Modeling and Testing of a Directly Heated Supercritical CO_2 Combustor

A.S.M. Arifur Chowdhury, Jad Aboud,
Norman Love
Center for Space Exploration and Technology Research
The University of Texas at El Paso
El Paso, Texas, USA

Hwanho Kim, Jiefu Ma

Air Liquide R&D
Delaware Research and Technology Center
Newark, Delaware, USA

Remi Tsiava
Air Liquide R&D
Paris-Saclay Research Center
Jouy-en-Josas, France

Presented by:
Jad G. Aboud
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Outline

- **Introduction and Background**
- **Motivation and Objective**
- **Design Methodology**
- **Numerical Methodology**
- **Experimental Methodology**
- **Results and Discussion**
- **Summary and Conclusions**

Introduction and Background

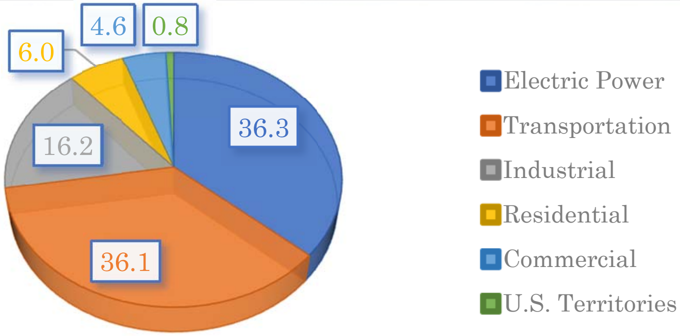
Introduction and Background

❑ United States Electricity Production

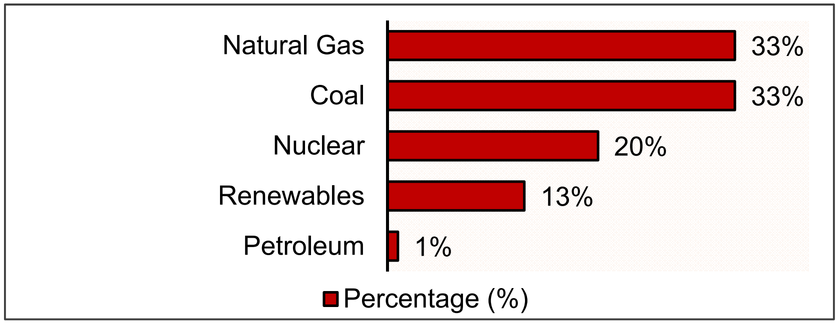
- In 2016, **36%** of CO_2 emissions came from sources associated with electrical power generation

- Significant greenhouse gases were produced due to fossil fuel burning, in 2015, **67%** of US electricity is produced from fossil fuels

- Possible solutions for greenhouse gas emission reduction include:
  - Increasing energy efficiency
  - Switching to less carbon intensive sources of energy
  - Carbon sequestration



Percentage of US greenhouse gas emission sources, 2016



US electricity generation sources, 2015

Source: [1] US Environmental Protection Agency (2018), Inventory of US Green House Gas Emissions and Sinks: 1990-2016
[2] US Energy Information Administration, Electric Power Monthly, February 2016, Preliminary data for 2015
[3] White, C., Strazisar, B., Granite, E., Hoffman, J., & Pennline, H. (2003). Separation and Capture of CO_2 from Large Stationary Sources and Sequestration in Geological Formations—Coalbeds and Deep Saline Aquifers. Journal of the Air & Waste Management Association, (53(6)), 645-715.

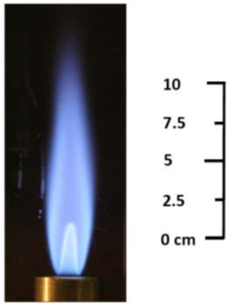
Introduction and Background

❑Carbon Sequestration

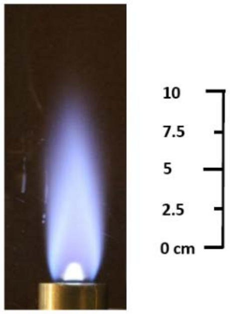
❑Oxy-fuel combustion

➢Oxy-fuel combustion involves burning a hydrocarbon with oxygen resulting in an exhaust stream which is composed mainly of carbon dioxide and water vapor

- ✓Oxy-combustion facilitates capturing as high as 100% carbon dioxide at the post combustion stage
- ✓Energy consumption for oxygen production is a drawback but higher temperatures theoretically allow for higher attainable efficiencies
- ✓Flue gas can be recirculated to reduce the combustion temperature keeping the material of the combustor components within the operating conditions



CH_4-O_2-CO_2



CH_4-O_2

Introduction and Background

❑ Directly heated oxy-fuel supercritical gas turbines

- ❖ Compact component size
- ❖ Have the potential to achieve more than 50% thermal efficiency
- ❖ Both natural gas and syngas can be utilized as fuel
- ❖ Provides the option of capturing as high as 100% carbon dioxide at the post combustion stage

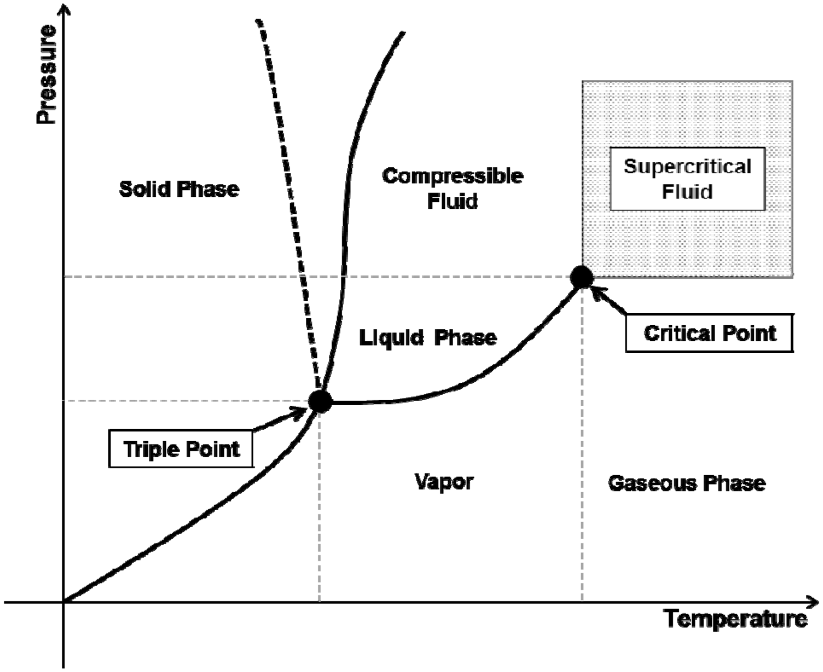


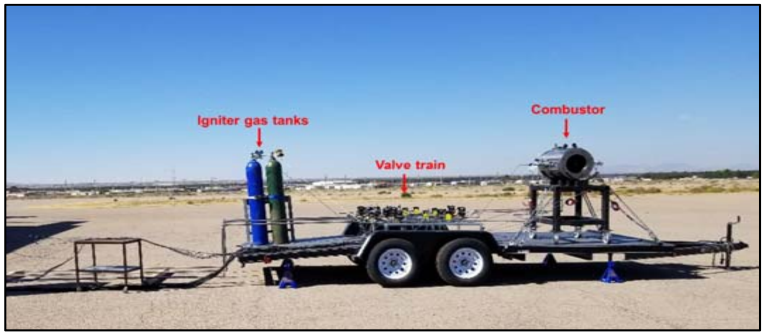
Figure: Phase diagram (Temperature – Pressure curve)

Source: [1] Hong, J., Field, R., Gazzino, M., & Ghoniem, A. F. (2010). Operating pressure dependence of the pressurized oxy-fuel combustion power cycle. Energy, 35(12), pp. 5391-5399. [2] McClung A, Brun K, Chordia L. Technical and economic evaluation of supercritical oxy-combustion for power generation. In: 4th International supercritical CO2 power cycles symposium (2014), Paper No. 40; Southwest Research Institute; Pittsburgh, Pennsylvania.

Motivation and Objective

Motivation and Objective

Obtain experimental results that can be used to improve computational modeling capabilities for supercritical combustors

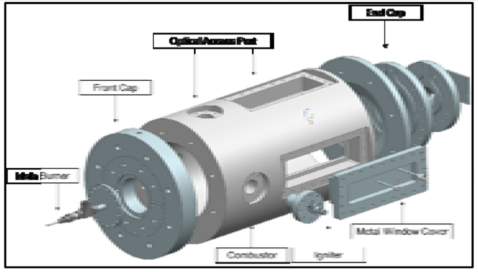


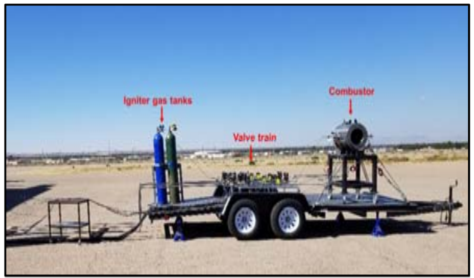
Elements	**Critical Pressure (bar)**	**Critical Temperature (K)**
CH_4	45	190
O_2	50	154
CO_2	74	304
H_2O	221	647

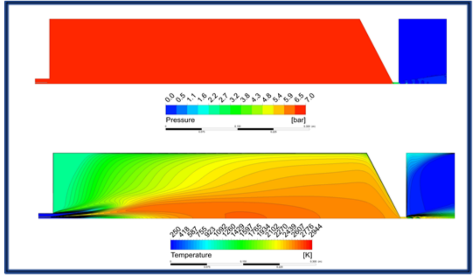
Motivation and Objective

- ❑ **Perform analysis on oxy-fuel flames at high pressure and compare to CFD model for future scale up to supercritical conditions**
  - ✓ Design and test a high pressure oxy-combustor with a power input of up to 250 kW and pressure up to 20 bar
  - ✓ Tests include two conditions listed in the table below: Case 1 and Case 2
  - ✓ Compare experimental pressure and temperature data to model

	Case 1	**Case 2**
Pressure (bar-g)	7	16
Firing Input (kW)	160	232
O/F Ratio	3	3.5





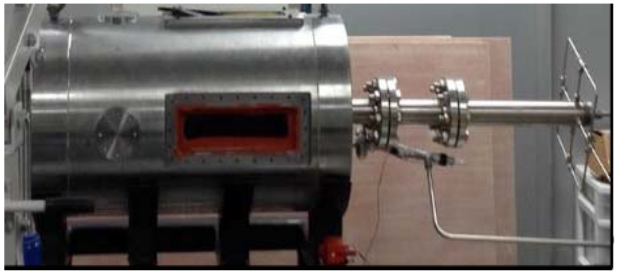


Design Methodology

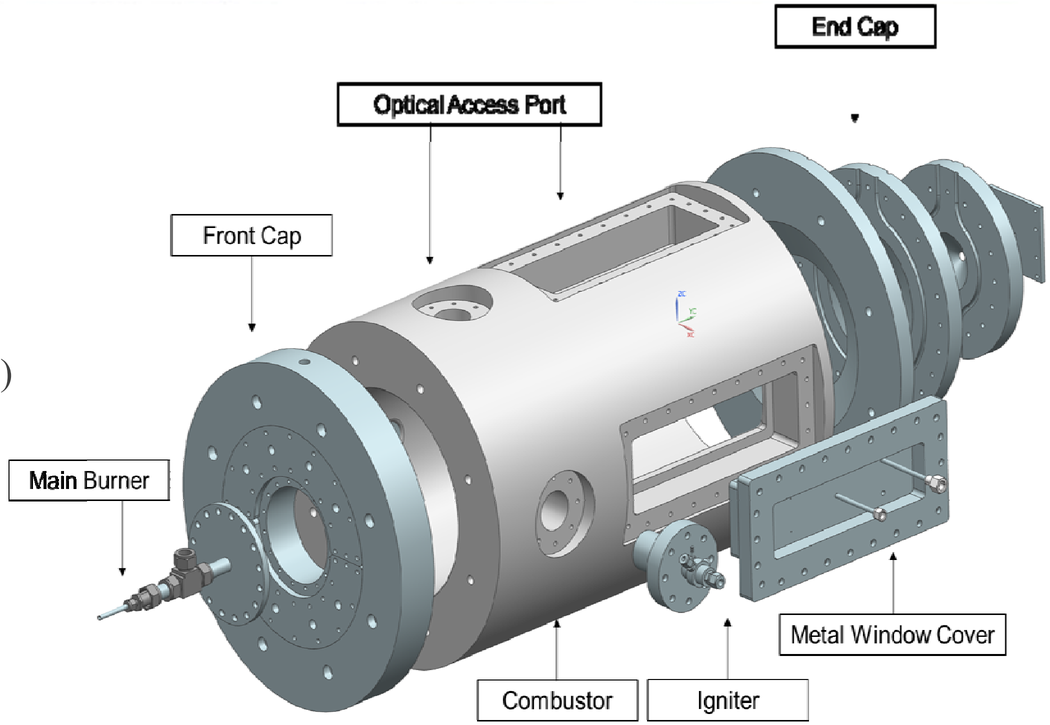
Design Methodology (Combustor)

❑ Combustor Modifications

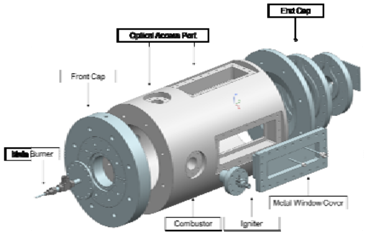
- Modify an existing combustor for steady state oxy-fuel combustion
  - ✓ Main burner system
  - ✓ Igniter system
  - ✓ Pressurizing system
  - ✓ Cooling System Design (not used in this study)



High Pressure Combustor



Design Methodology (Main Burner)

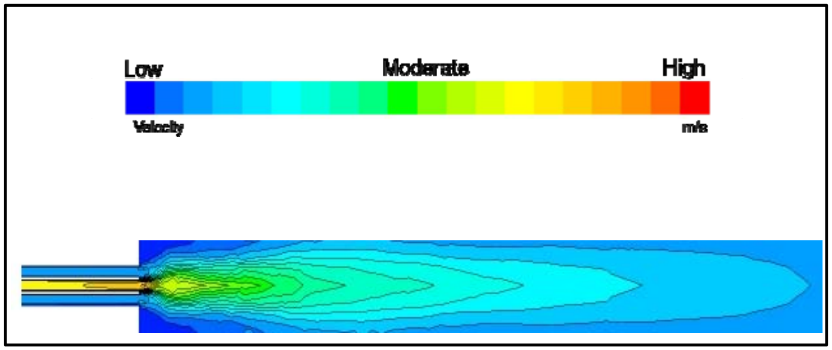


❑ Design Criteria

- Shear co-axial injector
- Oxy-methane combustion
- Gaseous delivery system

❑ Formulation

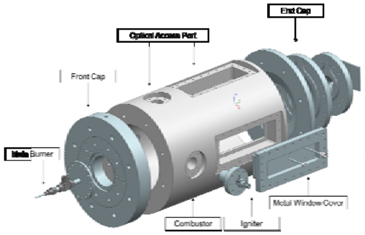
- Methane mass flowrate, $\dot{m}_{methane} = \frac{Firing\ Input}{LHV}$
  - ✓ $LHV, CH_4 = 50{,}000\ kJ/kg$
- Oxygen mass flowrate, $m^{\cdot}_{oxygen} = (m)^{\cdot}_{methane}\ x\ (O\ /\ F)_{st}$.
  - ✓ $({}^{O}/_{F})_{st.} = 4$
- Momentum flux ratio, $j = \frac{(\rho.v^2)_{methane}}{(\rho v^2)_{oxygen}}$
  - ✓ j= 2 - 25
- Mass flowrate, $\dot{m} = \rho\ A\ v$



Shear mixing due to momentum exchange

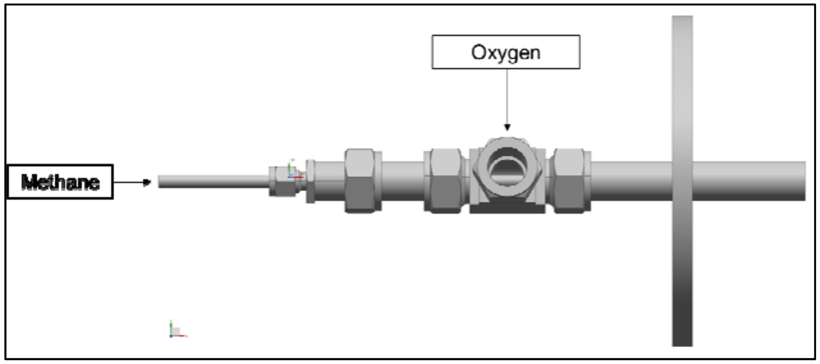
[1] Lux, J., & Haidn, O. (2009). Effect of recess in high-pressure liquid oxygen/methane coaxial injection and combustion. *Journal of Propulsion and Power*, *25*(1), pp. 24-32.

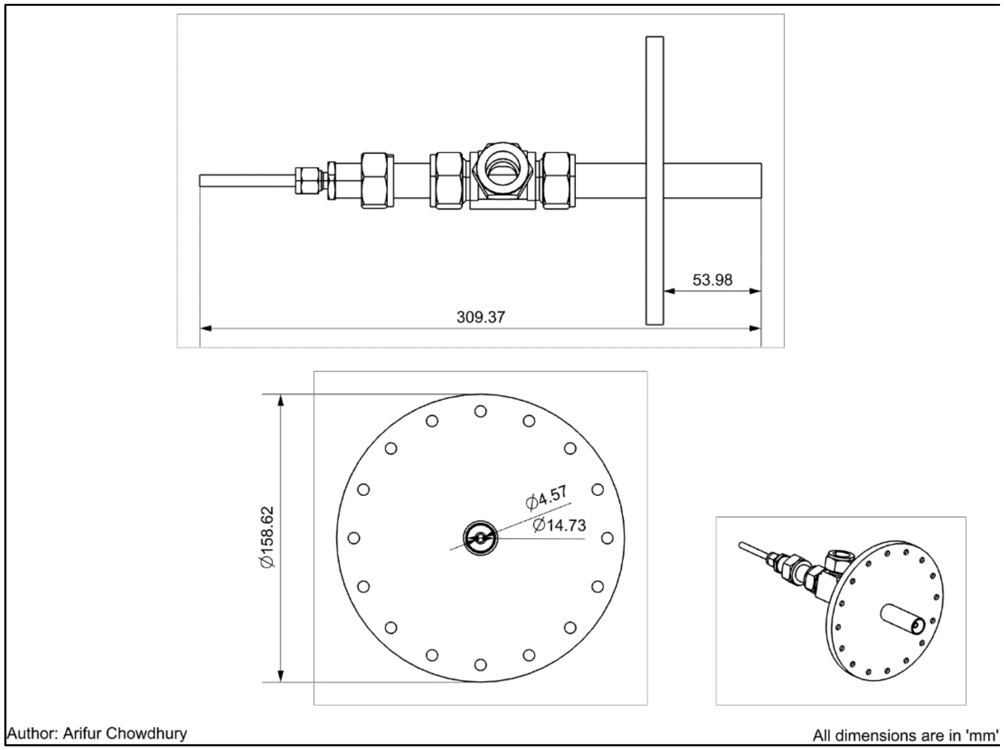
Design Methodology (Main Burner)



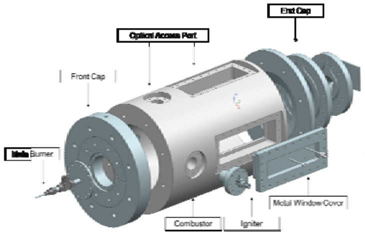
❑ Main Burner Parameters

Fuel	*Methane*	
Oxidizer	*Oxygen*	
Power Input	*up to 250*	*kW*
Operating Pressure	*up to 20*	*bar*
Momentum flux ratio	*2 - 20*	





Design Methodology (Main Burner)



❑ Recess Length

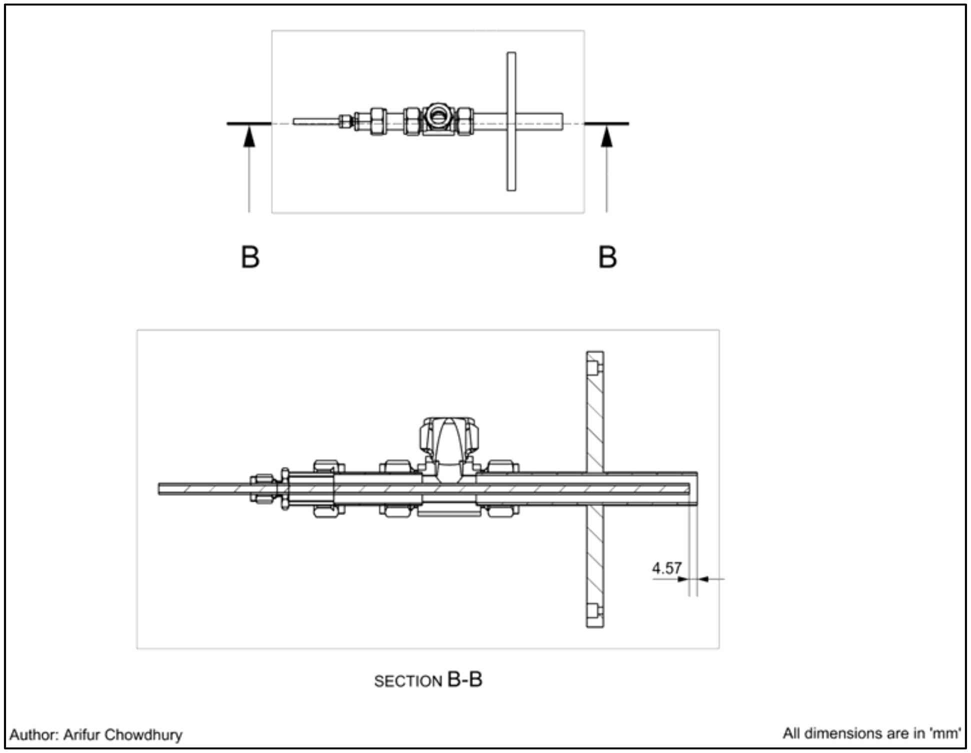
- Dimension: 1di
  [di : Diameter of high velocity jet]

- Literature

o The effect of recess length is higher when the momentum flux ratio is small.

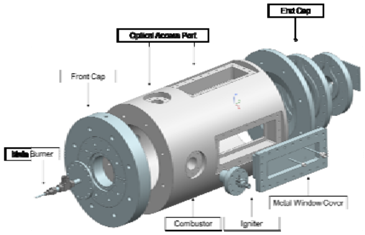
o The recess length above 1.5di does not further improve the combustion performance.

o Kendrick et al.
  - ✓ LOx/H_2 Shear co-axial Injector: 1di

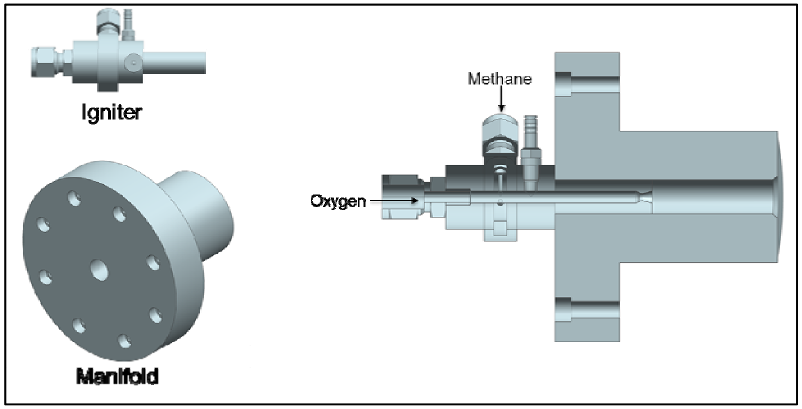


[1] Tripathi, A., Juniper, M., Scouflaire, P., Rolon, J. C., Durox, D., & Candel, S. (1999, June). Lox tube recess in cryogenic flames investigated using OH and H2O emission. In 35th Joint Propulsion Conference and Exhibit (p. 2490).
[2] Kendrick, D., Herding, G., Scouflaire, P., Rolon, C., & Candel, S. (1999). Effects of a recess on cryogenic flame stabilization. Combustion and Flame, 118(3), pp. 327-339.

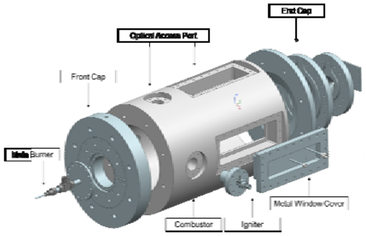
Design Methodology (Igniter)

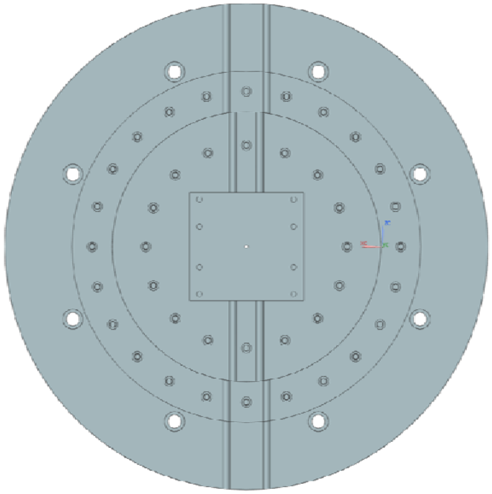


Operational Conditions		
Chamber Pressure	5 - 20	bar
Total Mass Flow	4.5 - 9	g/s
Maximum burn time	5	s
Igniter Body Temperature	150 – 800	K

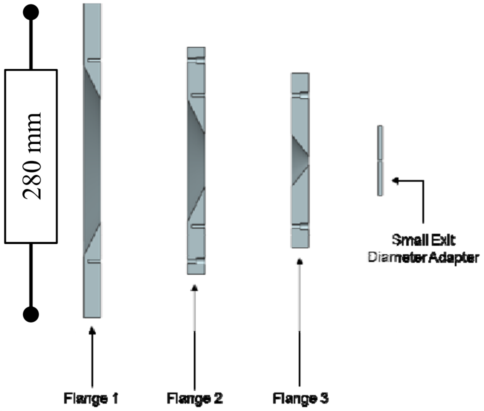


Design Methodology (Exhaust)





End Cap - Back View



End Cap - Cross Sectional View

- When the flow is choked:

$$P = (\dot{m} \times \sqrt{T_t}) \Big/ \left(A_t * \sqrt{\left(\frac{\gamma}{R}\right)}\left(\frac{\gamma+1}{2}\right)^{\frac{-\gamma+1}{2(\gamma-1)}}\right)$$

- Where:
  - $\dot{m}$ = Total mass flow rate (kg/s)
  - A = Throat cross sectional area (m^2)
  - P = Chamber pressure (Pa)
  - T = Chamber temperature (K)
  - γ = Specific heat ratio
  - R = Specific gas constant (J/kg-K)

Numerical Methodology

Numerical Methodology

❑ CFD Analysis

- ❖ CFD analysis was performed using ANSYS Fluent to replicate Case 1 (7 bar)
- ❖ 2-D transient density based solver was used
- ❖ Inlet parameters were obtained from the experimental study
- ❖ Experimental pressure and temperature data was compared with the CFD model

	Case 1
Pressure (bar-g)	7
Firing Input (kW)	160
O/F Ratio	3

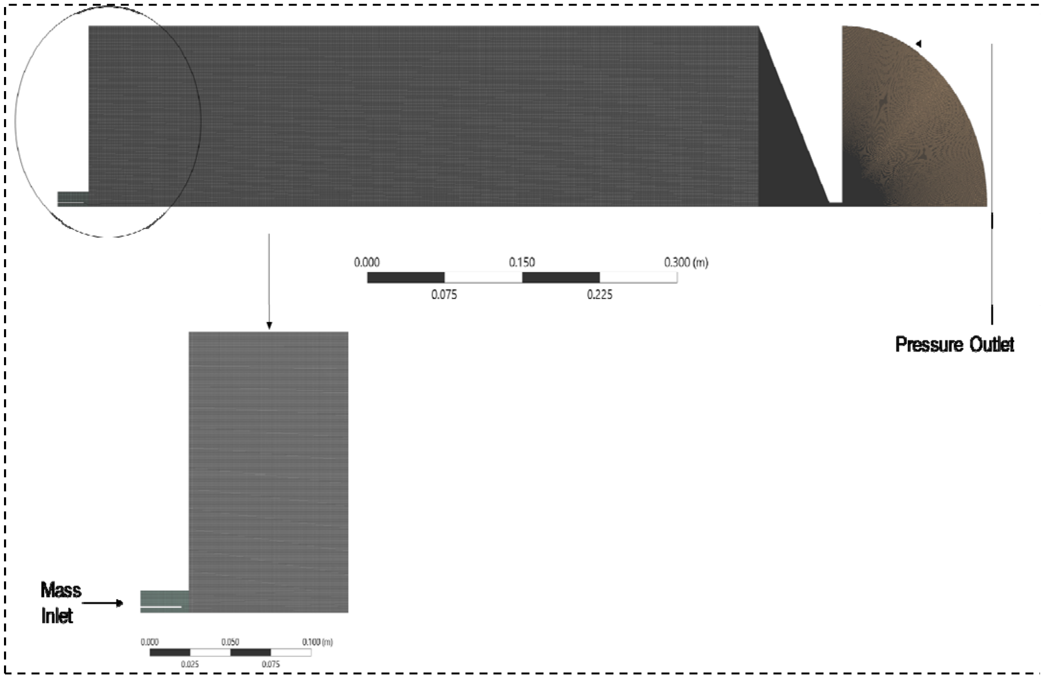
Numerical Methodology

- The 2D geometry is divided into three sections:
  - Inlet
  - Combustor
  - Additional fluid domain

- The additional fluid domain allows the software to calculate the pressure inside the combustor based on combustion product composition, gas temperature, and combustor exit area.

- The total number of elements and nodes are 74,082 and 73,171, respectively.

- The minimum orthogonal quality is 0.485



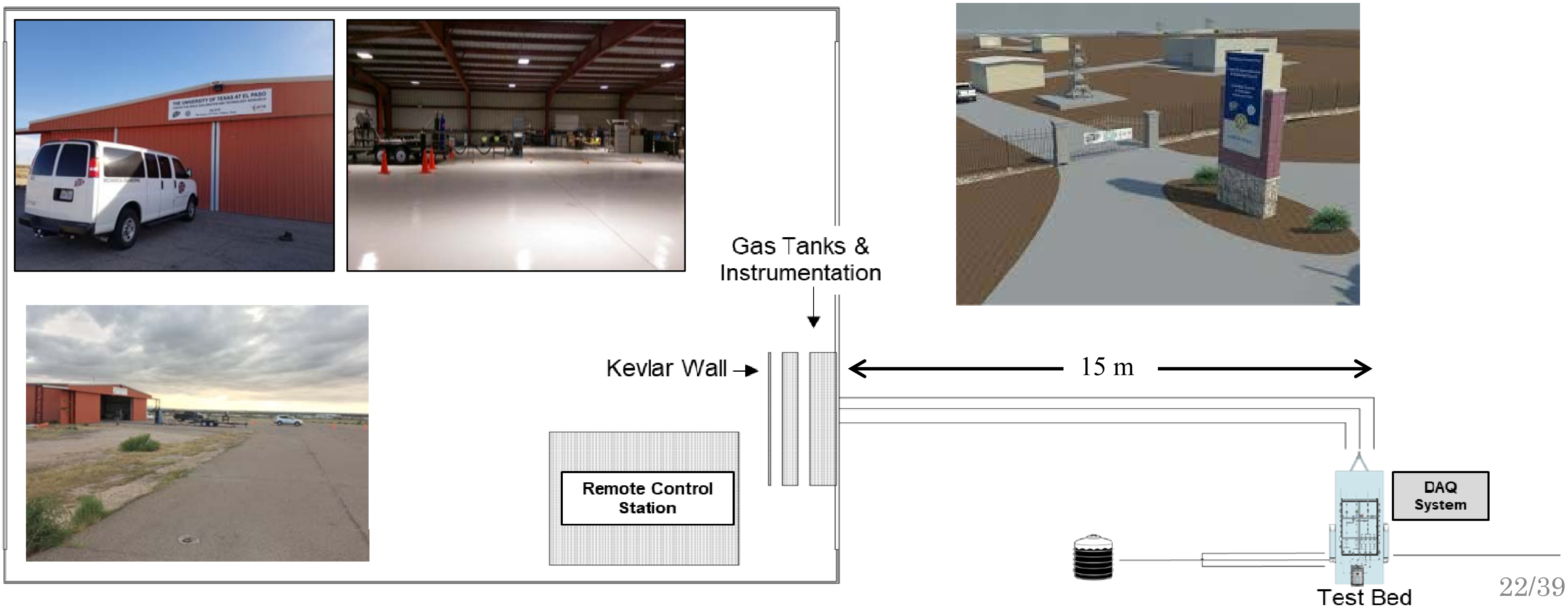
Numerical Methodology

Section	Input
General	
Type	Transient Density Based
Models	
Turbulence Model	Standard k- ε model
Radiation	Discrete-Ordinate model
Species	Species Transport (One Step Chemistry $CH_4+2O_2=2H_2O+CO_2$)
Turbulence-Chemistry interaction	Eddy-Dissipation model
Boundary Conditions	
Method	2D Axisymmetric
Inlets	- Pressure Inlet: Fuel (Methane) Inlet - Pressure Inlet: Oxidizer (Oxygen) Inlet
Outlet	Pressure Outlet: 1 bar
Wall	Wall: Adiabatic

Experimental Methodology

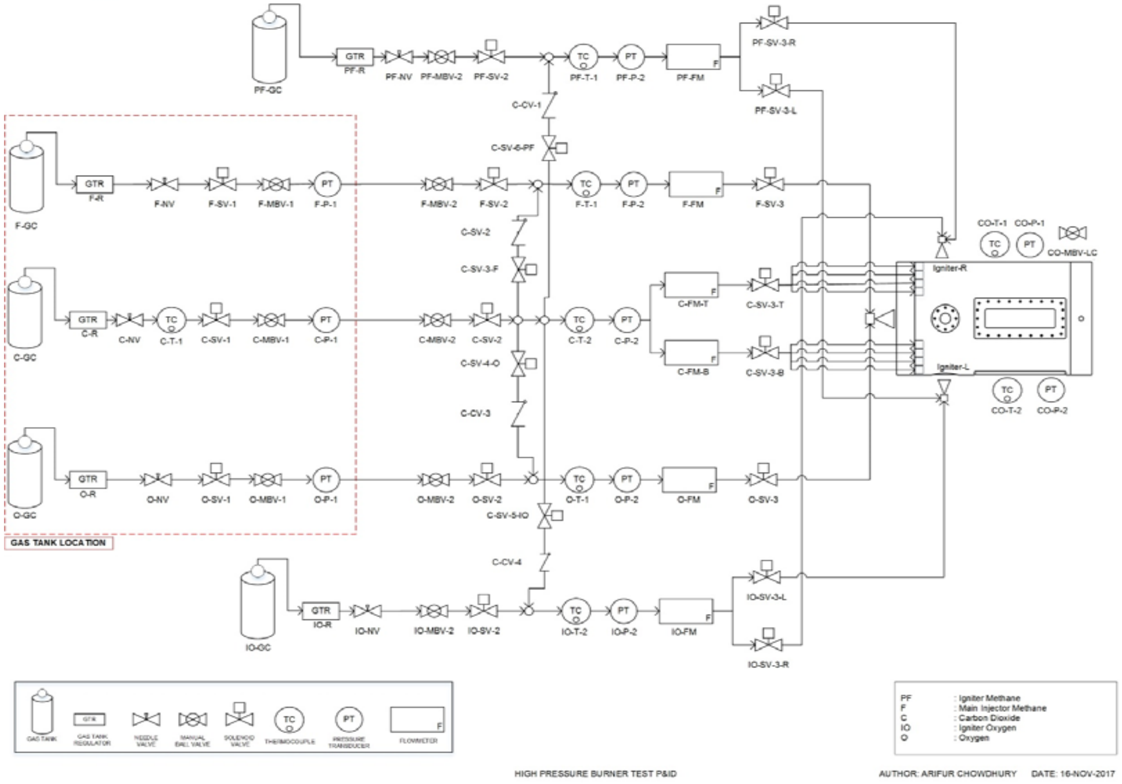
Experimental Methodology

❑ Setup Layout



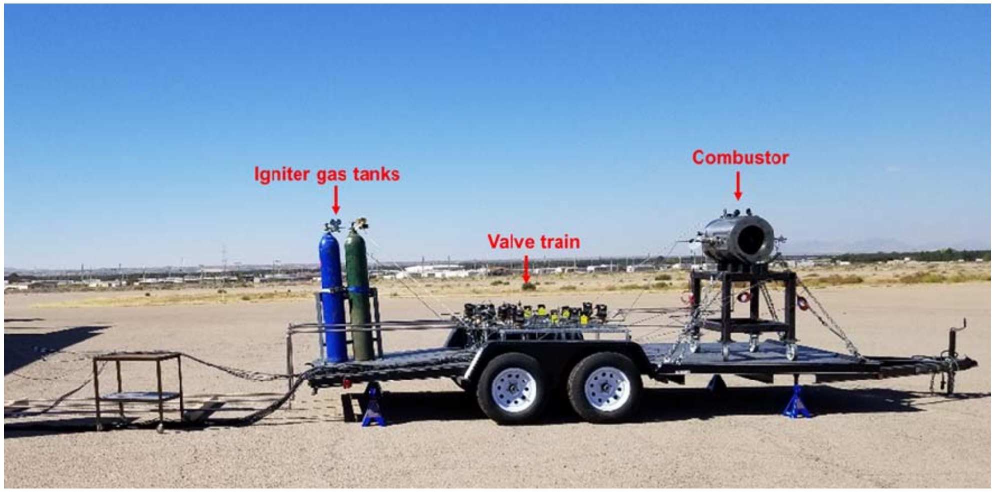
Experimental Methodology

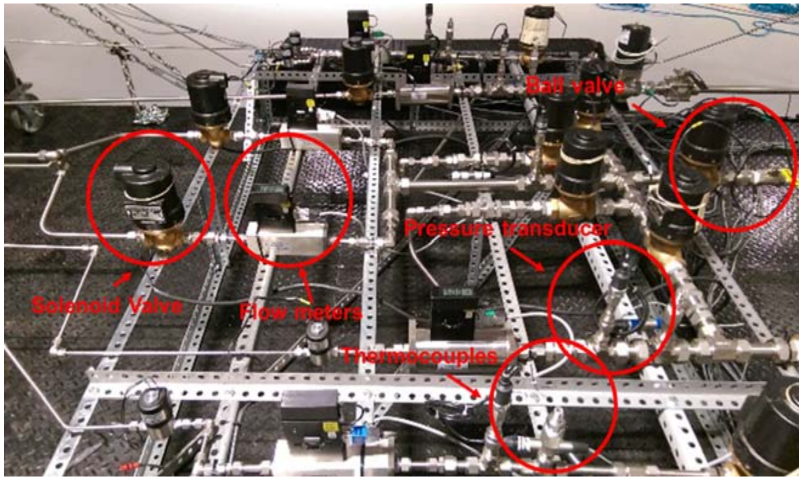
- **P&ID**



Experimental Methodology

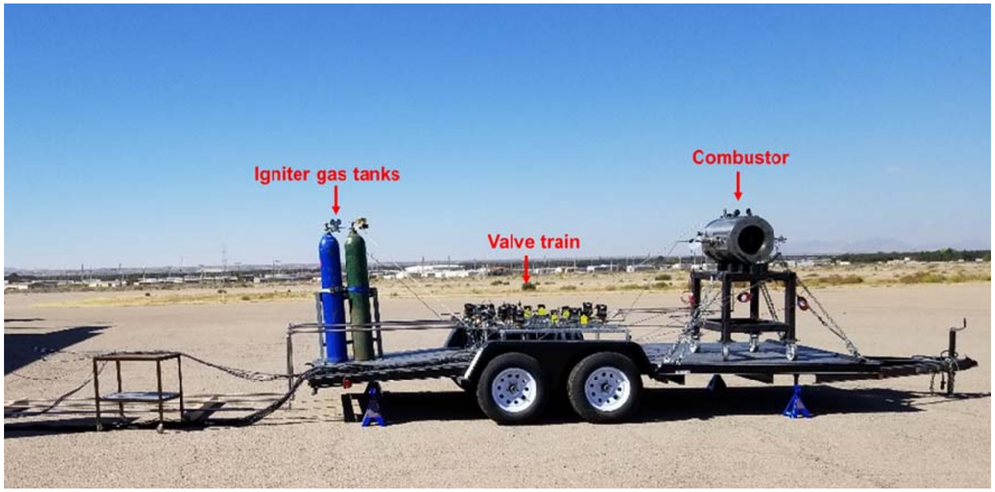
Experimental Setup

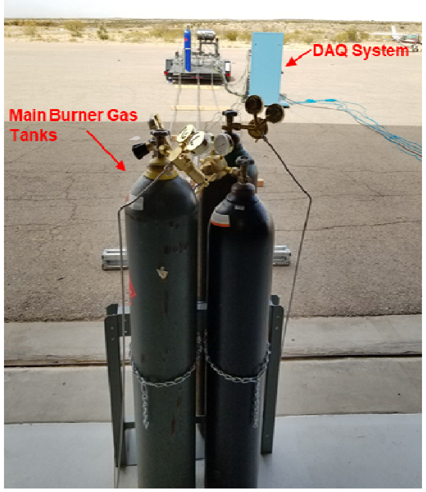


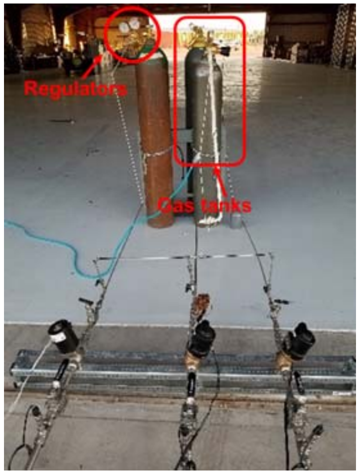


Experimental Methodology

- ☐ **Experimental Setup**

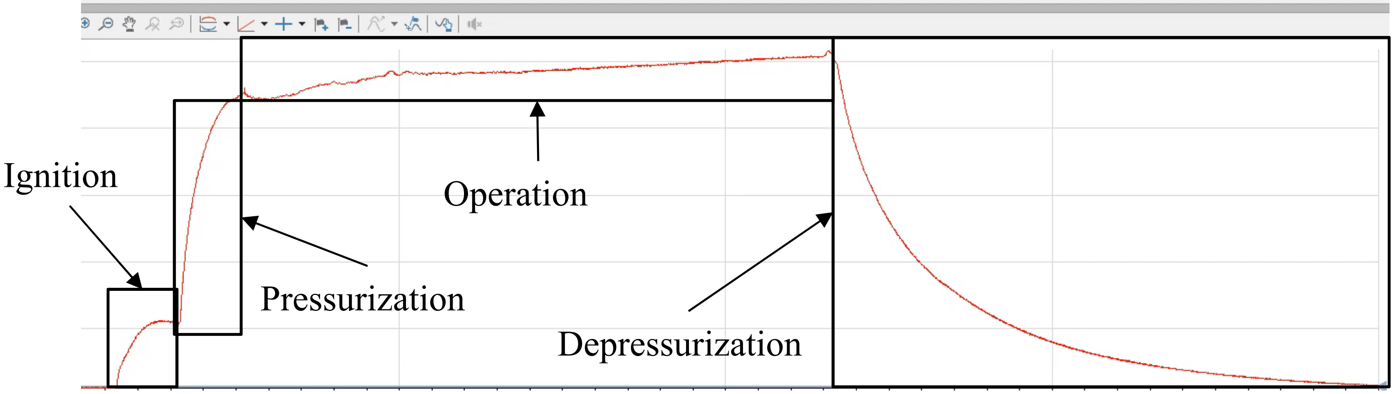






Results and Discussion

Results and Discussion (Case 1)

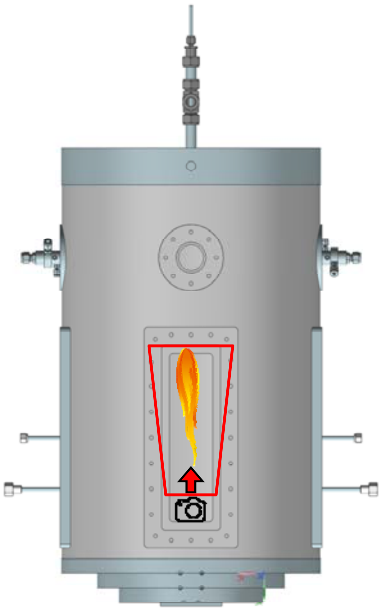


Ignition

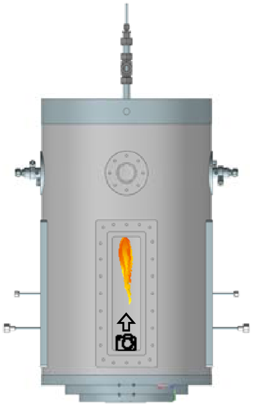
Operation

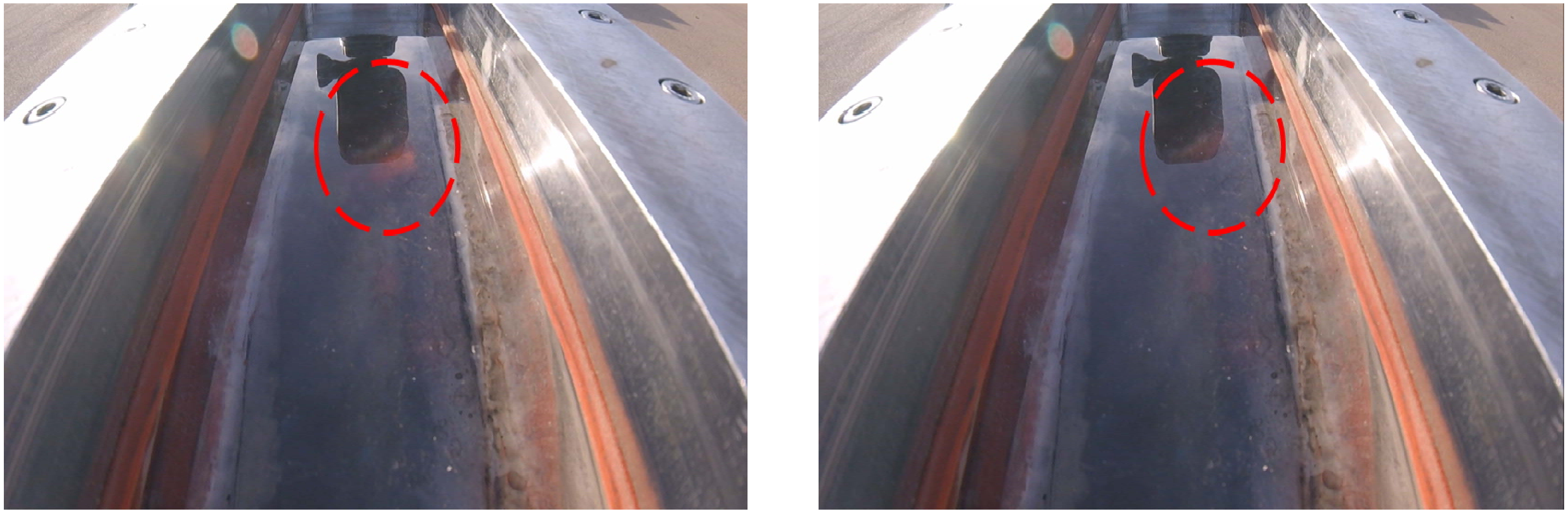
Pressurization

Depressurization



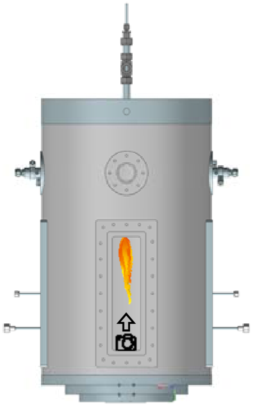
Results and Discussion (Case 1)

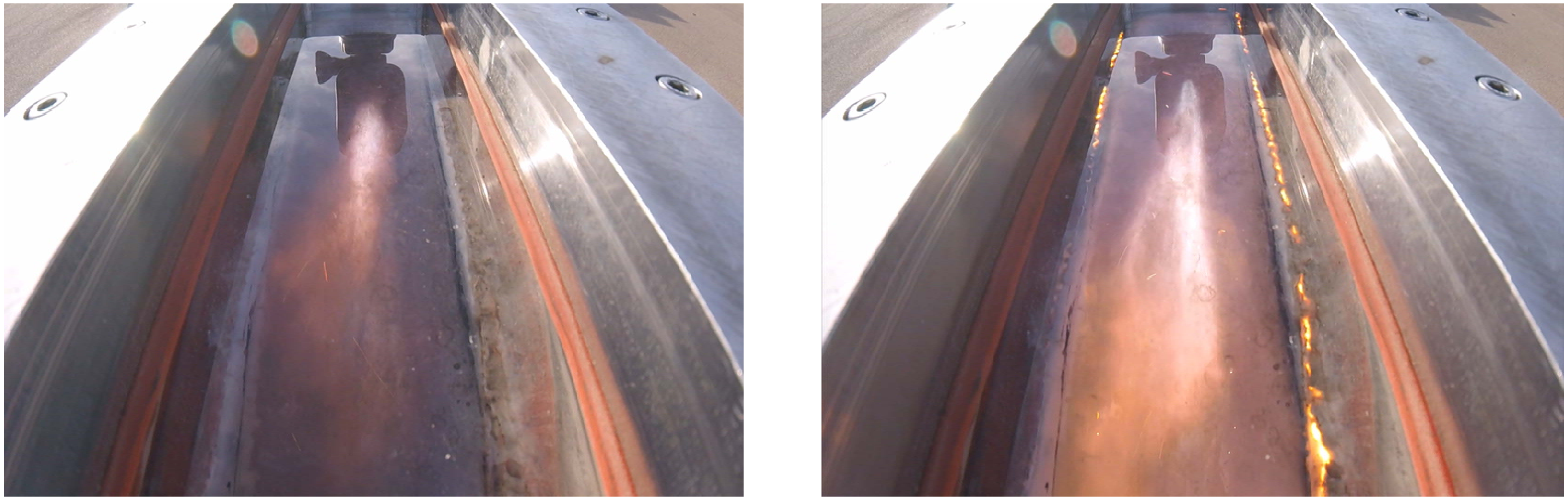




Igniter flame

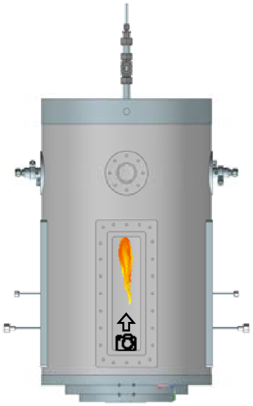
Results and Discussion (Case 1)





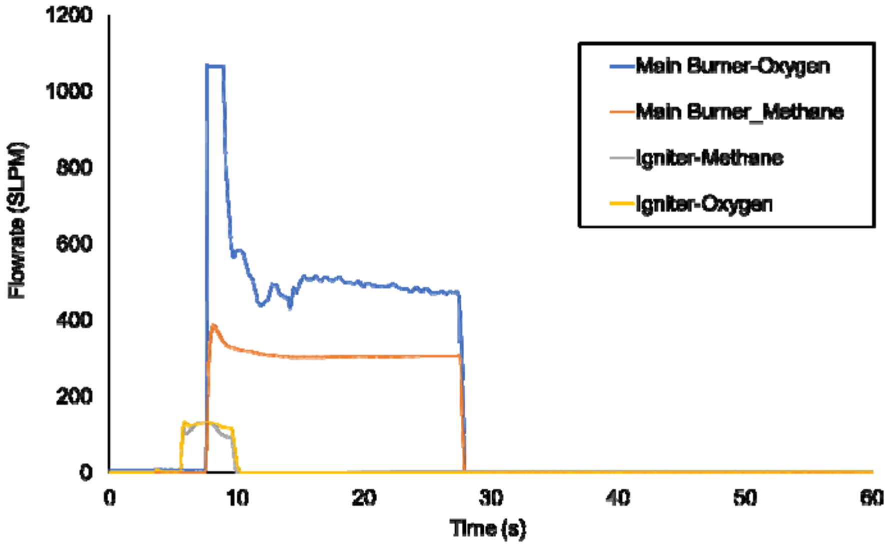
Main burner flame

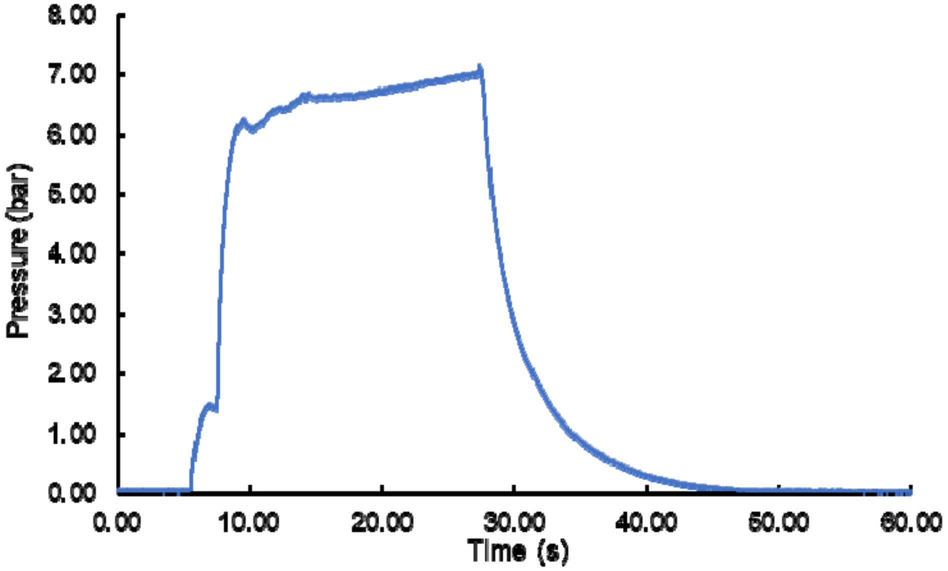
Results and Discussion (Case 1)



160 kW flame images during experiment

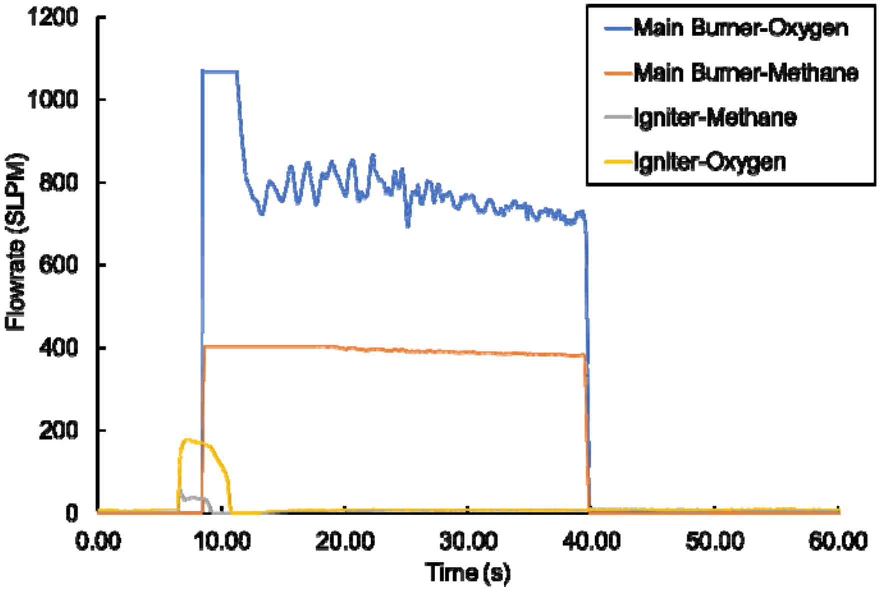
Results and Discussion (Case 1)

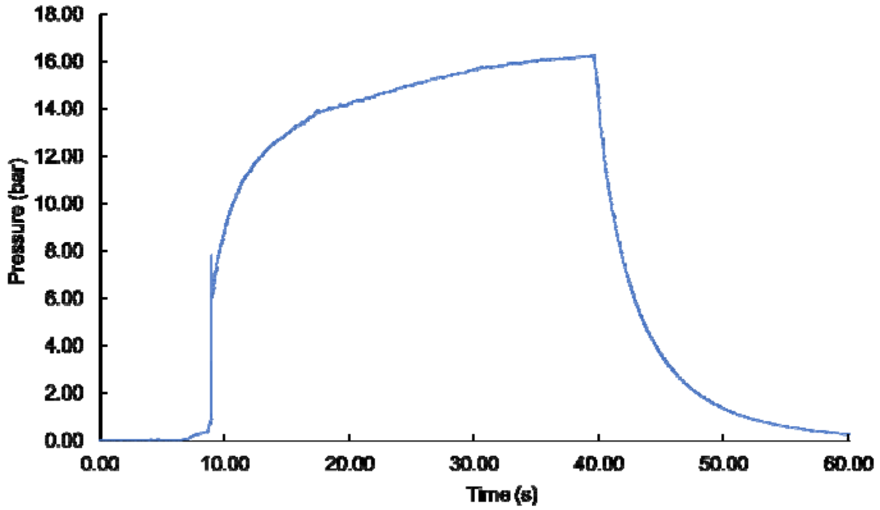




Case 1	Methane	Oxygen	Units
Volumetric Flowrate	306	472	SLPM
Mass Flowrate	3.5	10.5	g/s

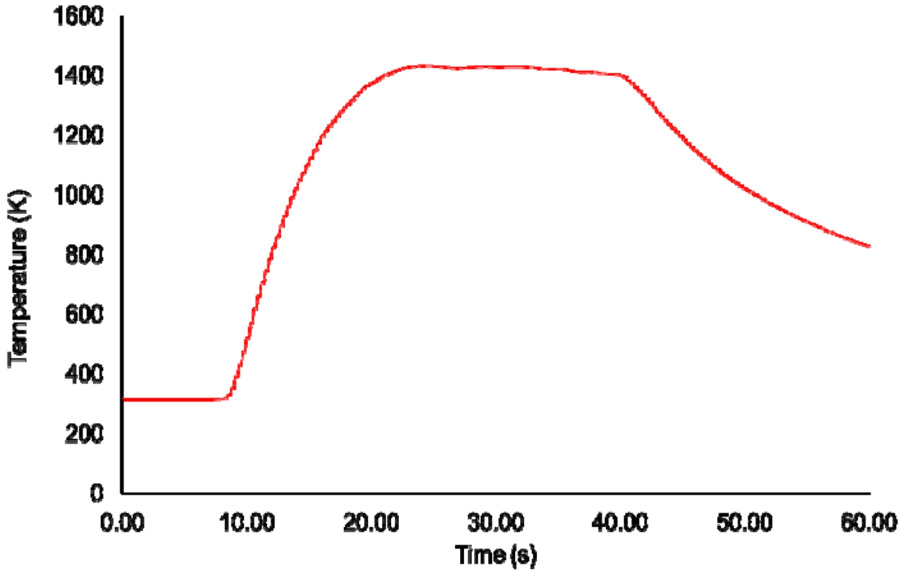
Results and Discussion (Case 2)





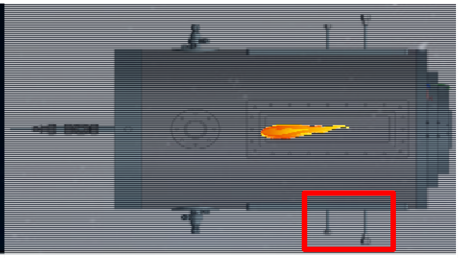
Case 2	Methane	Oxygen	Units
Volumetric Flowrate	400	730	SLPM
Mass Flowrate	4.6	16.3	g/s

Results and Discussion (Case 2)

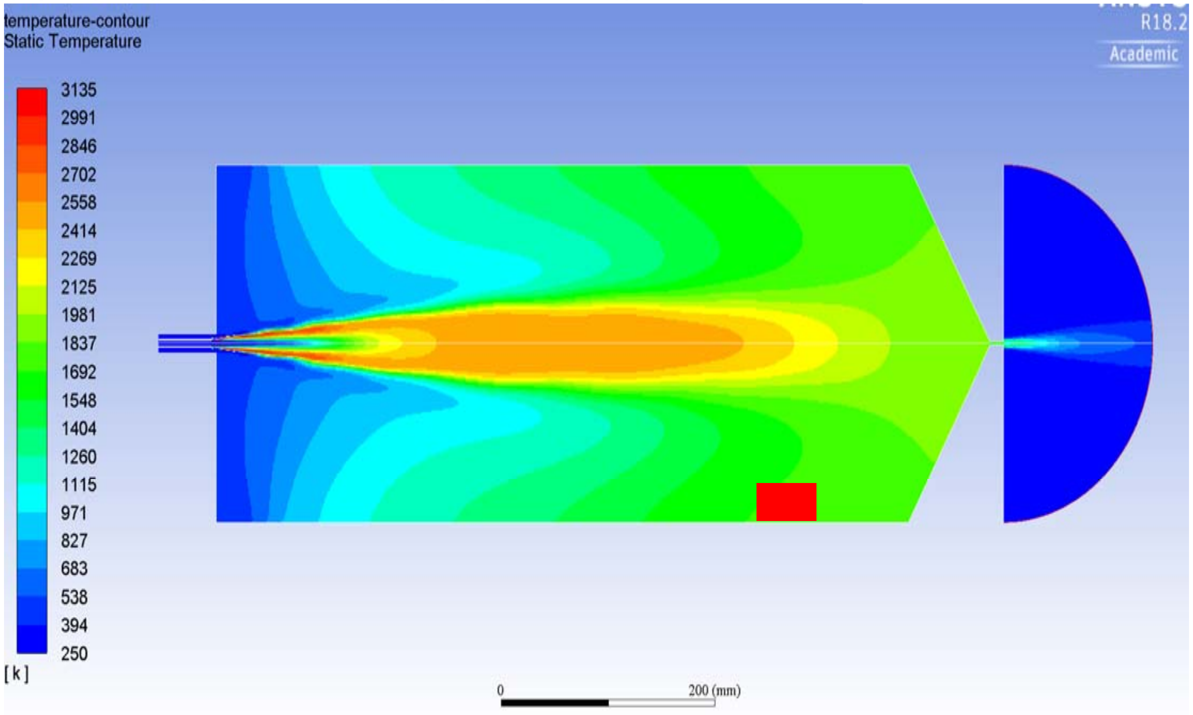


Case 2	Methane	Oxygen	Units
Volumetric Flowrate	400	730	SLPM
Mass Flowrate	4.6	16.3	g/s

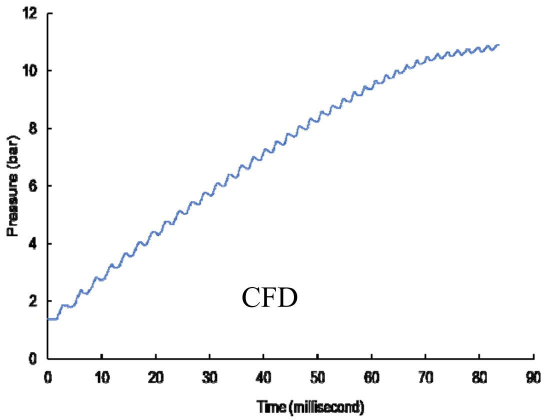
Results and Discussion (Case 1)

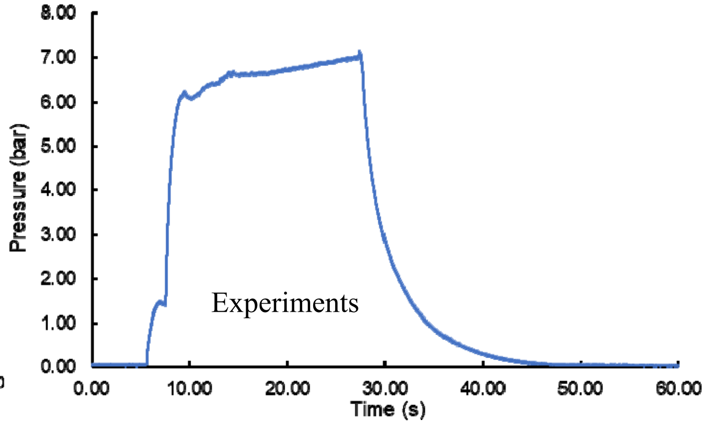


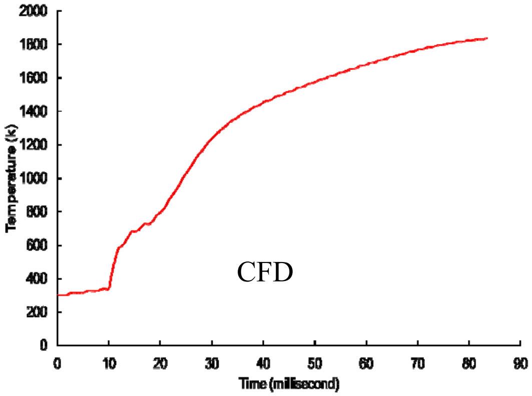
- Calculated flame temperature using NASA CEA: 3300 K
- Max temperature in combustor predicted by Fluent is 3135 K
- Temperature and pressure measured from same location as experiments
    - 438 mm away from the combustor inlet



Results and Discussion (Case 1)

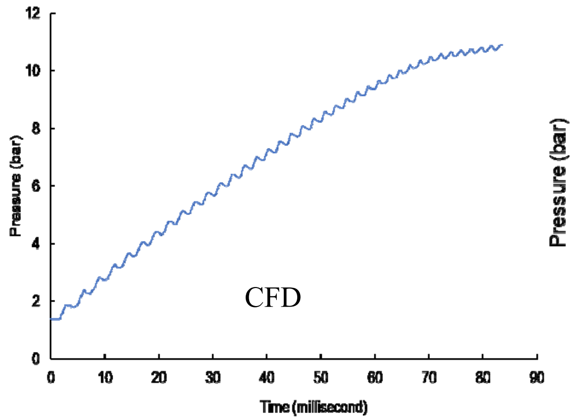


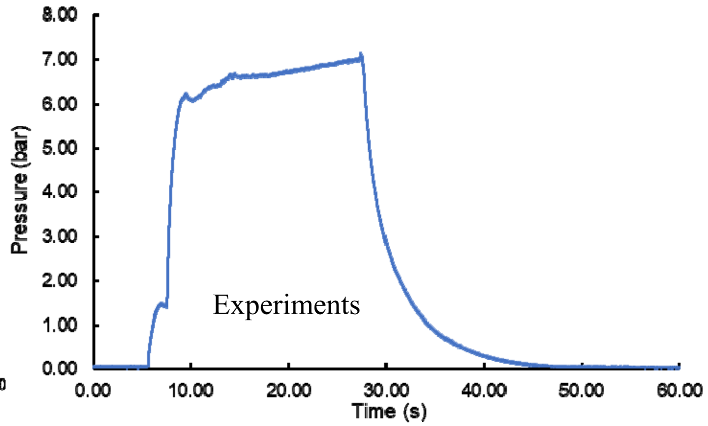


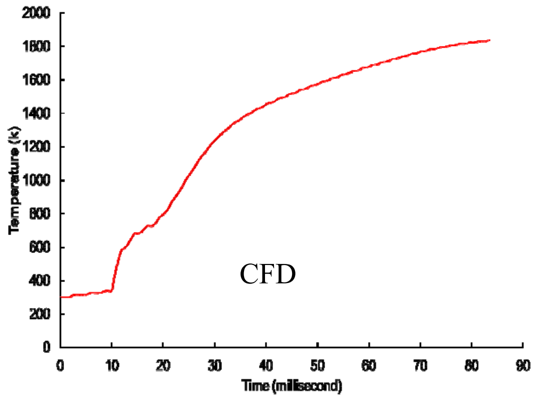


- Comparison between CFD and Experiments shows that pressure in model increases much faster than in experiments. Similar results are seen for temperature.
  - Leakage, heat losses to the walls, valve response times, combustor fill volume, and flow restrictions may account for this since they are not considered in the model.
  - Secondary reasons for the difference may be due to the simplified one-step model leading to inaccuracies in the specific heat values of the gas

Results and Discussion (Case 1)







- ❑ Future modeling efforts include the use of a reduced Aramco mechanism instead of single-step chemistry
- ❑ More experiments are needed including temperature profiles and emissions measurements (CO) to further refine the model

Summary and Conclusions

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- Design and test of an oxy-fuel combustor (operates up to 20 bar)
  - ✓ Combustor body, main burner system, igniter system, pressurizing system, cooling system

- Experimental data are acquired for 2 Cases:
  - ✓ Case 1: 160 kW firing input at a 7 bar combustor pressure
  - ✓ Case 2: 220 kW firing input and 16 bar combustor pressure
  - ✓ No cooling or CO_2 diluents are used for these experiments

- CFD analysis is done based on Case 1 Experimental Conditions
  - ✓ Flame temperatures from CFD results do not exceed calculated estimates from NASA CEA
  - ✓ Modeled temperatures and pressures rise in 100 milliseconds compared to 10s for experiments (100 times faster)

- Discrepancies in the temperature and pressures profiles may be due to:
  - ✓ Leakage, heat losses to the walls, valve response times, combustor fill volume, and flow restrictions may account for this since they are not considered in the model.
  - ✓ Secondary reasons for the difference may be due to the simplified one-step model leading to inaccuracies in the specific heat values of the gas

- Future work includes:
  - ✓ Use of a reduced Aramco mechanism instead of single-step chemistry
  - ✓ More experiments are needed including temperature profiles and emissions measurements (CO) to further refine the model

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