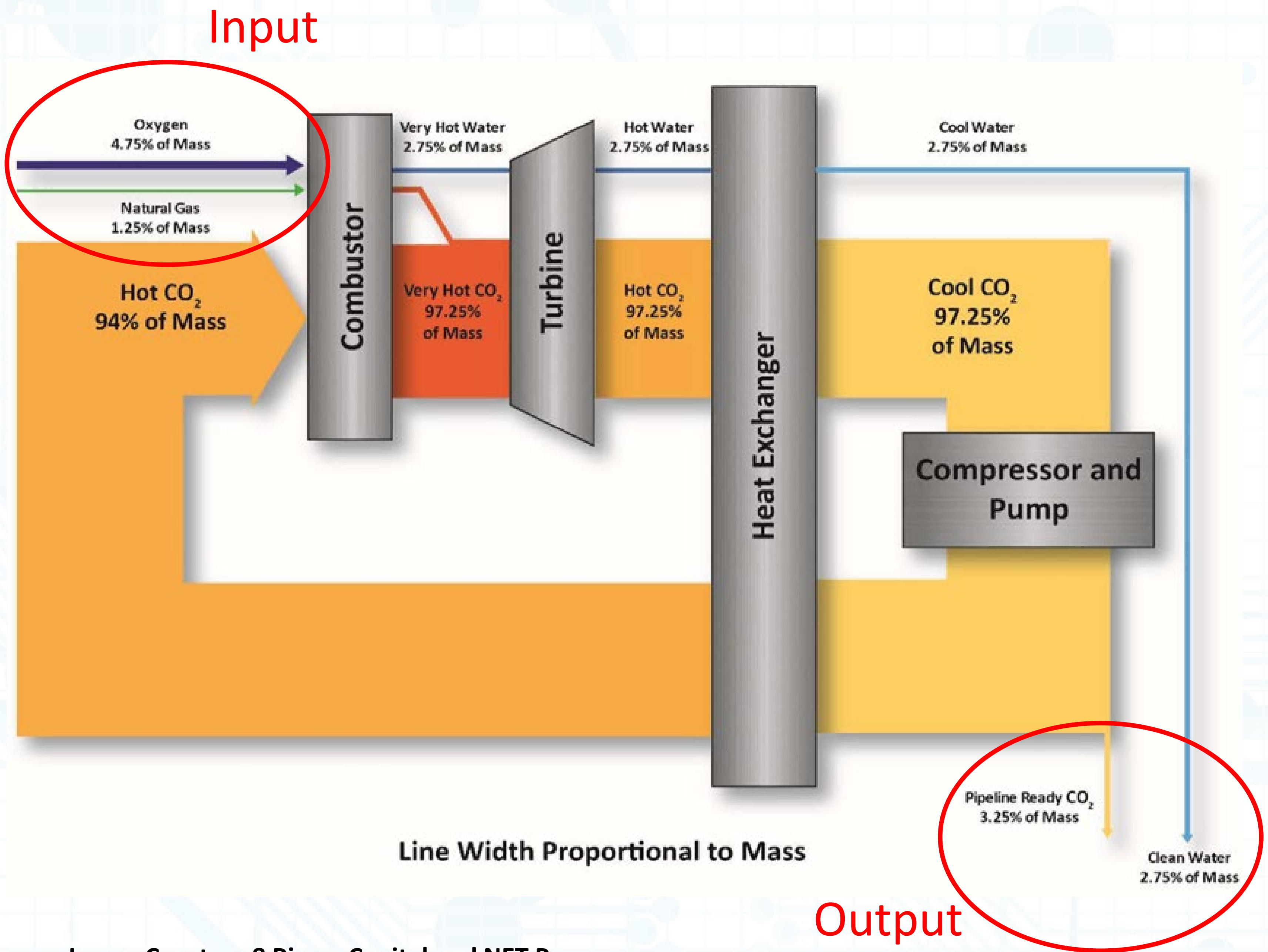
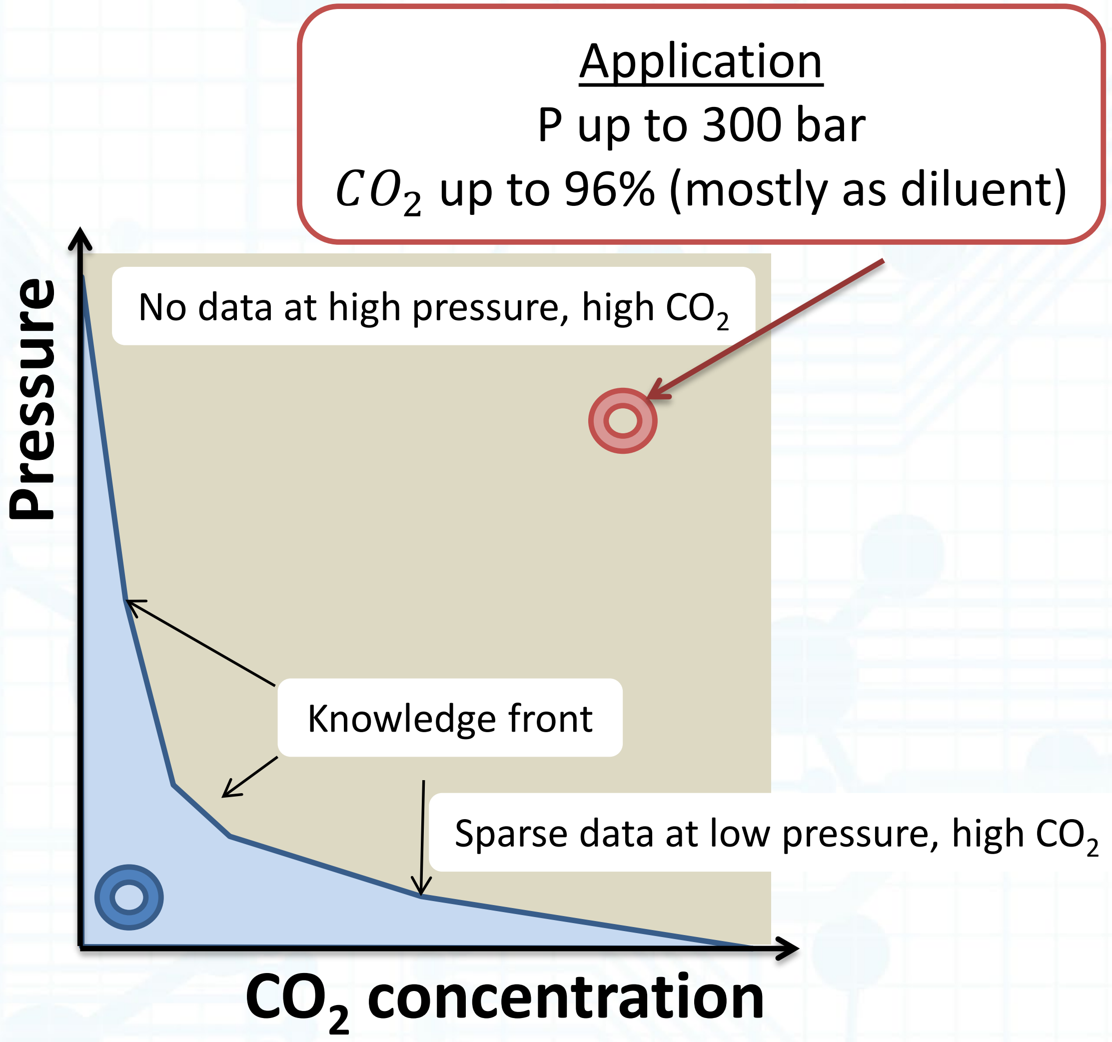


Image Courtesy 8 Rivers Capital and NET Power

sCO_2 Oxy Fuel Combustion

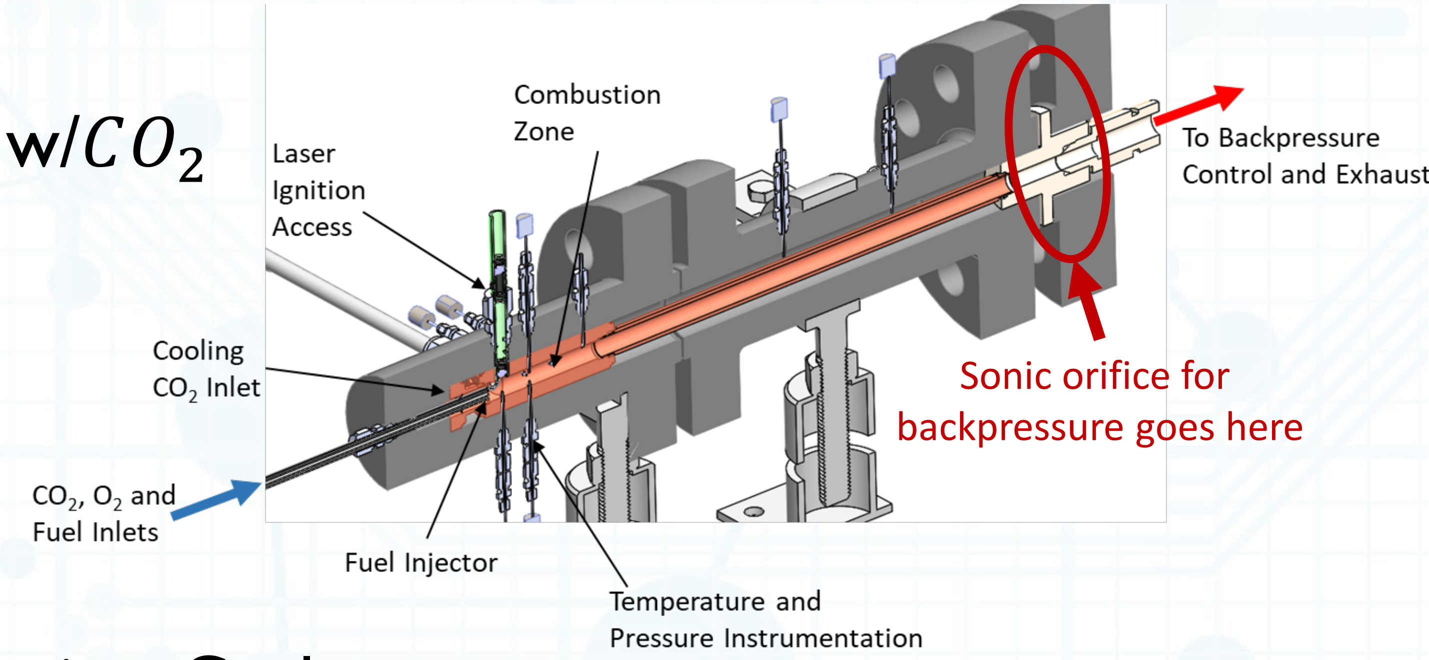
- Sparse data on sCO_2 relevant combustion conditions
  (Most combustion systems use air-like mixtures ~20% O_2 and ~80% N_2)
  - Hard to make predictions based on computational models w/o experimental control data
- High pressure literature "$25 - 50\ bar$"
  - Here: $100 - 300\ bar$ ($p_{crit} = 83.8\ bar$)
- Data necessary to predict flame speed, temperature, ignition limits

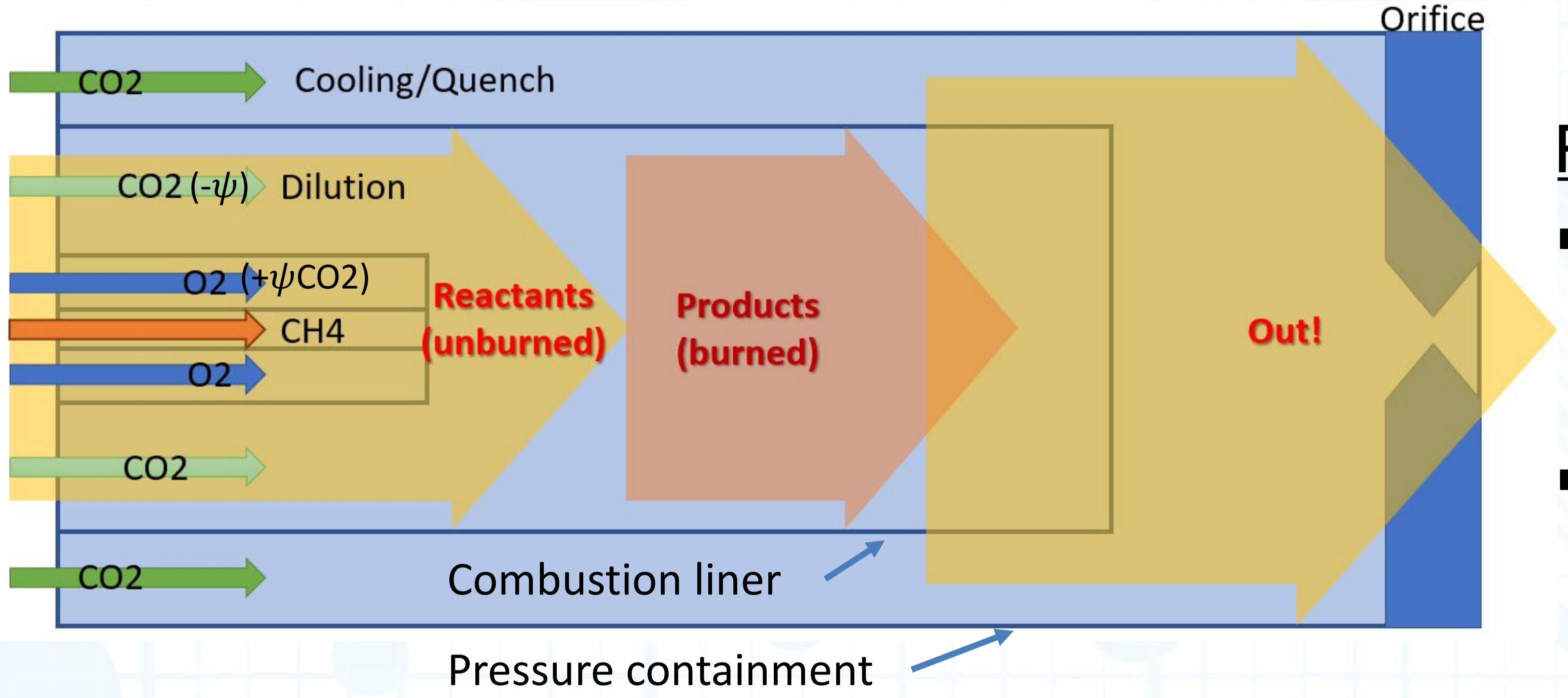


SwRI Benchtop Oxy-Fuel Combustor

Project Overview:

- Coax natural gas – oxygen combustor, cooled w/CO_2
- Challenges:
  Ignition, flame holding, pressure regulation





Project Goals:

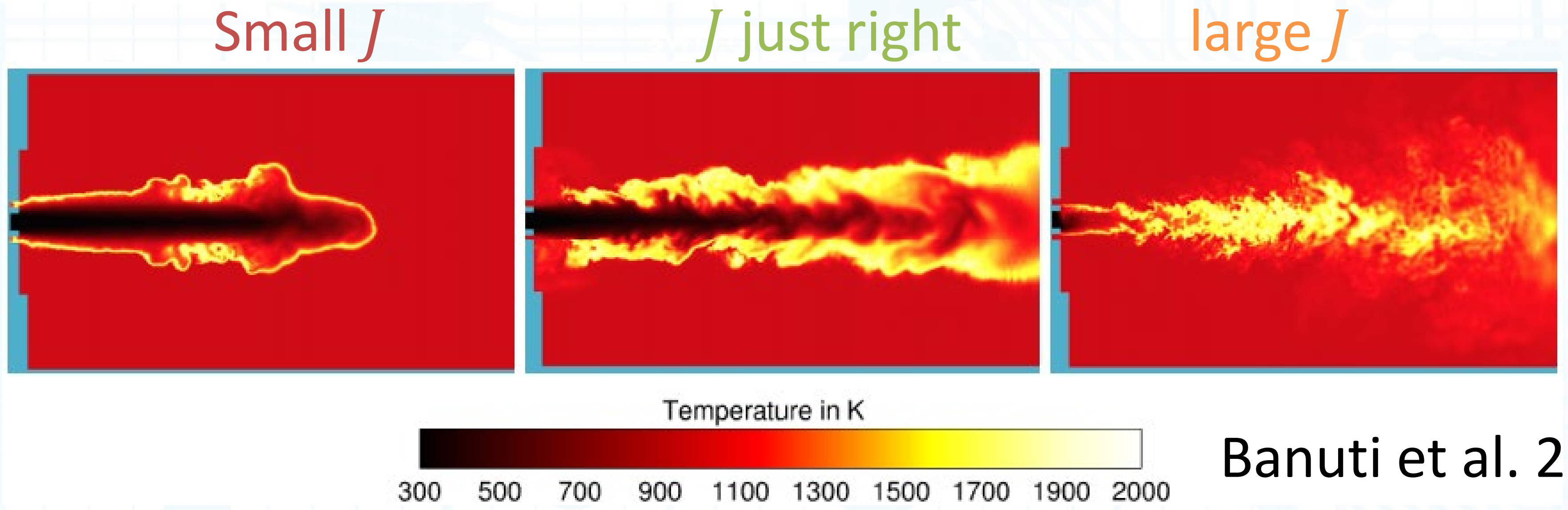
- Explore combustion/operating conditions of direct fired sCO_2 oxy-fuel combustion
  "Fill knowledge gap at high p and $\%CO_2$"
- Technology test bed for larger combustor (e.g. emission probe, stable flame regimes)

Benchtop Oxy-Fuel

- Momentum flux ratio $J_{in/out} = \frac{\dot{m}_{in} v_{in}^2}{\dot{m}_{out} v_{out}^2}$
  - J too small: insufficient mixing
  - J too large: high-strain causes blowout
  - J just right: stable flame

Driven by Geometry:
$\dot{m} = \rho v A$

- How does J change with operating conditions?
- How sensitive is J to external perturbations?



Banuti et al. 2018

Impact of governing parameters on J

- Global equivalence ratio ϕ
  - Flow rates fuel & oxidizer
- Global oxygen fraction Y_{O2}
- Pre dilution of oxidizer stream with CO_2 ψ

$$J_{f/ox} = c_{f/ox} \left(\frac{\dot{m}_f}{\dot{m}_{O2}}\right)^2 \left(\frac{1}{1+\psi\frac{\dot{m}_{CO2}}{\dot{m}_{O2}}}\right)^2$$

$$J_{ox/cool} = c_{ox/cool} \left[\left(\frac{\dot{m}_{O2}}{\dot{m}_{CO2}}\right)^2 \left(\frac{1}{1-\psi}\right)^2 + \left(\frac{\psi}{1-\psi}\right)^2\right]$$

$c_{i/o}$: constants determined by geometry and fluids

$\frac{\dot{m}_f}{\dot{m}_{O2}} \sim \phi$ equivalence ratio enters with a power of 2 into $J_{f/ox}$

$J_{f/ox}$ is directly proportional to stoichiometry.
Leaner = lower!

$$\frac{\dot{m}_{CO2}}{\dot{m}_{O2}} \sim Y_{O2}$$

$J_{f/ox}$ change due to ψ is limited in scope by global O2 fraction

$J_{ox/cool}$ is directly proportional to Y_{O2} for small ψ

ψ:

$J_{f/ox}$ decreases for increasing ψ (variation is larger for smaller global O_2 fraction)

$J_{ox/cool}$ increases for increasing ψ is directly proportional to Y_{O2} for small ψ.

While $J_{f/ox}$ varies between limits, this will go to $\lim_{\psi \to 1} J_{ox/cool} = \infty$.

Think no co-flow, into still surroundings.

$$\left|\frac{\partial J_{f/ox}}{\partial \psi}\right| \ll \left|\frac{\partial J_{ox/cool}}{\partial \psi}\right|$$

Benchtop Oxy-Fuel Contributions

- Evaluation of conceptual design
- Sensitivity to operating conditions
- Orifice sizing
- 0D reactor model
- Start-Up conditions
- Python toolkit for real-gas flow conditions
  and evaluation of combustor operating conditions

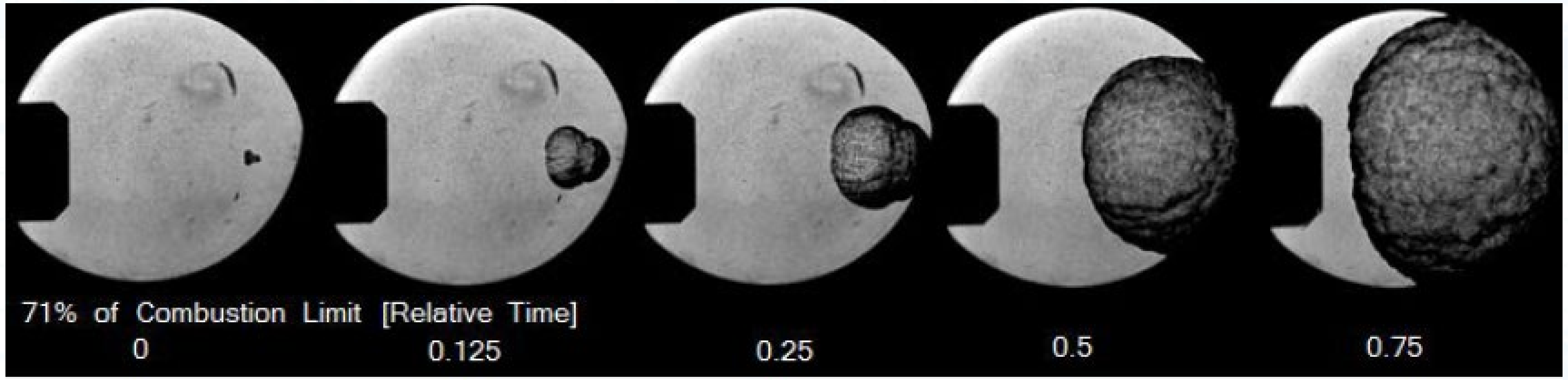
Laser Spark Ignition

- High power laser pulse creates "Laser spark"
- Advantages:
  - Non intrusive
  - Easier sealing
- Challenges:
  - Optical access to combustor
  - Focal length in sCO_2

Katcher et al. 2019

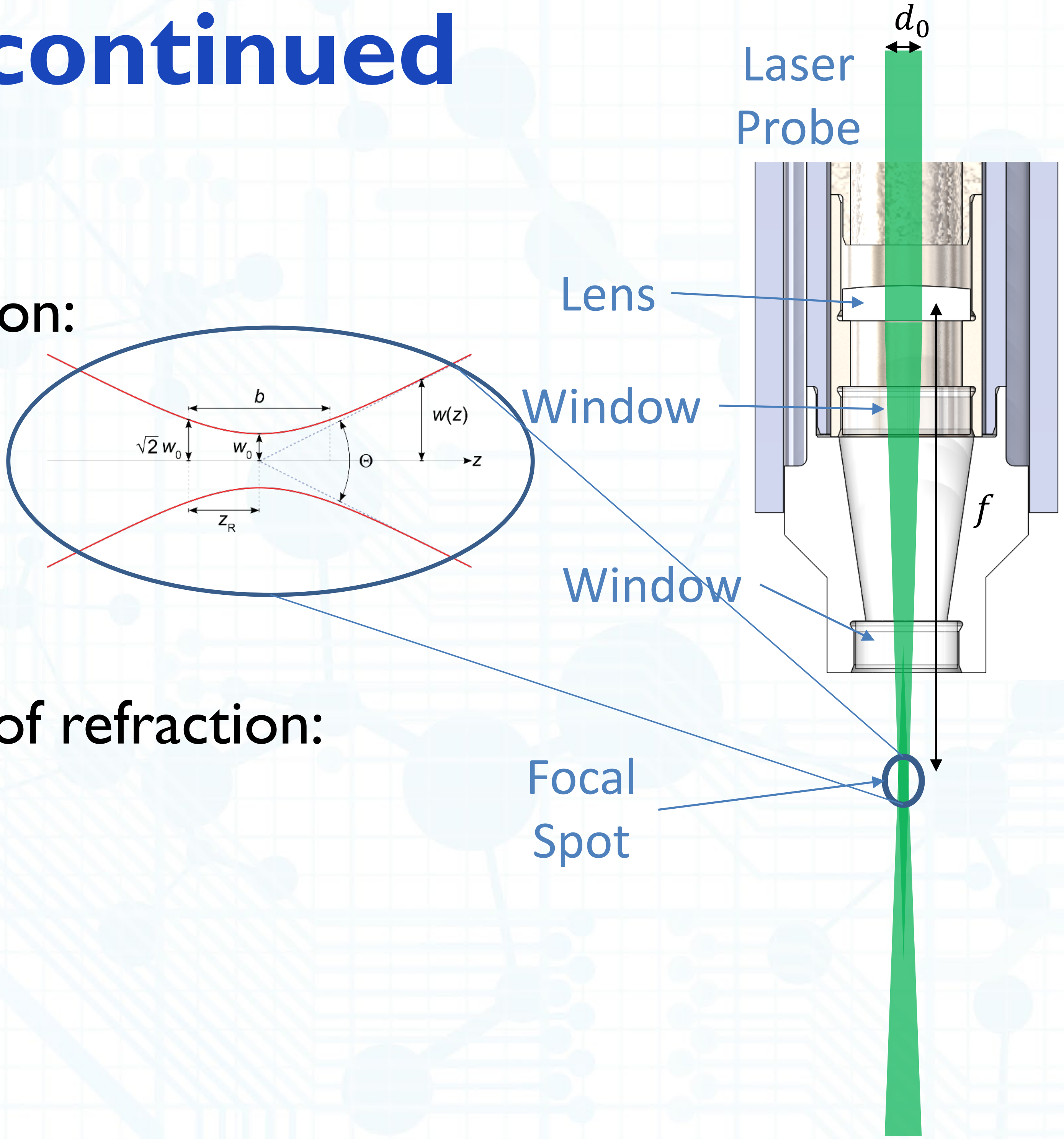
Figure 13. Laser-Induced Breakdown in Supercritical CO_2 at Varying Energy Levels

Katcher et al. 2019



Laser Spark Ignition continued

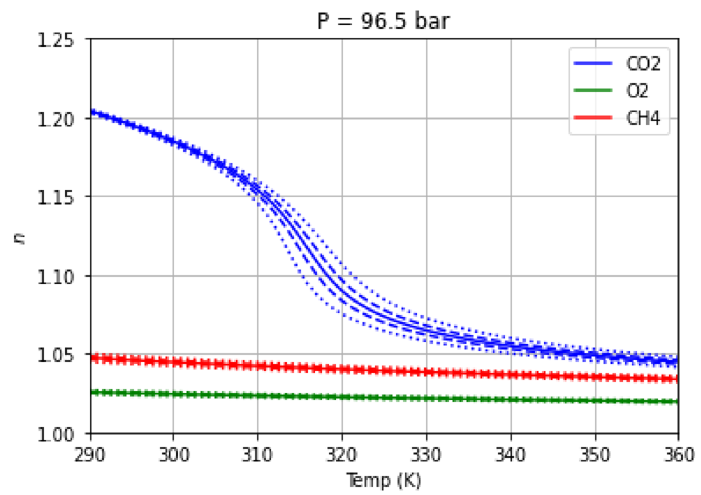
- Challenges:
  - Laser spark intensity dependent on: d_0, λ, f, n
    - Smaller f $\rightarrow$ higher Intensity
    - Larger n $\rightarrow$ larger f
  - Focal length f affected by index of refraction:
    $n_{air} = 1$ no Problem!
    n_{window} & $n_{sCO2} > 1.0$

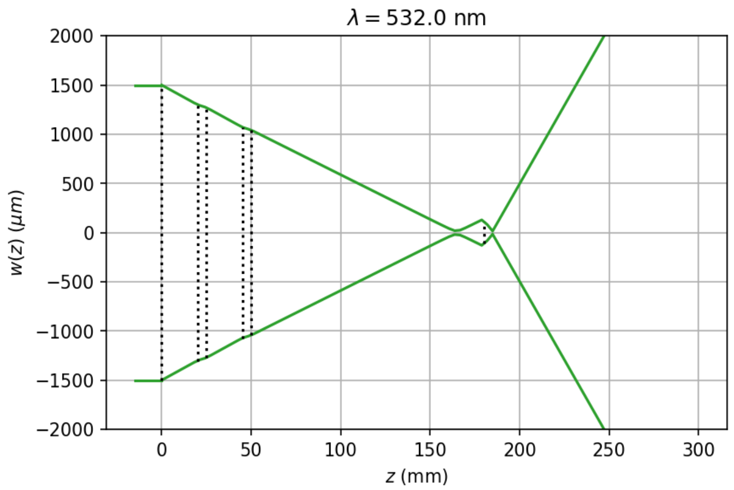


Laser Spark Ignition Contributions

Contributions:

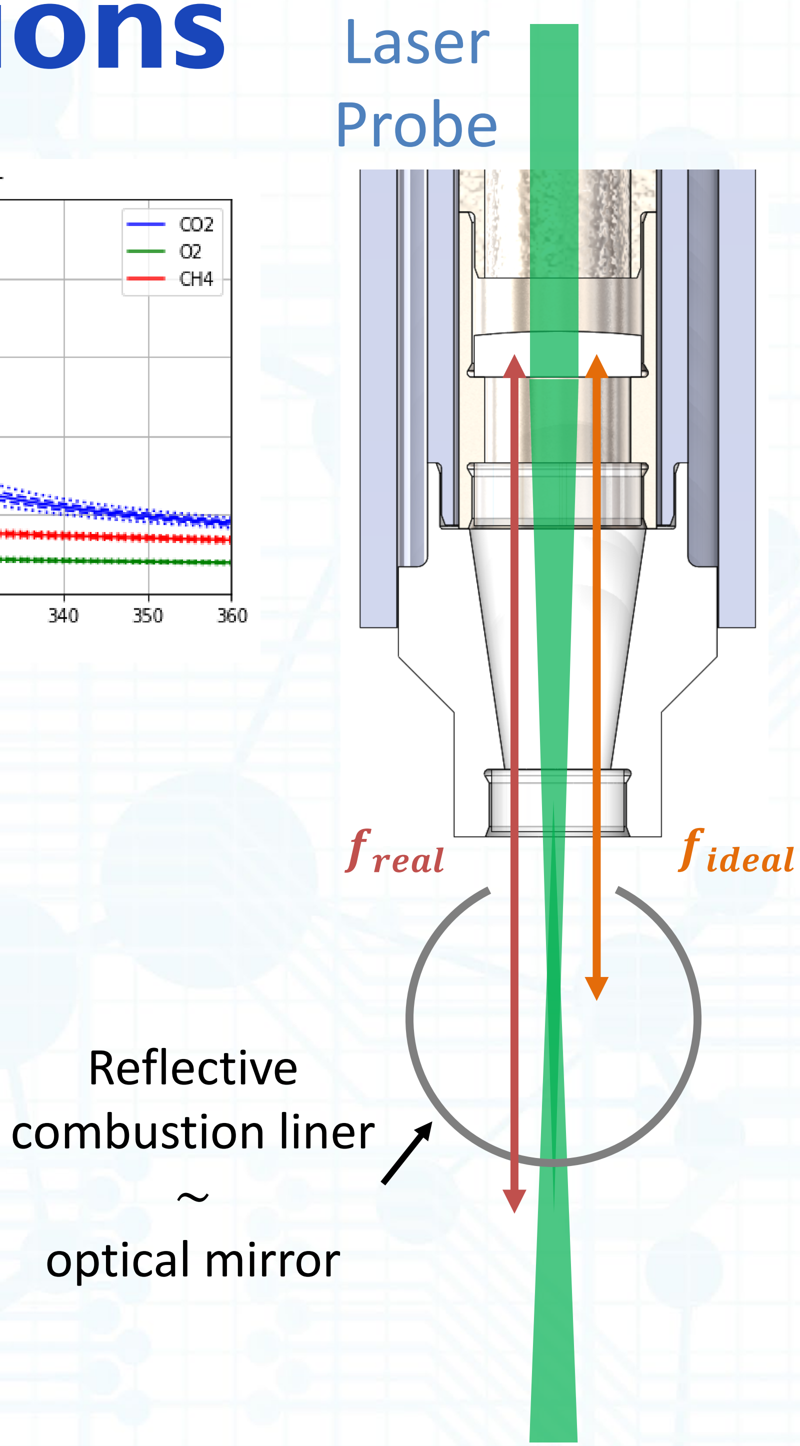
- Identify issues with Laser ignition system:
  - Focal length shift in sCO_2: 5-20%
  - Reflective backwall





- Build python toolkits:
  - Index of refraction of real gases
  - Gaussian beam propagation

→ Allows modeling of Laser ignition system



Contributions to misc. other projects

- Evaluated existing test infrastructure for chemical compatibility and identified necessary upgrades for future Ammonia combustion project
- Evaluated sensing options for future flameless combustion project
- Investigated light-off and start-up conditions for operation of Benchtop and 1MW oxy-fuel combustion projects

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