NASA MIRO Center for Space Exploration and Technology Research
The University of Texas at El Paso

Technology Demonstration of a High-Pressure Swirl Oxy-Coal Combustor

Award No: DE-FE0029113

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Associate Vice President and Director

Collaborator: Hwanho KIM
American Air Liquide

Oxy-Coal Combustor

- Grant No:
  - DE-FE-0029113
- Project Title:
  - Technology Demonstration of a High-Pressure Swirl Oxy-Coal Combustor
- Investigators:
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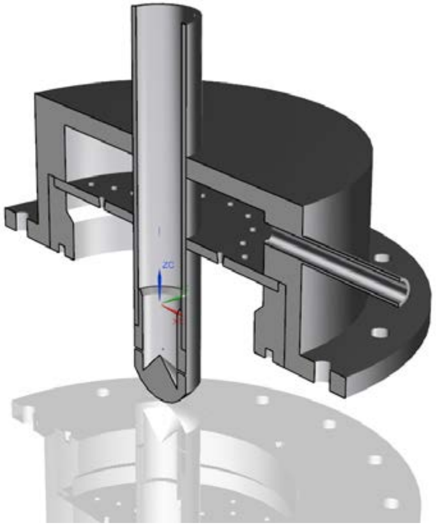
  The University of Texas at El Paso
  - Chendhil Periasamy
  American Air Liquide
- Project Period:
  - 10/01/2016 (01/01/2017)-09/30/2019 (12/31/2019)
- Project Manager:
  - Mark Freeman

Agenda

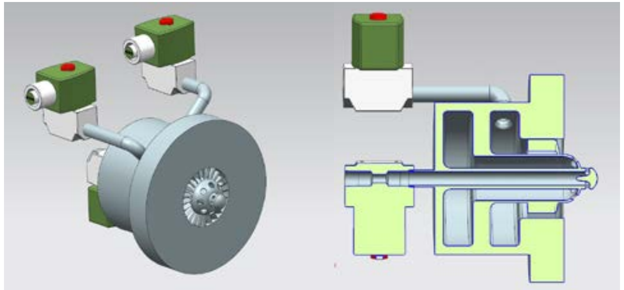
- Introduction and Background
- Objective and Timeline
- Cycle Analysis
- Combustor Design
- Secondary Burner & Ignitor
- Injector Design
- Injector Water Test
- Exhaust System Concept



Introduction & Background

Pressurized Oxy-Coal Combustion

- **Pressurized oxy-coal combustion systems**
  - Improve efficiency by recovering latent heat of the steam in the flue gas
  - Achieve 90% CO_2 capture [1]
  - Smaller system size and capital cost due to the reduction of flue gas at higher pressure
- **Swirl burners[2]**
  - Widely used combustion devices
  - Have superior flame holding
  - Higher conversion rate
  - Low pollutant emission characteristics



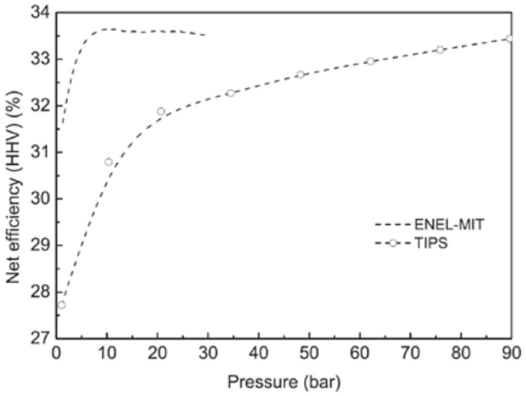
Concept design for pintle injector

cSETR swirl injector element using additive manufacturing

[1] Chen, L., Yong, S. Z., and Ghoniem, A. F. (2012) Oxy-Fuel Combustion of Pulverized Coal: Characterization, Fundamentals, Stabilization And CFD Modeling, Progress in Energy and Combustion Science, Vol. 38, pp. 156-214
[2] Warzecha, P. and Boguslawski, A. (2014) Simulations of pulverized coal oxy-combustion in swirl burner using RANS and LES methods, Fuel Processing Technology, Vol. 119, pp. 130-135.

Proposed Cycles

- **ThermoEnergy Integrated Power System (TIPS) Cycle [1,2]:**
  - Proposed and studied by CANMET and Babcock Power
  - Contain:
    - Flue Gas Condenser (FGC)
    - Radiative and convective heat exchangers
  - Suggested pressure with the benefit of latent heat recovery:
    - CANMET- **80 bar**
    - Babcock Power- 20.7 bar



- **ENEL Cycle [1,2]:**
  - Based on combustion process patented by ITEA and analyzed by MIT
  - No use of radiant heat exchanger
  - Most of the latent heat can be recovered at 11 bar

Source: [1] Chen, L., Yong, S. Z., & Ghoniem, A. F. (2012). Oxy-fuel combustion of pulverized coal: characterization, fundamentals, stabilization and CFD modeling. Progress in Energy and Combustion Science, 38(2), 156-214.
[2] Yang T, Hunt P, Lisauskas R, Ballas EN, Vitalis B. Pressurized Oxycombustion Carbon Capture Power System. In: The 35th international technical conference on clean coal & fuel systems. Clearwater, FL; 2010.

Objectives & Timeline

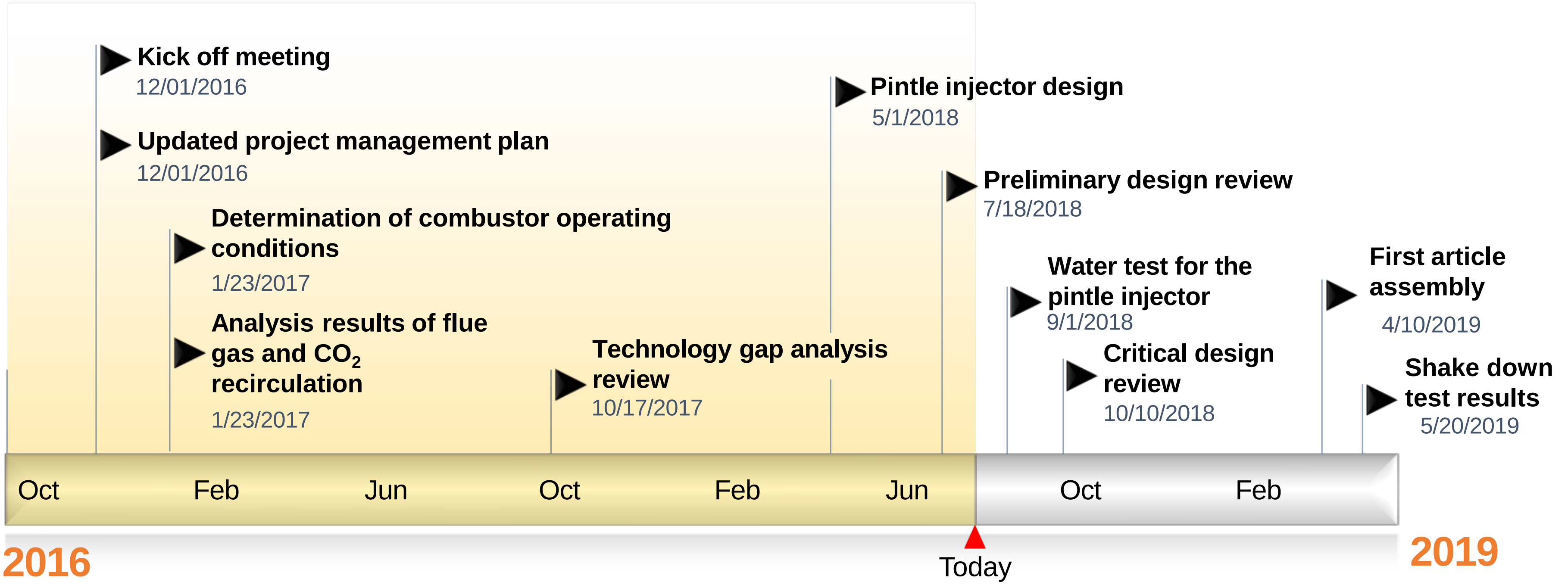
Objectives

- **Objective 1: Systems Configuration Analysis of a 1 MW_{th} Pressurized Oxy-Coal Swirl Combustor**
  - 550 MW_e TIPS and ENEL pressurized oxy-coal systems with CO2 recirculation modeled with ASPEN PLUS®

- **Objective 2: Design and Construction of a 1 MW_{th} Pressurized Oxy-Coal Swirl Combustor**
  - Detailed structural analysis
  - Flow and combustion optimizations
  - Manufacturing (conventional and advanced additive manufacturing)

- **Objective 3: Test of the Combustor Performance and Operability**
  - Flame stability analysis and flame temperature and heat flux measurements at range of pressure
  - Swirl number (ratio of axial flux of the angular momentum to the axial flux of axial momentum)
  - Flue gas analysis will be performed to produce fundamental combustion information
    - Effects of pressure
    - Swirl number
    - Stoichiometric ratio on burnout
    - Pollutant emissions

Timeline



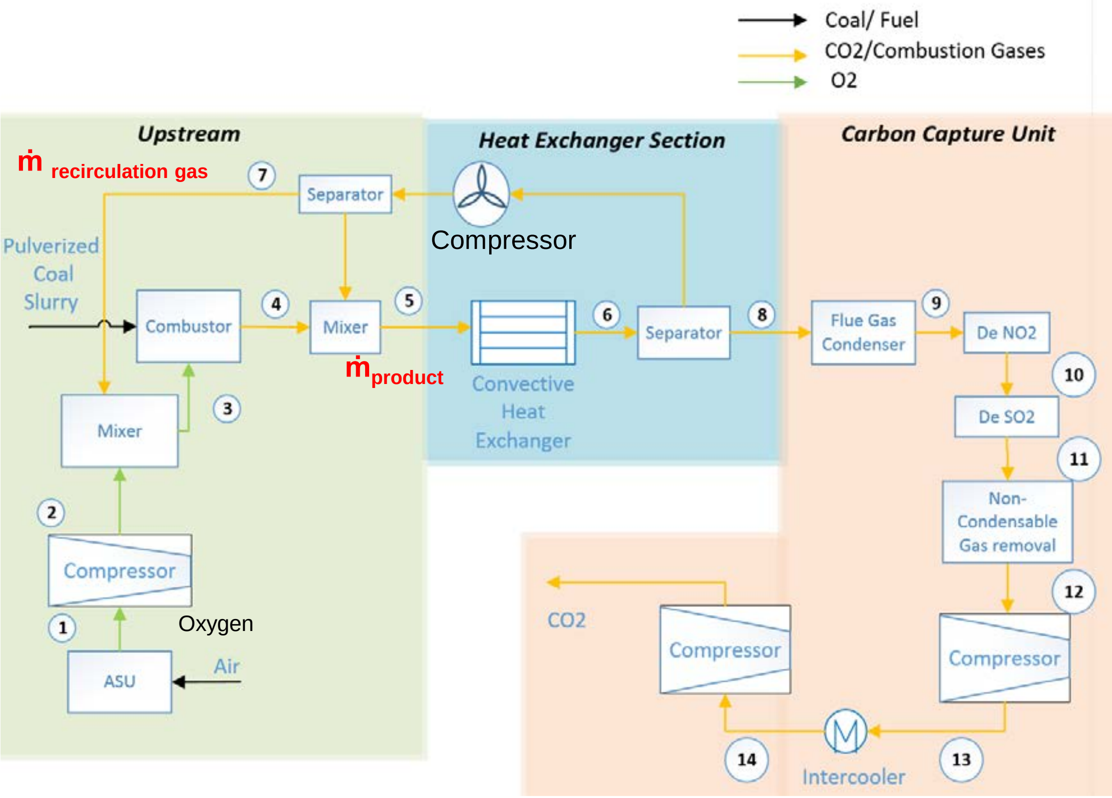
Kick off meeting
12/01/2016
Updated project management plan
12/01/2016
Determination of combustor operating conditions
1/23/2017
Analysis results of flue gas and CO_2 recirculation
1/23/2017
Technology gap analysis review
10/17/2017
Pintle injector design
5/1/2018
Preliminary design review
7/18/2018
Water test for the pintle injector
9/1/2018
Critical design review
10/10/2018
First article assembly
4/10/2019
Shake down test results
5/20/2019
Oct
Feb
Jun
Oct
Feb
Jun
Oct
Feb
2016
Today
2019

Cycle Analysis

Cycle Analysis

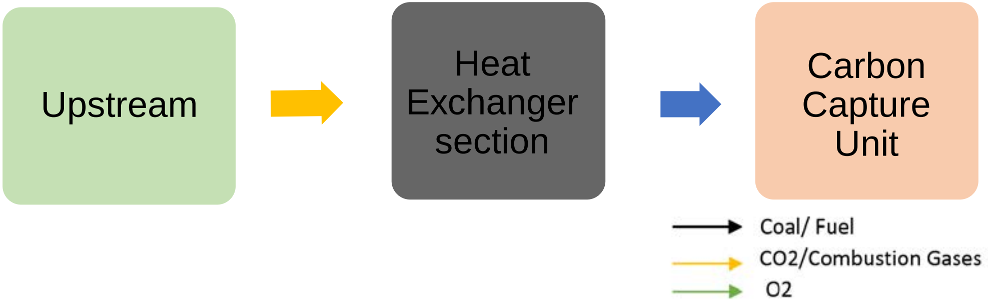
❖ ENEL

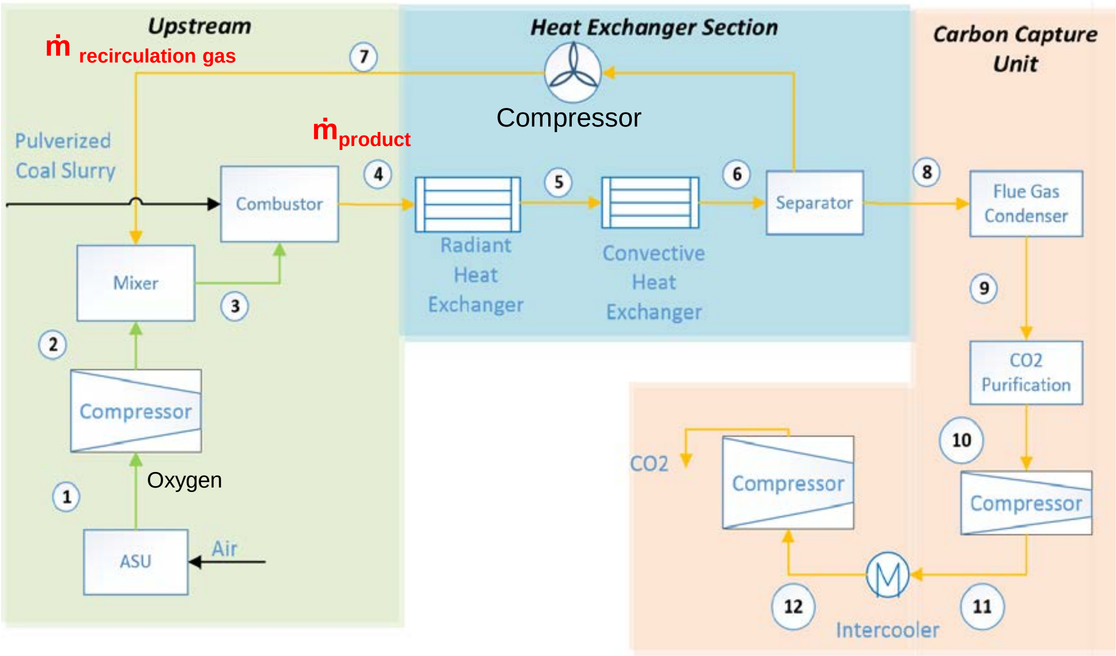
- Main sections:
  - o Upstream
  - o Heat Exchanger
  - o Carbon Capture Unit
- Has convective heat exchanger
- Turbomachinery must operate up to 10 bar pressure
- Increased efficiency



❖ **TIPS**

- Main sections:
  - Upstream
  - Heat Exchanger
  - Carbon Capture Unit
- Has radiative heat exchanger in addition to convective heat exchanger
- Turbomachinery has to operate up to 80 bar pressure





Cycle Analysis

❖ Cycle Simulation Parameters:

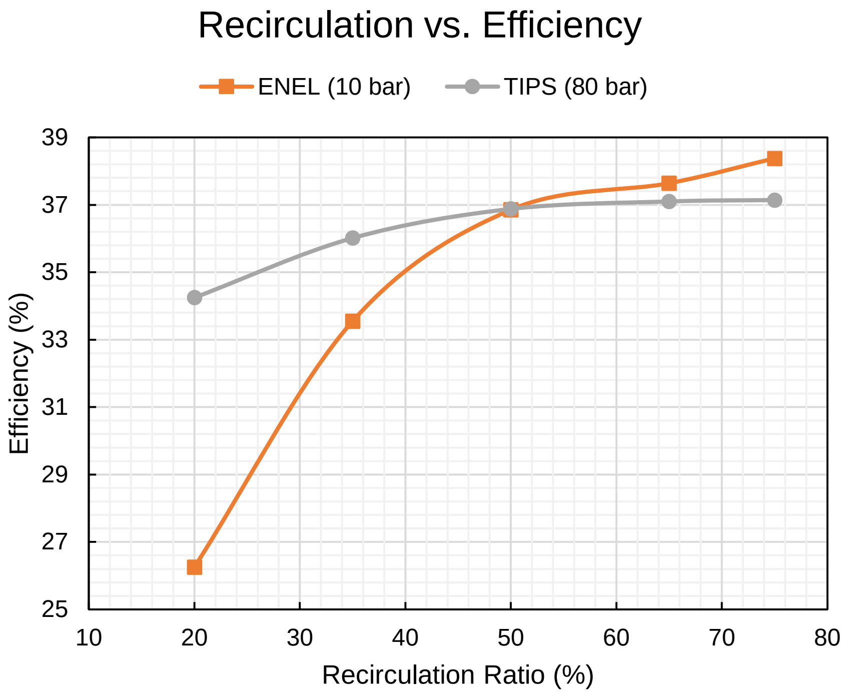
Input Parameters	
Element	Mass Flow Rate [kg/s]
Coal	18.87
Water	16.15
Oxygen	50
Equivalence Ratio: 0.95	
Total Thermal Input: 550 MW	

❖ Simulations Completed:

Case	Recirculation Ratio
1	20%
2	35%
3	50%
4	65%
5	75%

Efficiency

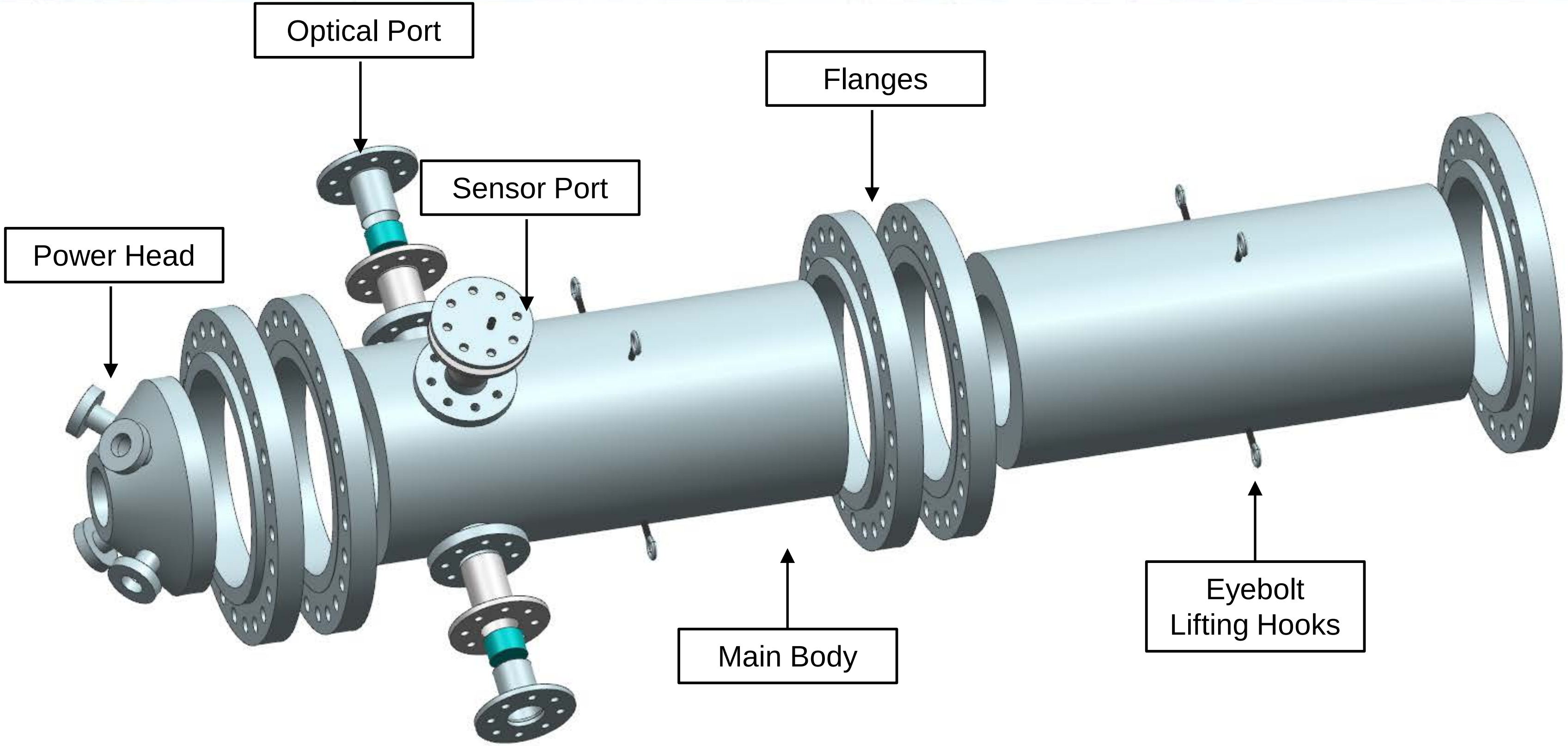
- ❖ Efficiency Ranges
  - ➢ ENEL = 26-38%
  - ➢ TIPS = 32-35%
- ❖ ENEL increases the burning rate of char and the heat transfer rates in the convective sections of the heat transfer equipment[1]
- ❖ ENEL reduces the energy penalties
  - ➢ Turbomachinery



Source: [1] Analysis of oxy-fuel combustion power cycle utilizing a pressurized coal combustor Jongsup Hong a, Gunaranjan Chaudhry a, J.G. Brisson a, Randall Field b, Marco Gazzino c, Ahmed F. Ghoniem a,*
[2] Chowdhury, Mehrin, et al. "Thermodynamic Analysis of ENEL and TIPS Oxy-Coal Power Cycles." 2018 AIAA Aerospace Sciences Meeting, no. January, 2018, pp. 1–11, doi:10.2514/6.2018-2254.

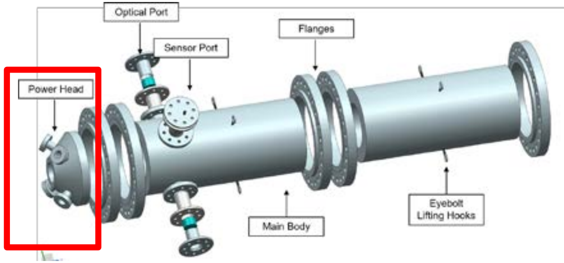
Combustor Design

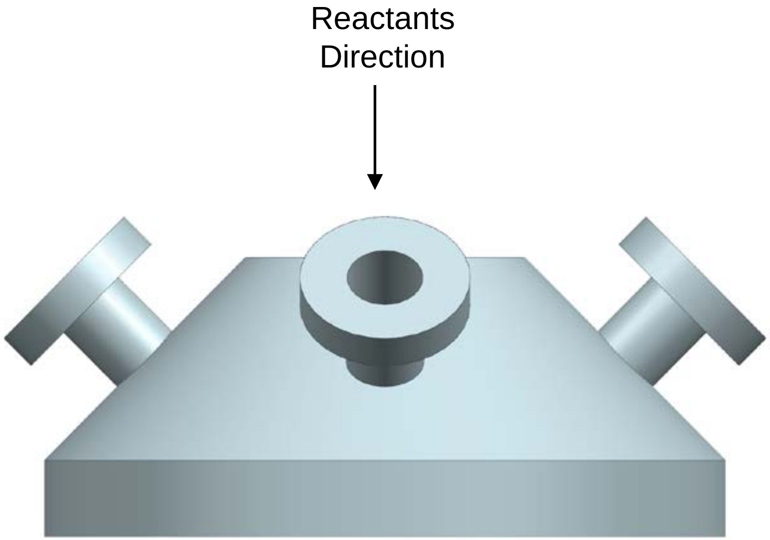
Combustor Design

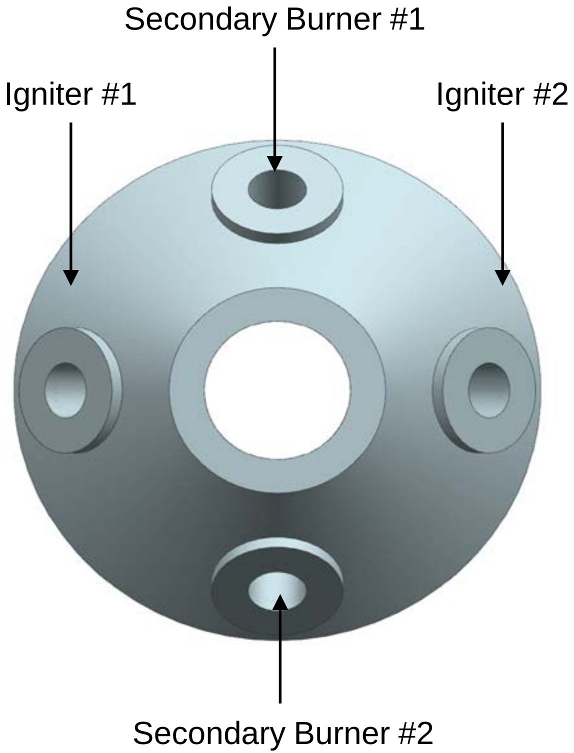


Combustor Design

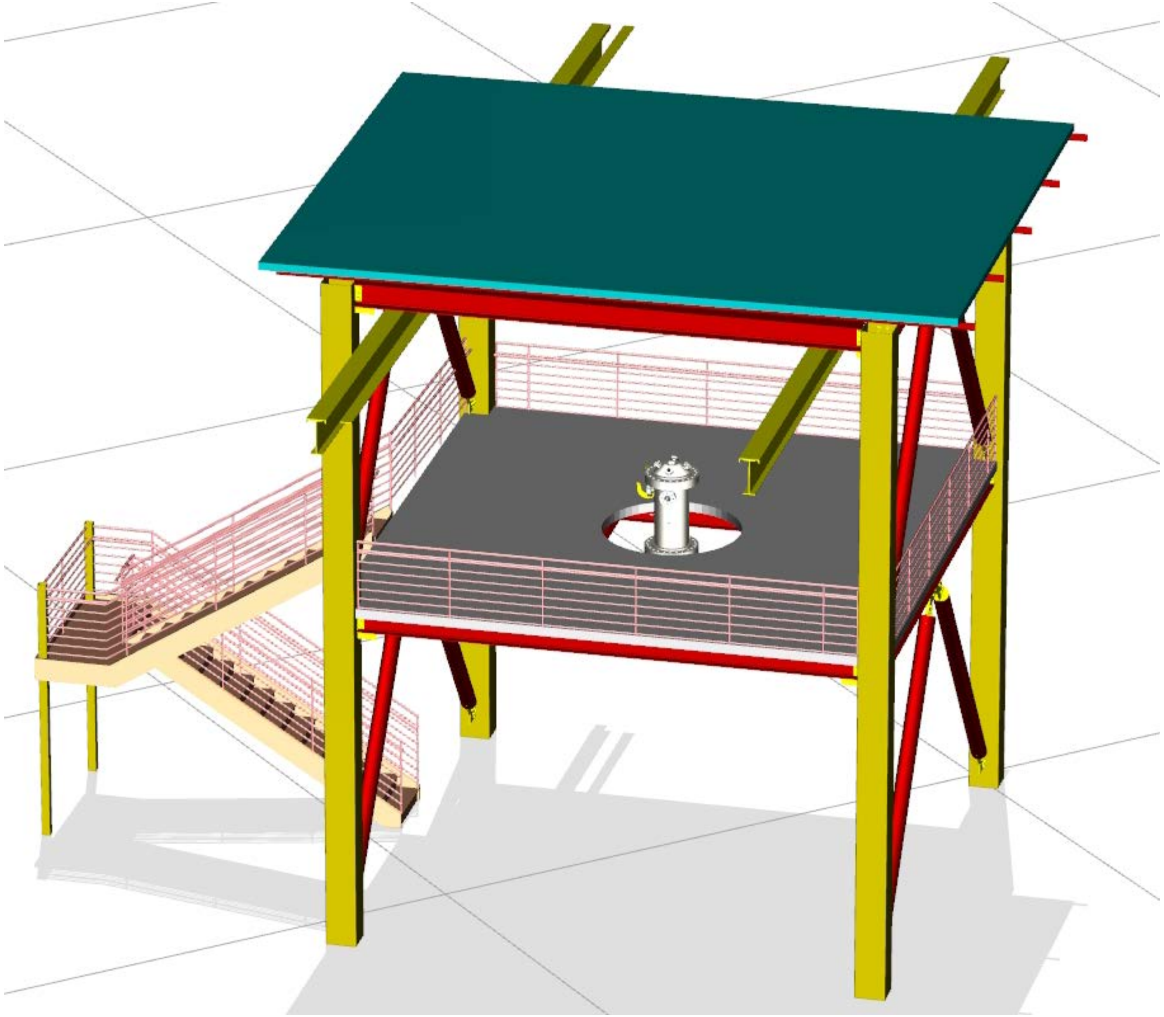
❖**Power Head**







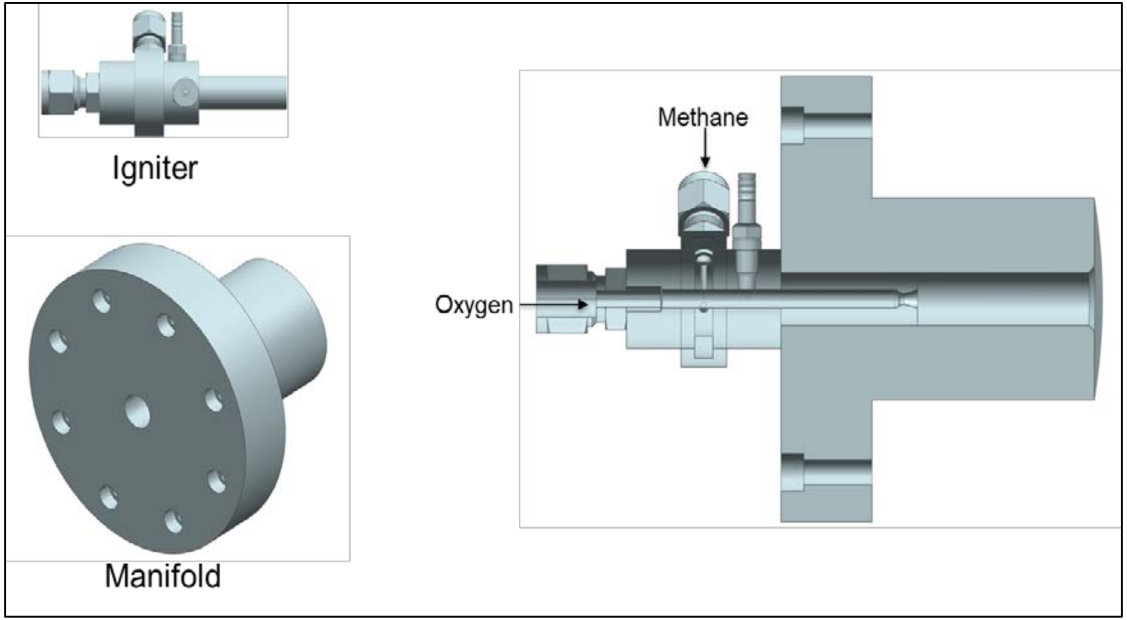
Test Stand



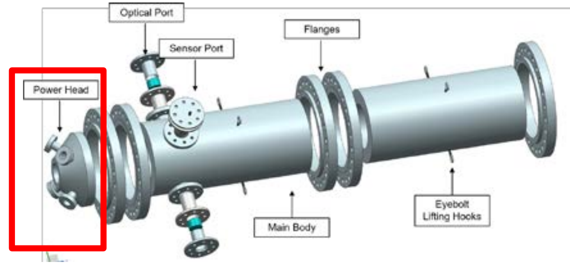
Secondary Burner & Igniter

Design Methodology (Igniter)

Operational Conditions		
Chamber Pressure	5 - 20	bar
Total Mass Flow	4.5 - 9	g/s
Maximum burn time	5	s
Igniter Body Temperature	150 – 800	K



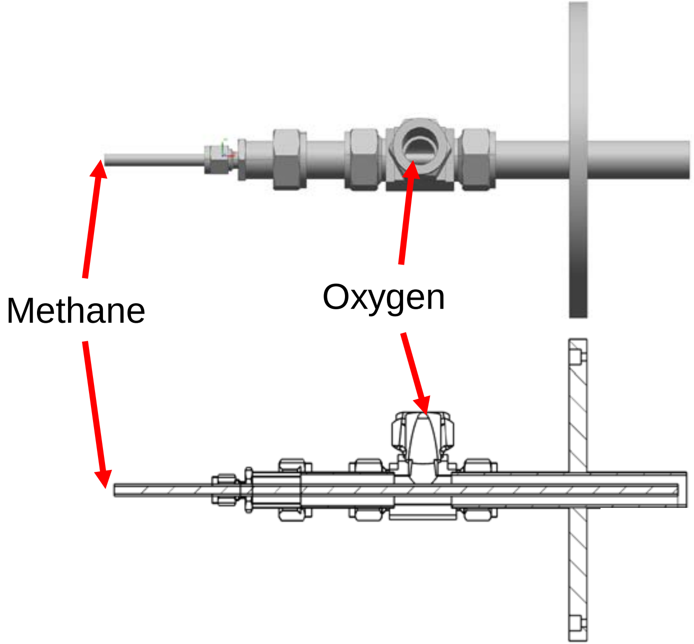
Secondary Burner



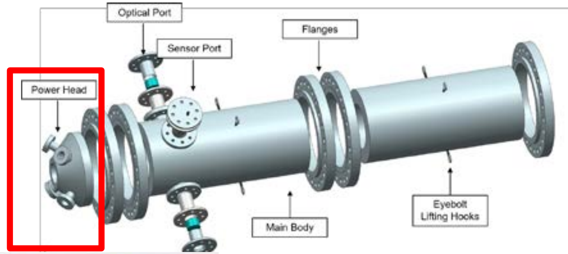
- ❖ Two secondary burners
  - ➢ 125kW firing input each
- ❖ Co-axial shear injector
  - ➢ Fuel centered

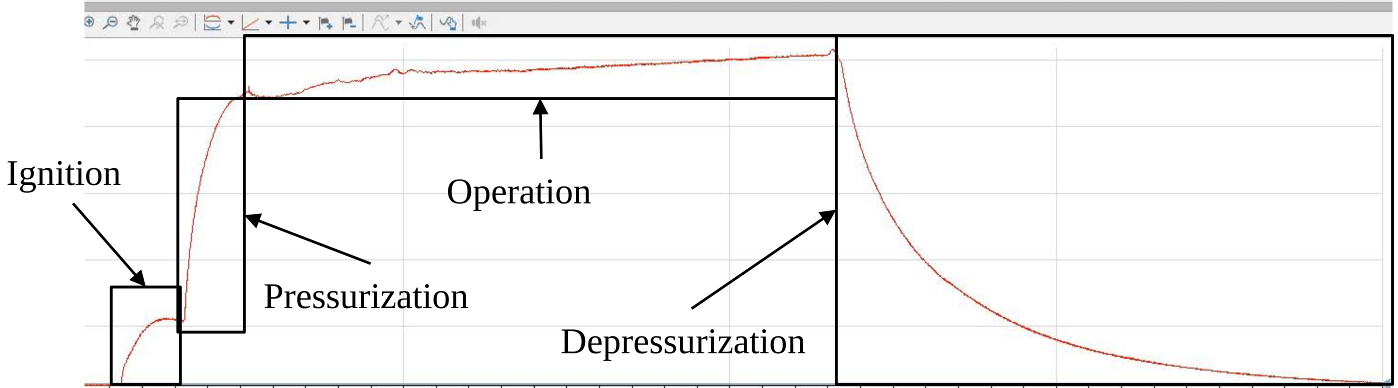
Mass Flow Rate	Value	Unit
Methane	2.5	g/s
Oxygen	10	g/s
Total	12.5	g/s

Velocities	Value	Unit
Methane	23.14	m/s
Oxygen	4.20	m/s
Velocity Ratio	5.51	N/A
Momentum Flux Ratio	15.38	N/A



Secondary Burner Test





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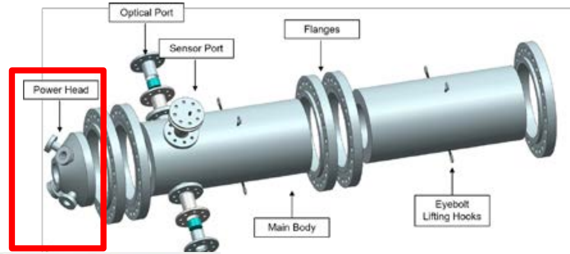

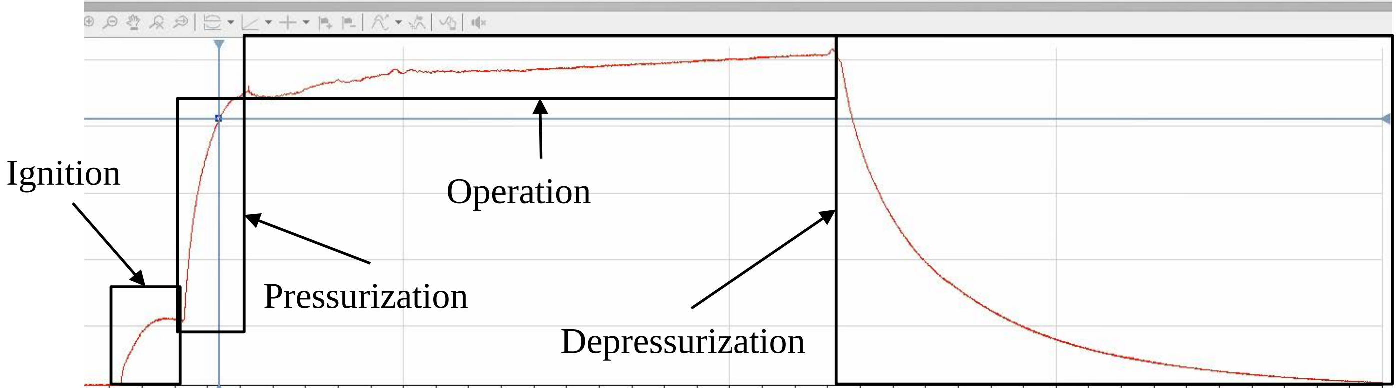

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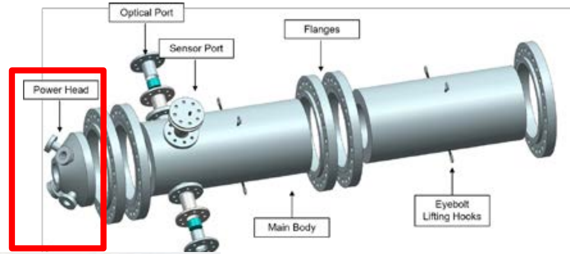

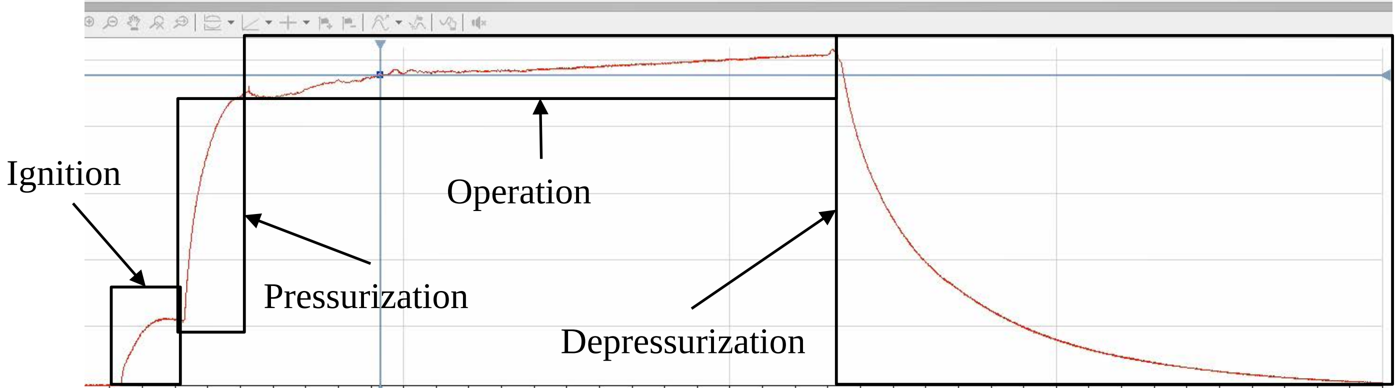

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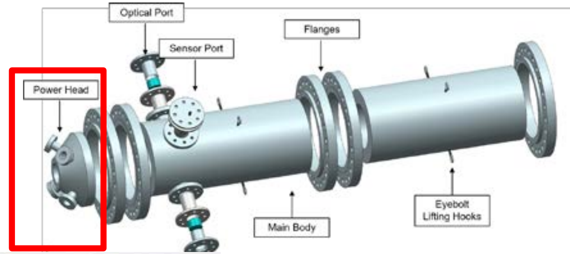

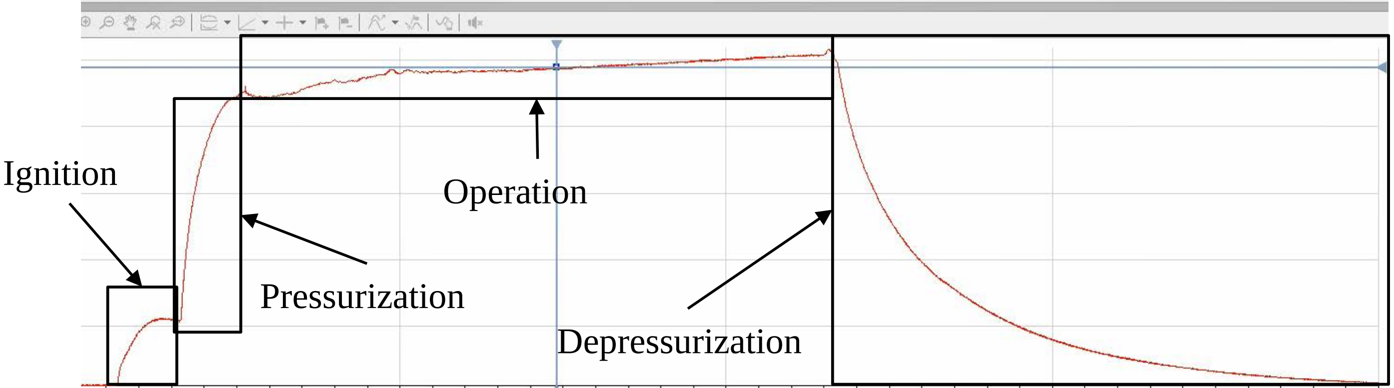

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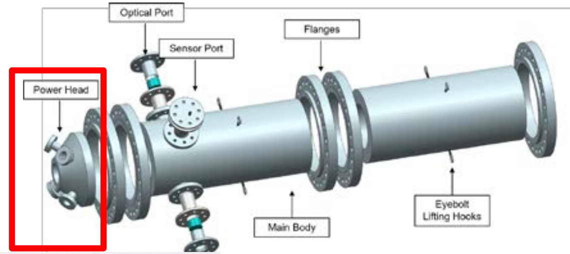

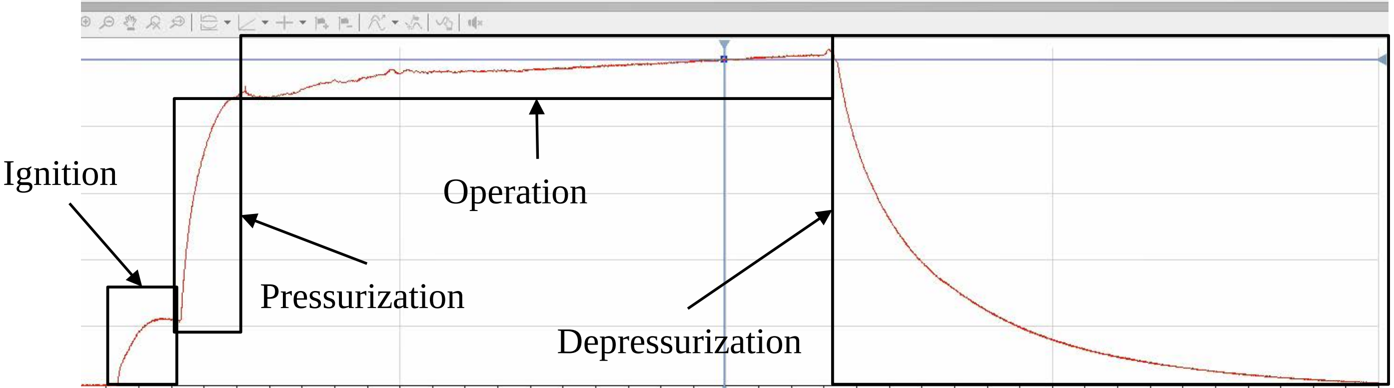

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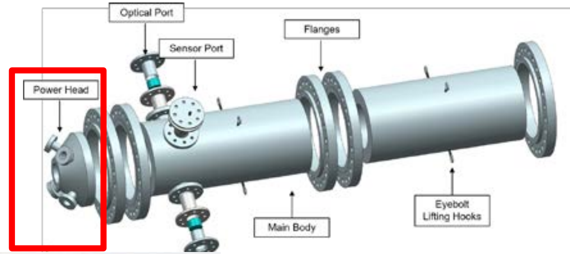
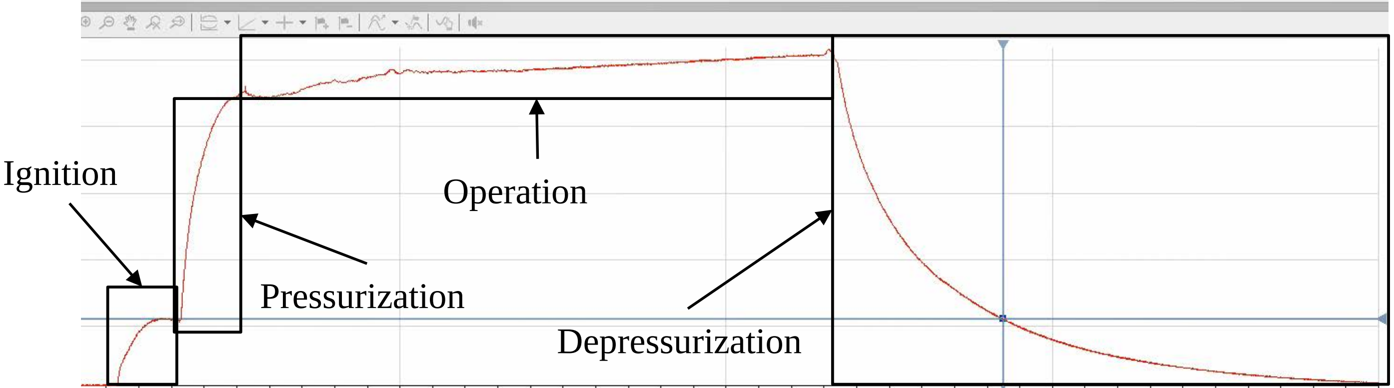




Secondary Burner Test

Secondary Burner Test

Secondary Burner Test

Secondary Burner Test

Injector Design

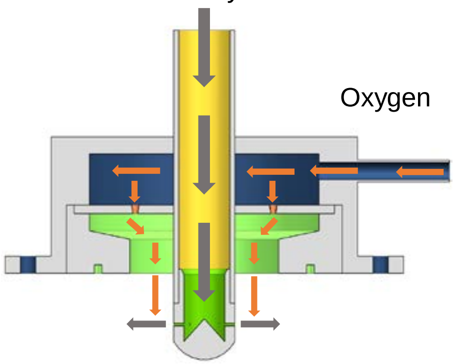
Injector Design: Pintle

❖**Benefits**
- ➢Utilized for liquid injection
- ➢Wide range of firing input
- ➢90% of burning efficiency

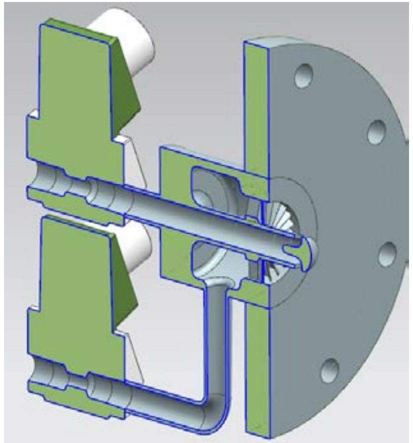
❖**Pintle Injector History**
- ➢Developed in mid 1950s[1]
- ➢Atomization and mixing propellants in rocket engines
- ➢Performance in range of 96-99%[2]

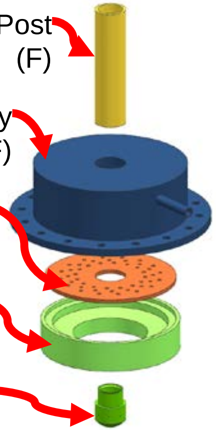
❖**Design Criteria**
- ➢Coal slurry as fuel (Radially)
- ➢Gaseous oxygen as oxidizer (Axially)

❖ **Advantages**
- ➢Variety of firing input
- ➢Range of spray angle
- ➢Maintenance



Sketch of bipropellant pintle injector





F: Fixed
I: Interchangeable

[1] G. A. Dressler and J. M. Bauer, "TRW Pintle Engine Heritage and Performance Characteristics," Aiaa, pp. 2000–3871, 2000
[2] R. N. Rezende and A. Pimenta, "Experiments with Pintle Injector Design and Development," *51st AIAA/SAE/ASEE Jt. Propuls. Conf.*, pp. 1–11, 2015.

Injector Design: Pintle

❖Coal Slurry

- The coal powder mixed with water
- The percentage of solids concentration is $C_w = 75\%$ by weight [1]-[2]
- The maximum powder size is $200\ \mu m$

❖Properties

- The density of slurry $\rho_{sl} = \frac{100}{\left(\frac{C_w}{\rho_{co}}\right)+\left(\frac{1-C_w}{\rho_w}\right)}$
- The oxygen density is obtained at 11 bar

Name	Value	Unit
Firing input	250	kW
Lower Heating Value	27.5	MJ/Kg
O/F stochiometric	2.56	N/A

Density	Value	Unit
Oxygen	14.3	kg/m^3
Coal	850	kg/m^3
Water	998.6	kg/m^3
Slurry	882.8	kg/m^3

[1]*А. Зенков and Э. Соколова, “Coal-water slurry,” Конференции, Г. Томск, 24-27 Апреля …, pp. 152–157, 2016*
[2] R. N. Rezende and A. Pimenta, “Experiments with Pintle Injector Design and Development,” *51st AIAA/SAE/ASEE Jt. Propuls. Conf.*, pp. 1–11, 2015

Injector Design: Pintle

- Flow rates
  - Coal mass flowrate, $\dot{m}_{coal} = \frac{Firing\ Input}{lower\ heating\ value}$
  - Oxygen mass flowrate, $\dot{m}oxygen\ = (\dot{m})coal \times \left(\frac{O}{F}\right)_{st}$
    - Slurry mass flow rate $\dot{m}_{slurry} = \frac{100 * \dot{m}_{coal}}{C_W}$

Coal Powder

Mass Flow Rate	Value	Unit
Coal	9.1	g/s
Oxygen	23.3	g/s
Slurry	12.1	g/s
Total	35.4	g/s

Injector Design: Pintle

Total momentum ratio $TMR = \frac{\dot{m}_{sl}\, v_{sl}}{\dot{m}_o v_o} = tan\, \alpha$

α: Spray angle

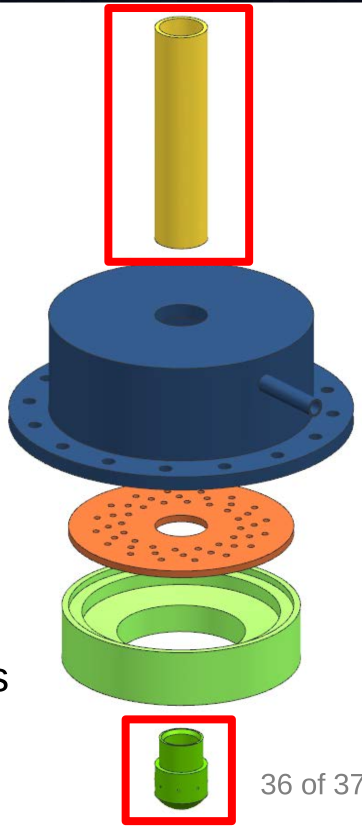
The velocity of the slurry $v_{sl} = \frac{\dot{m}_{sl}}{A_{sl}\, \rho_{sl}}$

The area of slurry $A_{sl} = N \frac{\pi}{4} D_{po}^2$

N: The number of orifices on pintle tip

D_{po}: The orifice diameter

Number of orifices



Injector Design: Pintle

The velocity of the oxygen $v_o = \frac{TMR\, \dot{m}_{sl}\, v_{sl}}{\dot{m}_o}$

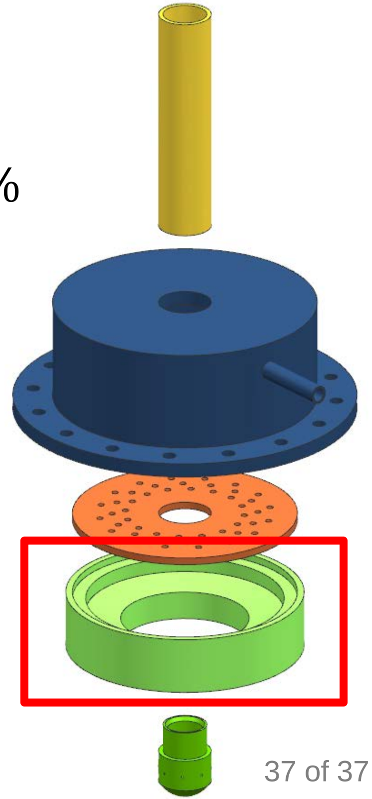
The area of oxygen $A_o = \frac{\dot{m}_o}{v_o \rho_o}$

The Closing Plate hole diameter $D = \sqrt{\frac{4A_O}{\pi} + D_p^2}$

D_p: The pintle post outer diameter

The annulus gap $Gap = \frac{D - D_p}{2}$

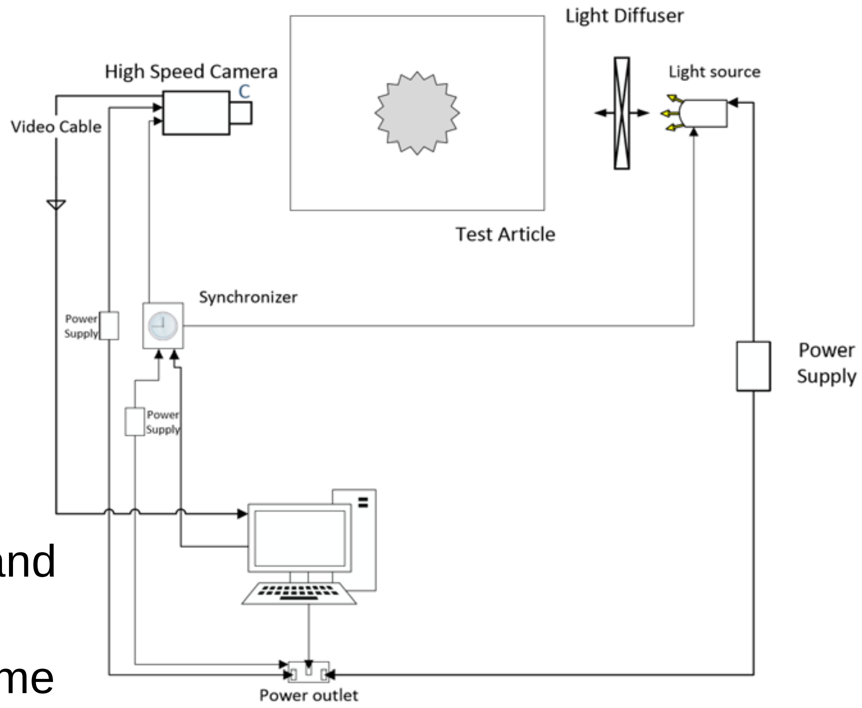
Pintle post diameter 10% of Chamber diameter



Injector Water Test

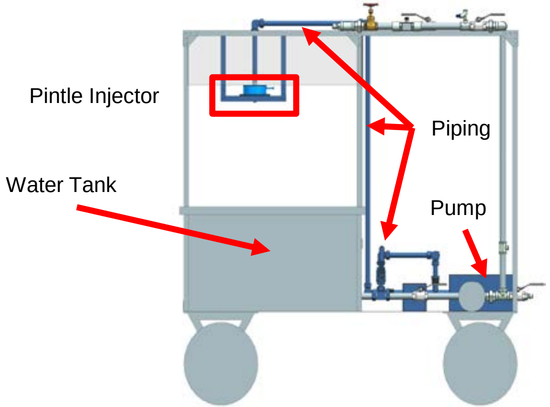
Shadow Sizing

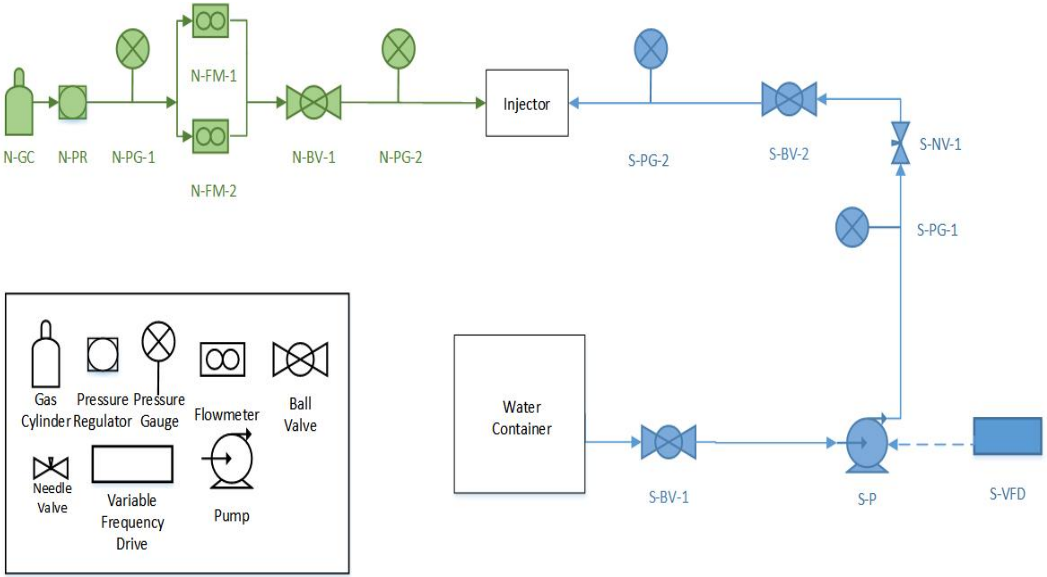
- ❖ An optical method based on:
  - ➢ High resolution imaging
  - ➢ High illumination
- ❖ Used for visualizing:
  - ➢ Particles, droplets, and structures
- ❖ Advantages
  - ➢ Better identification of droplets and flow patterns
  - ➢ Ideal for water testing
  - ➢ Measure droplets
  - ➢ Monitor atomization
- ❖ DynamicStudio controls camera settings and acquires images
- ❖ Shadow sizing of droplets analyzed by same program



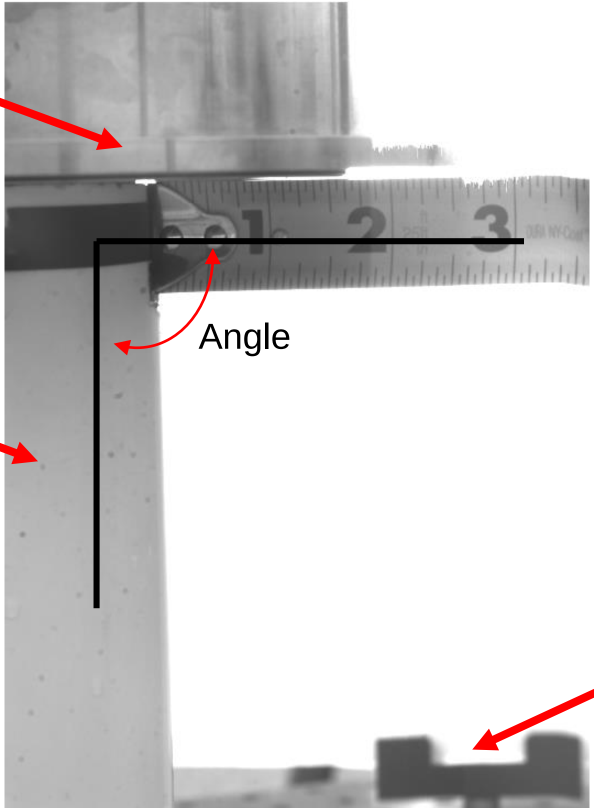
Shadowgraph Set-Up

Water Set-Up

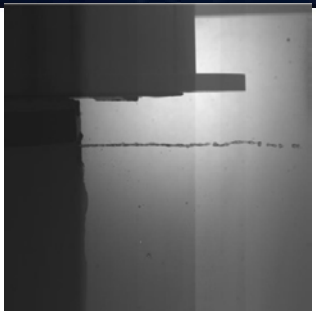
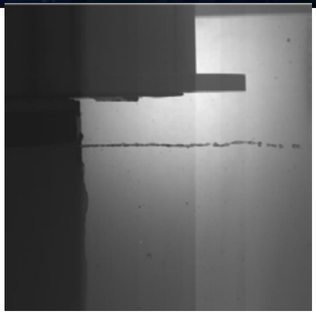
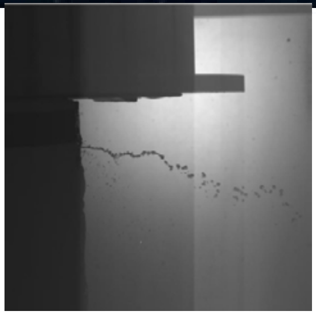
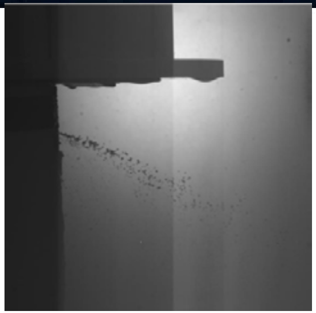
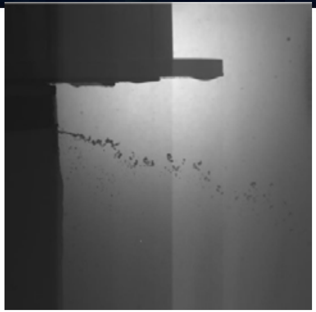

Pintle Injector
Piping
Water Tank
Pump


N-GC
N-PR
N-PG-1
N-FM-1
N-FM-2
N-BV-1
N-PG-2
Injector
S-PG-2
S-BV-2
S-NV-1
S-PG-1
Water Container
S-BV-1
S-P
S-VFD
Gas Cylinder
Pressure Regulator
Pressure Gauge
Flowmeter
Ball Valve
Needle Valve
Variable Frequency Drive
Pump

Water Set-Up


Pintle injector
Isolation device
Angle
Diffuser plate
and LED light

Water Set-Up Results

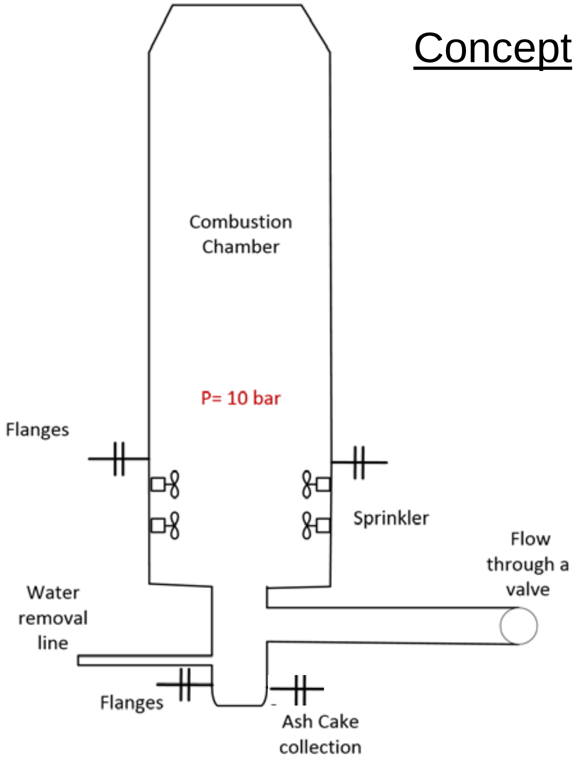






Run	1	2	3	4	5
Theoretical Angle (Degree)	90	88	87	86	85
Water Flowrate (g/s)	37.6	37.6	37.6	37.6	37.6
Nitrogen Flowrate (g/s)	0	7.6	14.7	19.9	26.3
Experimental Angle (Degree)	90	89	85	73	80
error(%)	0.0	-1.1	2.4	17.8	6.3

Exhaust Design Concept

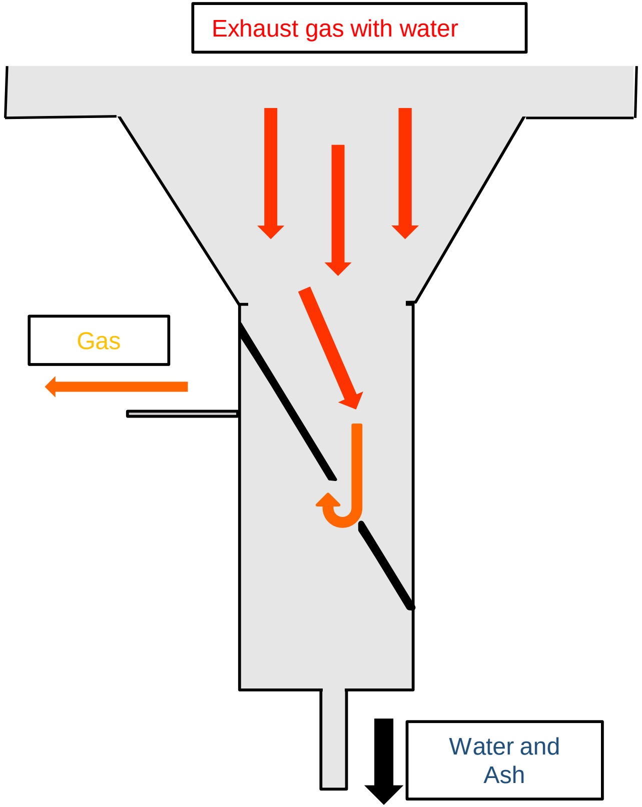
Exhaust Design Concept

- ❖ A small pressure vessel is attached with flanges
- ❖ Ash removal
  - ➢ Water added with sprinklers
  - ➢ Ash drained and collected at the bottom
- ❖ Modular design for the ash collection
  - ➢ Maintenance
- ❖ Pressurized with chocked flow
  - ➢ Valve



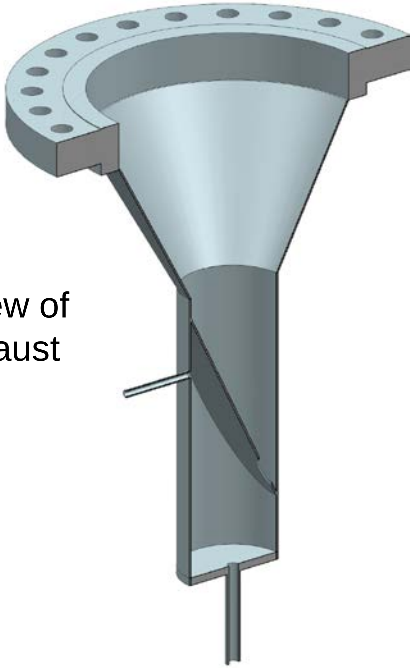
Concept

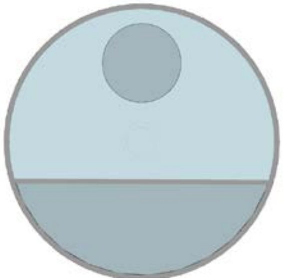
Exhaust Concept Design



Schematic of exhaust system

Side View of
the Exhaust





Top View of
the Exhaust

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