High-Pressure Ignition and Flame Propagation Studies of CO_2 Diluted Oxy-Fuel Mixtures

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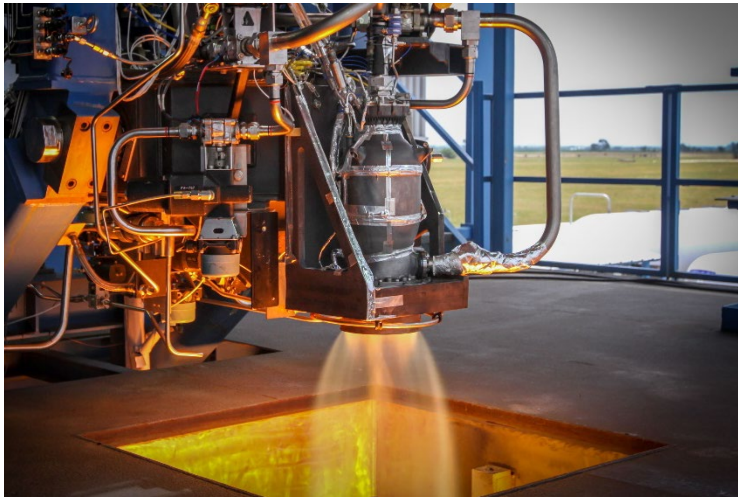
Outline

- Introduction
- Experimental setup
  - High voltage CDI electrical spark generation
  - Laser ignition
- Ignition limit
- Pressure data and peak pressure
- Flame images
- Summary and conclusion

Introduction

- Combustion of CO_2 diluted mixtures at high pressures
  - Direct fired sCO_2 power cycles
  - Carbon capture and storage
  - Biogas and future alternative energy resource
  - Propulsion devices

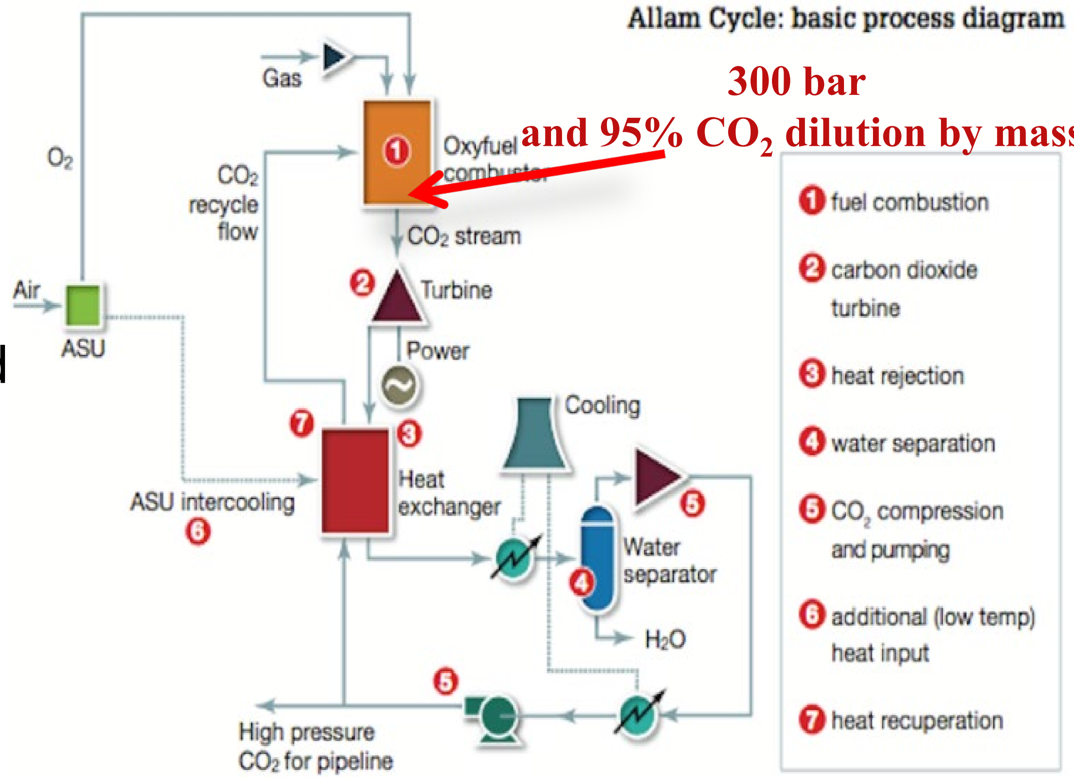


Rocket engine test by SpaceX

Direct fired sCO2 plant by NET Power

Introduction

- Combustion and ignition characteristics of CO_2 mixtures provide an important basis
- Extreme conditions in direct-fired sCO_2 power cycles
  - Very high pressure, over 300 bar in the combustors
  - High temperature



Introduction

Experimental combustion research with CO_2 mixtures

- Low chemical reaction rate
  - CO_2 dissociation into CO and reduced H radicals
  - H is necessary for initiating branching reactions
  - Reduction of H reduces overall reaction rate

$$CO_2 + H \leftrightarrow CO + OH$$

- High heat loss
  - CO_2 enhances radiation heat loss
  - Reduced temperature of the flame
  - Further reduction of the reaction rate

- Flame speed of highly CO_2 diluted mixture is very low
- Cellular instability of flame front surface
- Difficult flame initiation in experiments

Introduction

- Combustion of CO_2 diluted mixtures were previously studied in previous studies
- The effect of CO_2 dilution on flame speed is well studied experimentally at low pressures
- Conditions were limited to relatively low pressures
  - **Highest pressure: 8 bar** by [de Persis 2013]

- To reflect realistic conditions in sCO_2 systems, we investigated ignition characteristics and flame speeds in constant volume facility with an emphasis on high pressure conditions

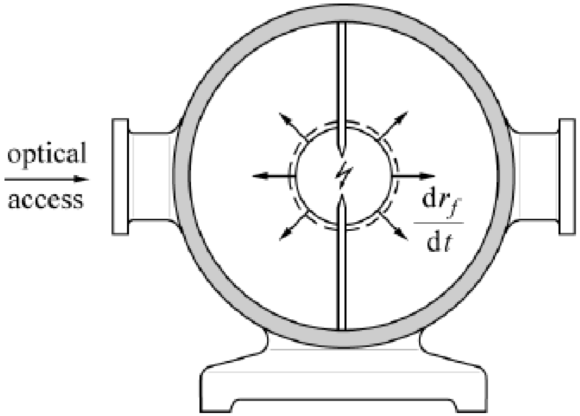
Flame speed measurement

Flame speed measurements at constant volume facility

- Flame initiated by a electric spark or a focused laser pulse
- Spherical propagation of a flame
- Measurements of flame radius growth rate

$$dr_f/dt$$

- Constant pressure and constant volume methods



Flame speed measurement

Constant volume method – pressure data analysis

- Linear X-P relation

$$X_b = Y_b = \frac{p(t) - p_i}{p_e - p_i}$$

- Isentropic compression of unburnt mixture

$$T_u = T_i \left(\frac{p_i}{p}\right)^{1-1/\gamma_u}$$

- Flame speed and volume balance

$$S_u = \frac{R_c}{3}\left[1 - (1 - X_b)\left(\frac{p_i}{p}\right)^{1/\gamma_u}\right]^{-2/3}\left(\frac{p_i}{p}\right)^{1/\gamma_u}\frac{dX_b}{dt}$$

Flame speed measurement

Constant pressure method – flame image tracking

- From kinematic relation

$$\frac{dr_f}{dt} = v_u + s_{L,u}$$

- velocity on the unburnt side

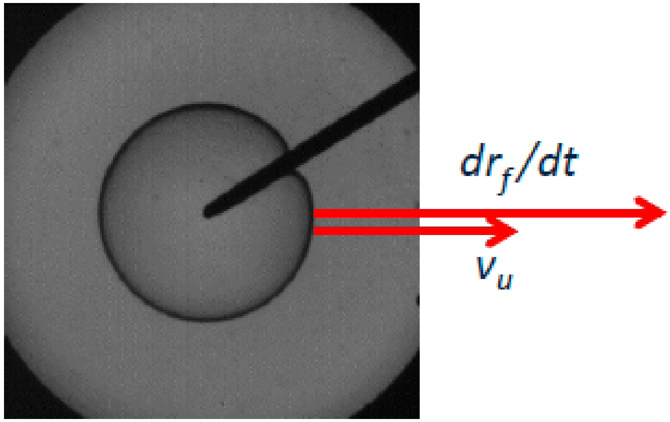
$$v_u - dr_f/dt$$

- Burnt side of the front

$$v_b - dr_f/dt$$

- From mass balance and kinematic relation

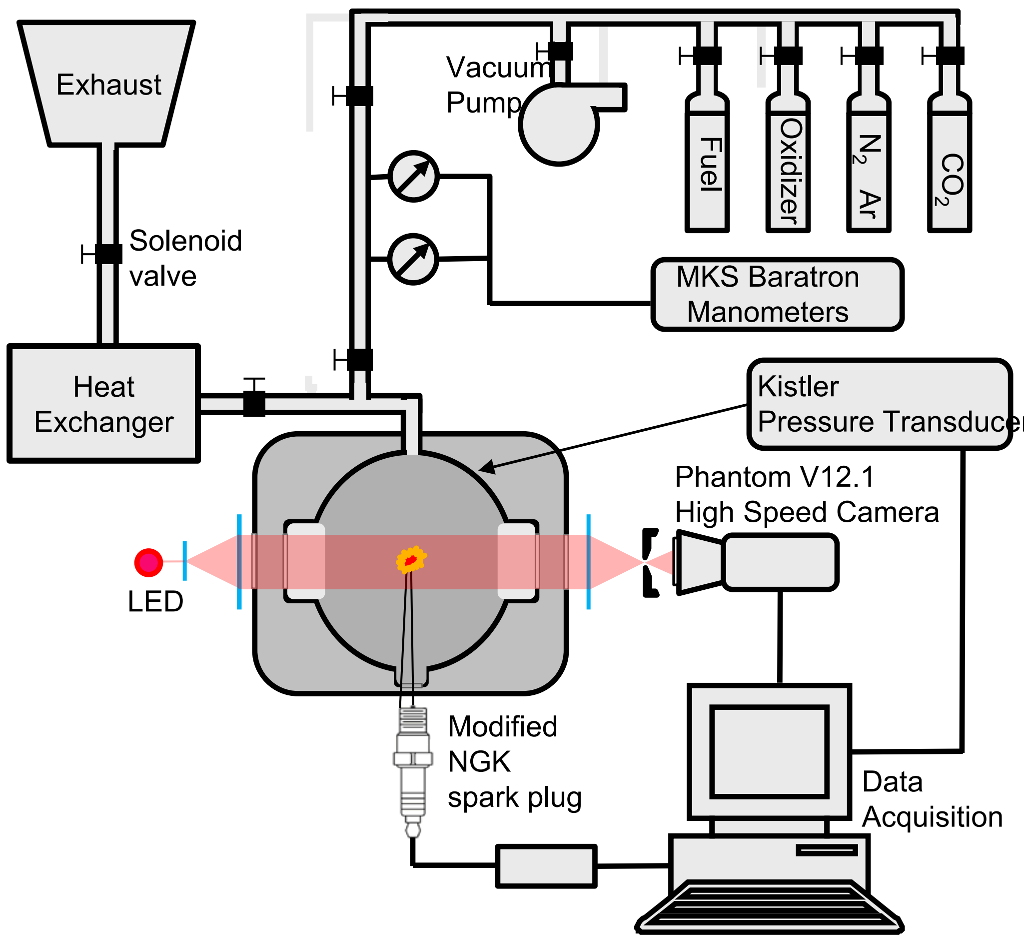
$$\frac{dr_f}{dt} = \frac{\rho_u}{\rho_u - \rho_b} v_u = v_u + s_{L,u}$$



- Laminar flame speed :

$$s_{L,u} = \frac{\rho_b}{\rho_u} \frac{dr_f}{dt}.$$

Setup with electrical spark generator



Ignition issues with CO_2 diluted mix

Challenges: Ignition was not achieved

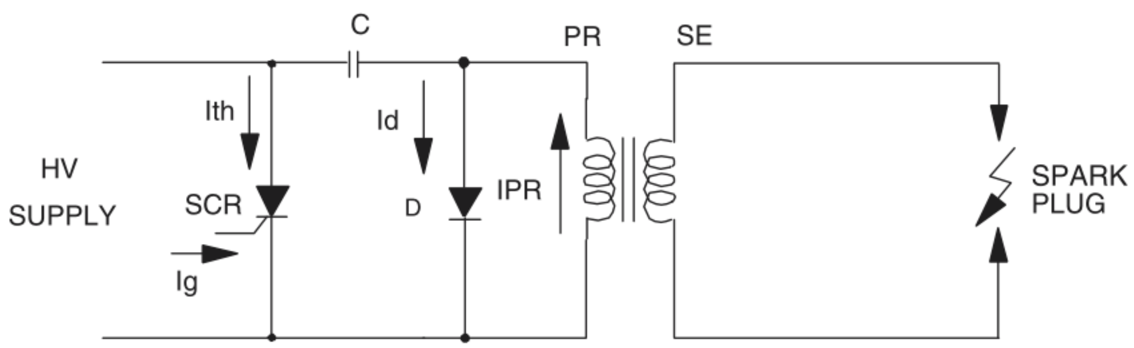
- Ignition was difficult with high CO_2 diluent
- Spark was not visible with a regular spark generator
- Voltage across electrodes is not enough to generate spark by an inductive spark generator circuit

Solutions

- High voltage electric spark generator
- Laser ignition with focused laser pulses

Capacitive discharge ignition

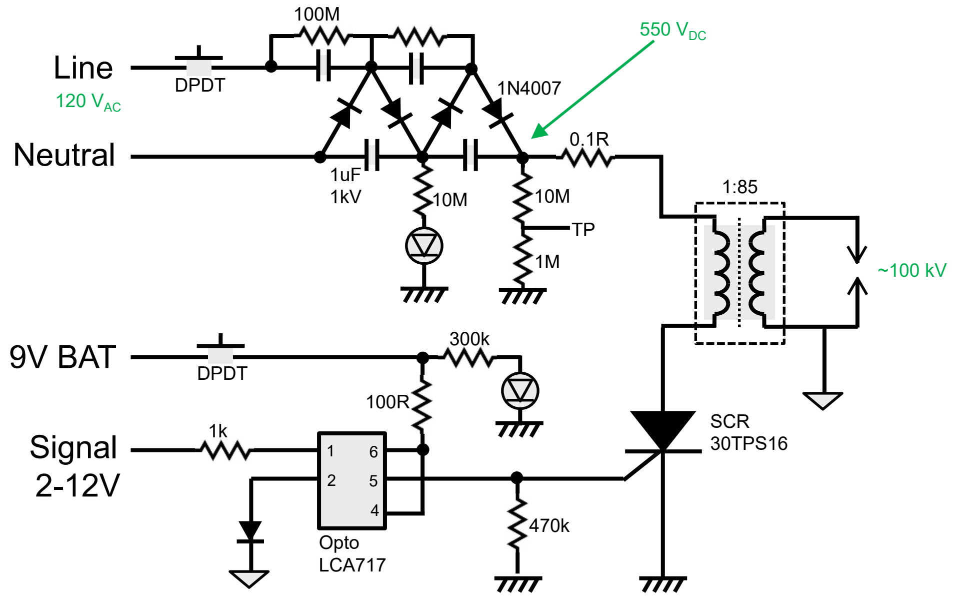
- Two widely used types of ignition system in combustion research are inductive discharge ignition (IDI) and capacitive discharge ignition (CDI).
- Ignition coil is used for both. Difference is how to store energy for primary coil current.
- Common ignition system is IDI. Spark energy is limited by current increase rate to approx. 50 A/ms due to switching devices (mechanical relay and capacitor).
- Performance of CDI systems are better in terms of spark energy and voltage.

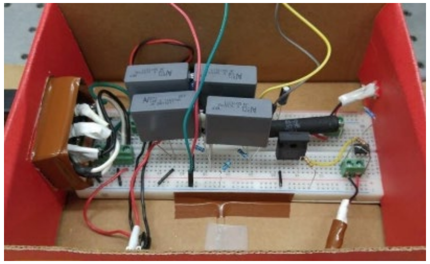


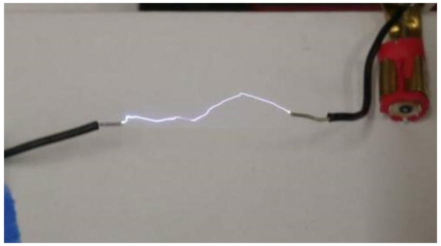
High voltage spark generator circuit

Diagram of the final CDI spark driver circuit

- 120 V AC power was used
- 2 stages of voltage multiplier with 1kV 1uf capacitors to store energy
- MSD 8251 coil 1 mH 85:1
- Opto-coupler LCA717 to receive trigger signal on a different ground
- SCR 30TPS16 was used to switch high voltage and high current







CDI circuit spark discharge across 3 cm air gap

Performance of CDI spark generator

- Conventional inductive ignition circuits generate maximum ~10 kV.
- Spark voltage of new system was estimated to be 47 – 102 kV, with spark energy ~100 mJ.

- Calculations
  - Paschen's law 3.4 MV/m, 102 kV at 3 cm gap.
  - Smooth sine wave assumption: 550 * 85 = 47 kV (conservative)
  - Capacitor energy: $\frac{1}{2}CV^2 = \frac{10^{-6}\times 550^2}{2} = 100\ \mathrm{mJ}$

- Maximum air gap was more than 3 times greater.
- Spark was consistently generated

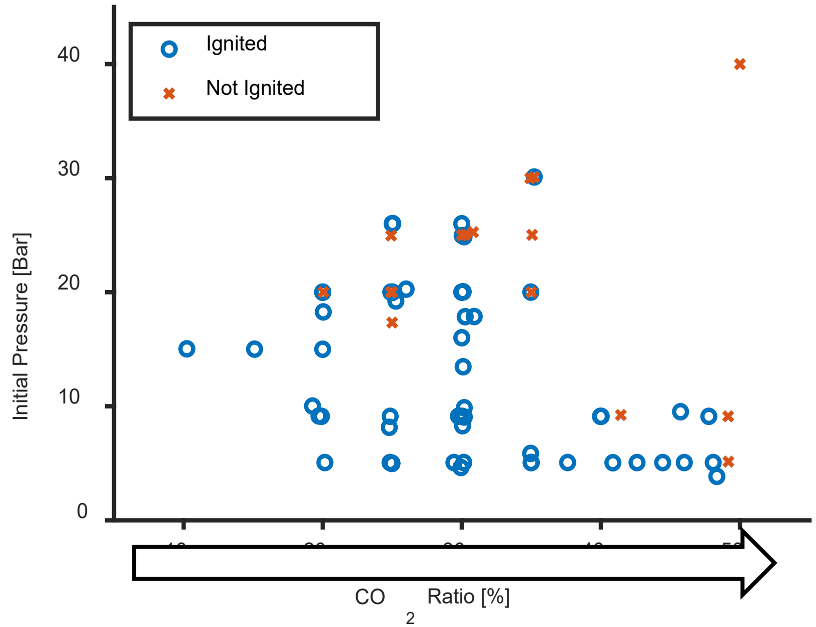
Mixture preparation

Gases	Vol. ratio without CO_2	Vol. percentage with 30% CO_2
Fuel	1	11%
Oxygen	2.1	23%
Nitrogen	2.1	23%
Argon	3.9	43%
CO2	0	30%
Total	9.1	130%

P w/o CO_2 [Bar]	CO_2 20%	CO_2 25%	CO_2 30%
20	24.0	25.0	26.0
32	38.4	40.0	41.6

- Fuel: natural gas hydrocarbon mix, >90% methane
- Ratios of gases were fixed without CO_2
- Added amount of CO_2 was varied up to 48 %
- Equivalence ratio was 1 for the most of cases

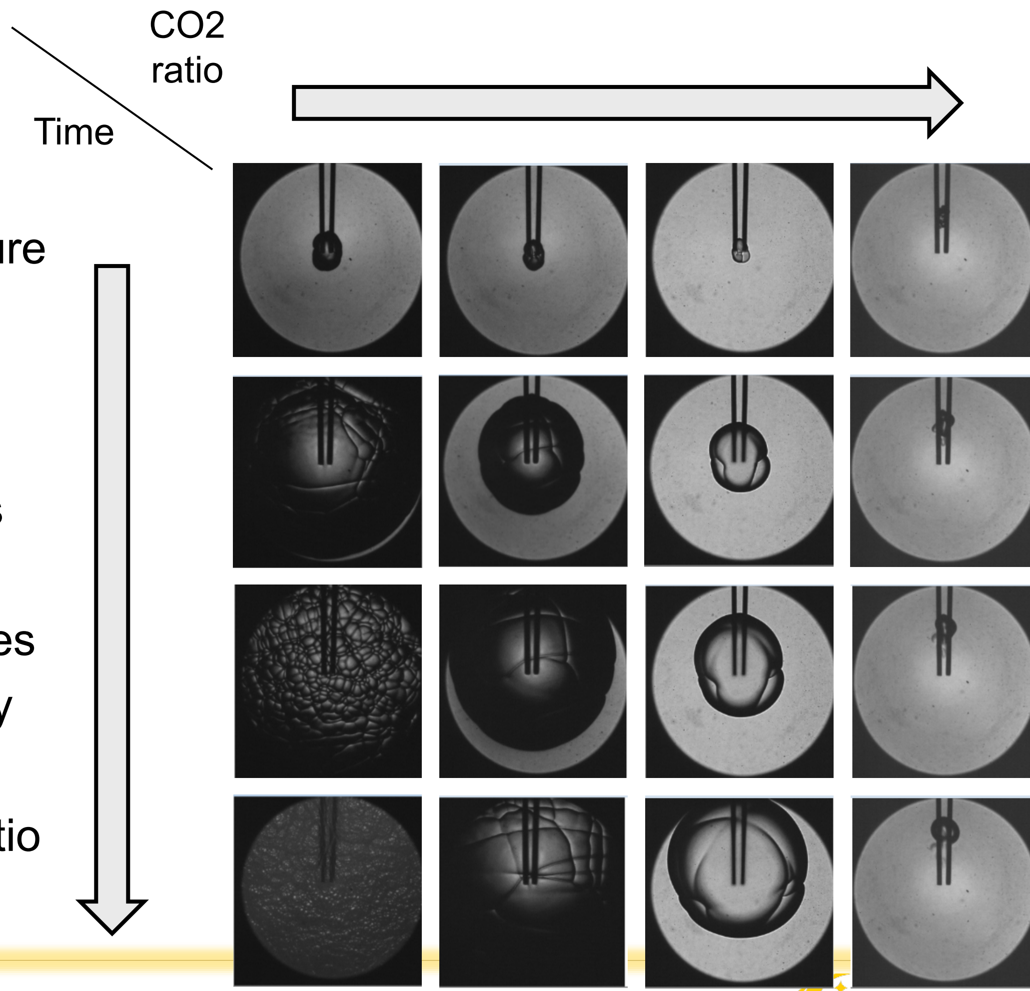
Ignition limit with spark ignition



- It was found that the ignition depends on the amount of CO_2 and initial pressure
- Ignition with high CO_2 dilution at high pressure is difficult

Shadow graph images

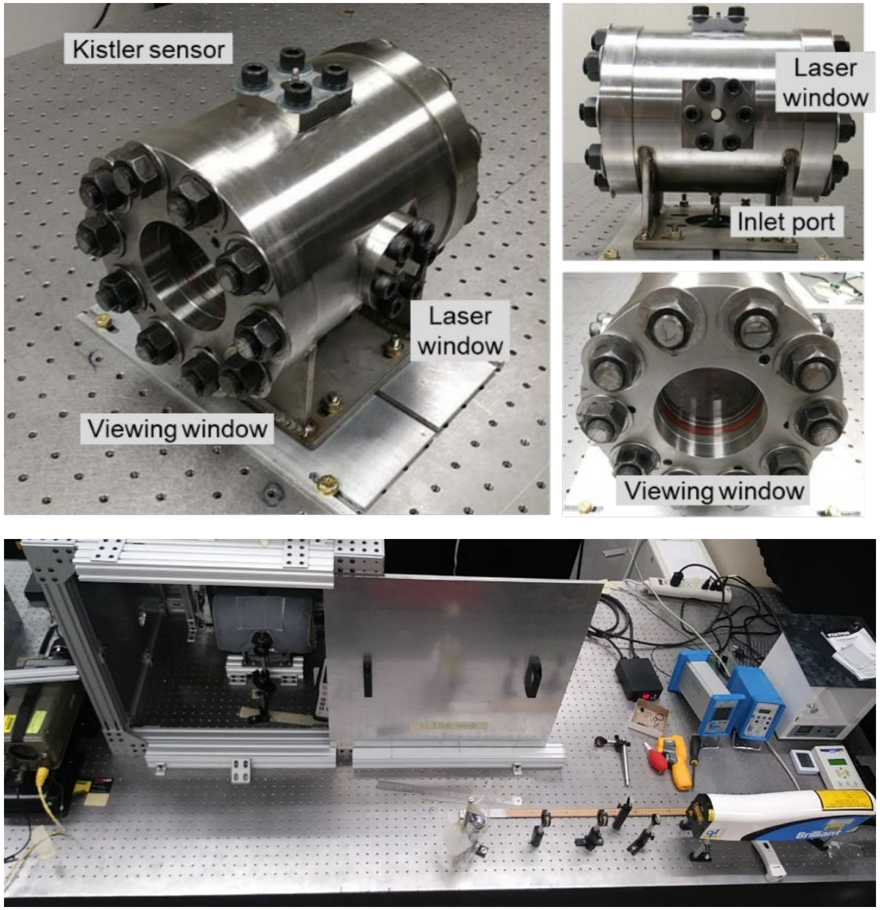
- 9 atm initial pressure
- Additional amount of CO_2 added to the prepared mixture was varied
- Flame surface has cellular structure
- High dilution with CO_2 slows down the flame propagation
- Reduced flame speed causes increases effect of buoyancy
- Flame extinction was observed at highest CO2 ratio



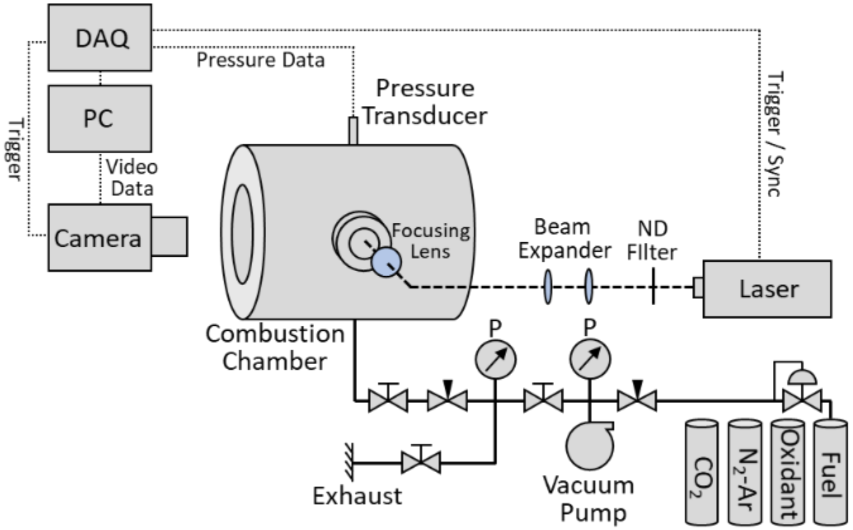
Initial pressure > 20 bar

20% CO_2 of total mixture

Laser ignition experimental setup



- High pressure combustion chamber (max 400 bar)
- A 3-inch sapphire viewing window and a laser window
- Q-switched Nd:YAG laser



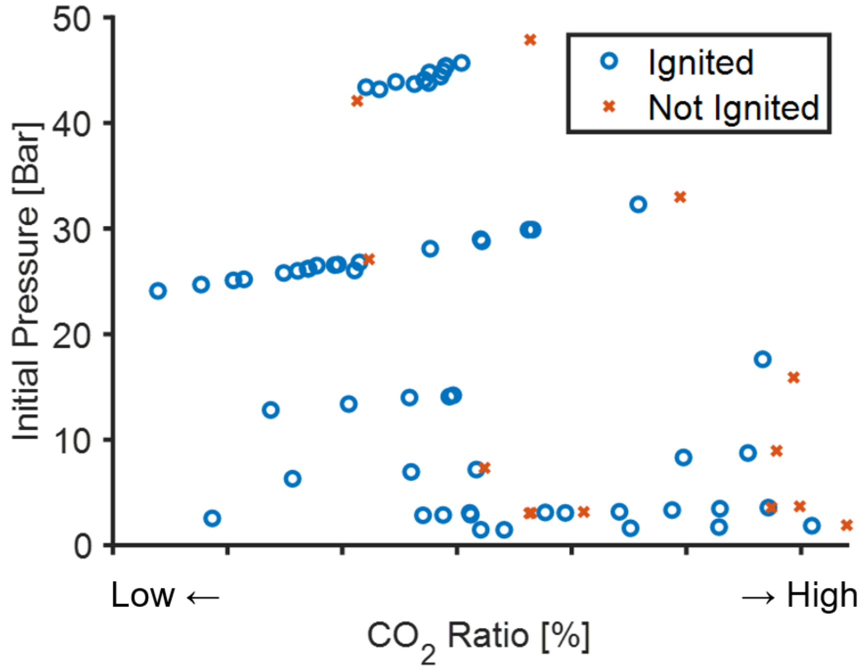
Mixture preparation

- Fuel: natural gas hydrocarbon mix, >90% methane
- Ratios of gases were fixed without CO_2
- Added amount of CO_2 was varied
- Equivalence ratio was 1 for the most of cases

Gases	Vol. ratio without CO_2	Vol. percentage with 30% CO_2
Fuel	1	11%
Oxygen	2.1	23%
Nitrogen	2.1	23%
Argon	3.9	43%
CO2	0	30%
Total	9.1	130%

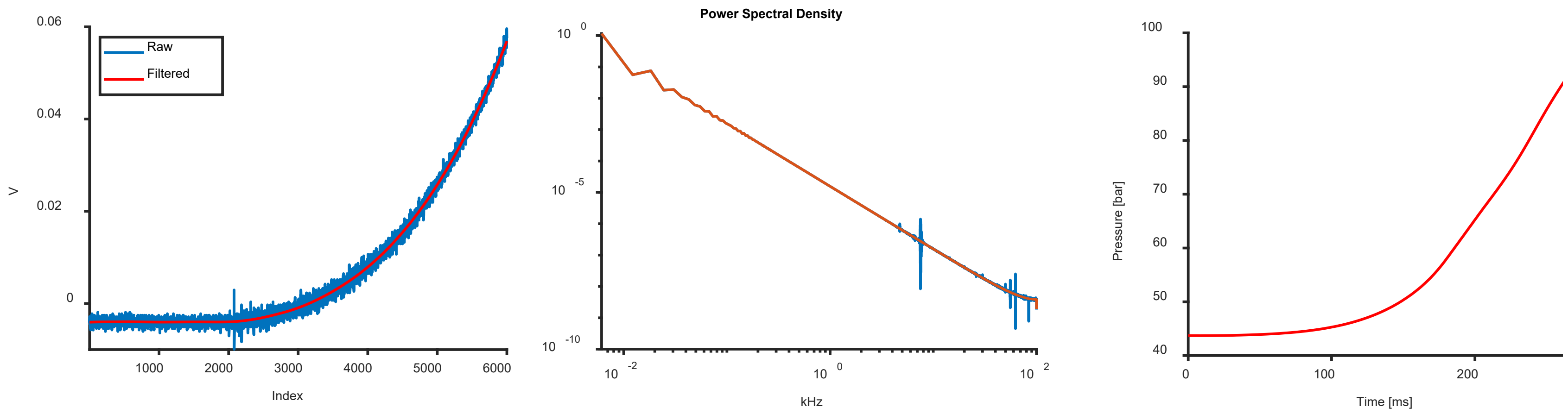
Ignition limit with laser ignition

- It was found that the ignition depends on the amount of CO_2 and initial pressure
- Ignition with high CO_2 dilution at high pressure is still difficult, **but laser ignition can go to higher pressures than with the spark igniter**



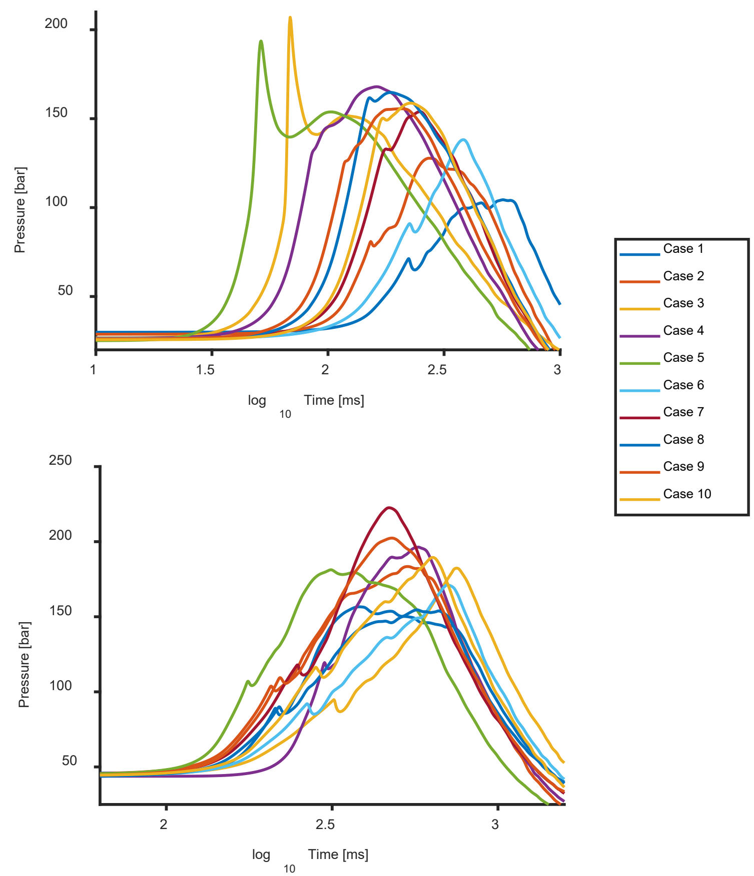
Pressure data analysis

- For flame speed calculation, smoothing was applied by low pass filter
- 2nd order low-pass filter at 300 Hz was used to remove high frequency noise
- Noise related to fundamental Helmholtz resonance frequency exists at 3-5 kHz

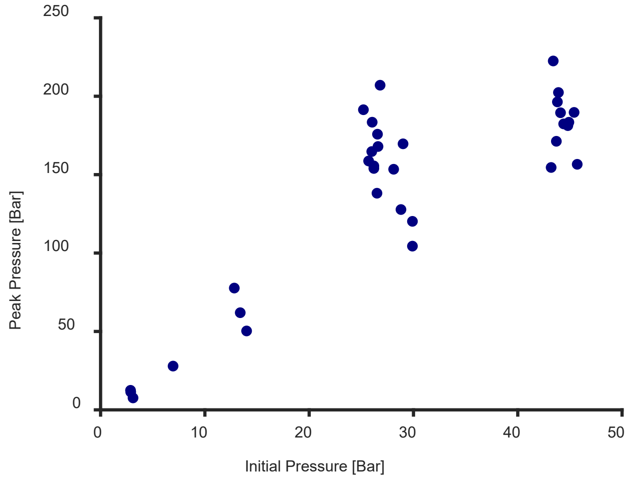


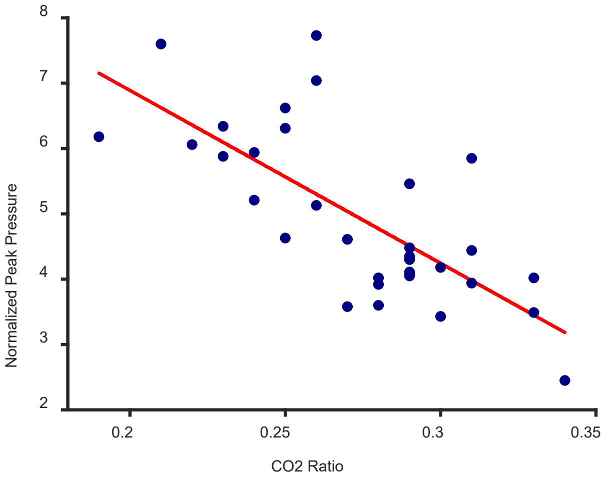
Pressure data analysis

Case #	Initial T [°C]	Initial P [Bar]	ϕ	Peak P [Bar]	Peak time [ms]
Peak pressure ~ 150 Bar					
1	50	29.9	1.0	104.4	568.3
2	50	28.8	1.0	127.8	274.2
3	50	26.8	1.0	207.0	68.8
4	50	26.6	1.0	168.0	162.1
5	50	25.2	1.0	191.4	52.0
6	50	26.5	1.1	138.2	383.1
7	50	26.2	1.1	154.0	248.3
8	50	26.0	0.9	164.7	185.2
9	50	26.2	0.9	155.6	210.2
10	50	25.7	1.1	158.7	226.1
Peak pressure ~ 200 Bar					
1	50	45.7	1.0	156.6	385.2
2	50	44.9	1.0	183.4	533.3
3	50	44.4	1.0	182.4	748.7
4	50	43.8	1.0	196.4	575.0
5	50	44.8	1.0	181.3	313.4
6	50	43.7	1.0	171.3	702.8
7	50	43.4	1.0	222.5	473.2
8	50	43.2	0.9	154.6	571.7
9	50	43.9	0.9	202.4	477.6
10	50	44.1	1.1	189.5	633.0



Pressure data analysis



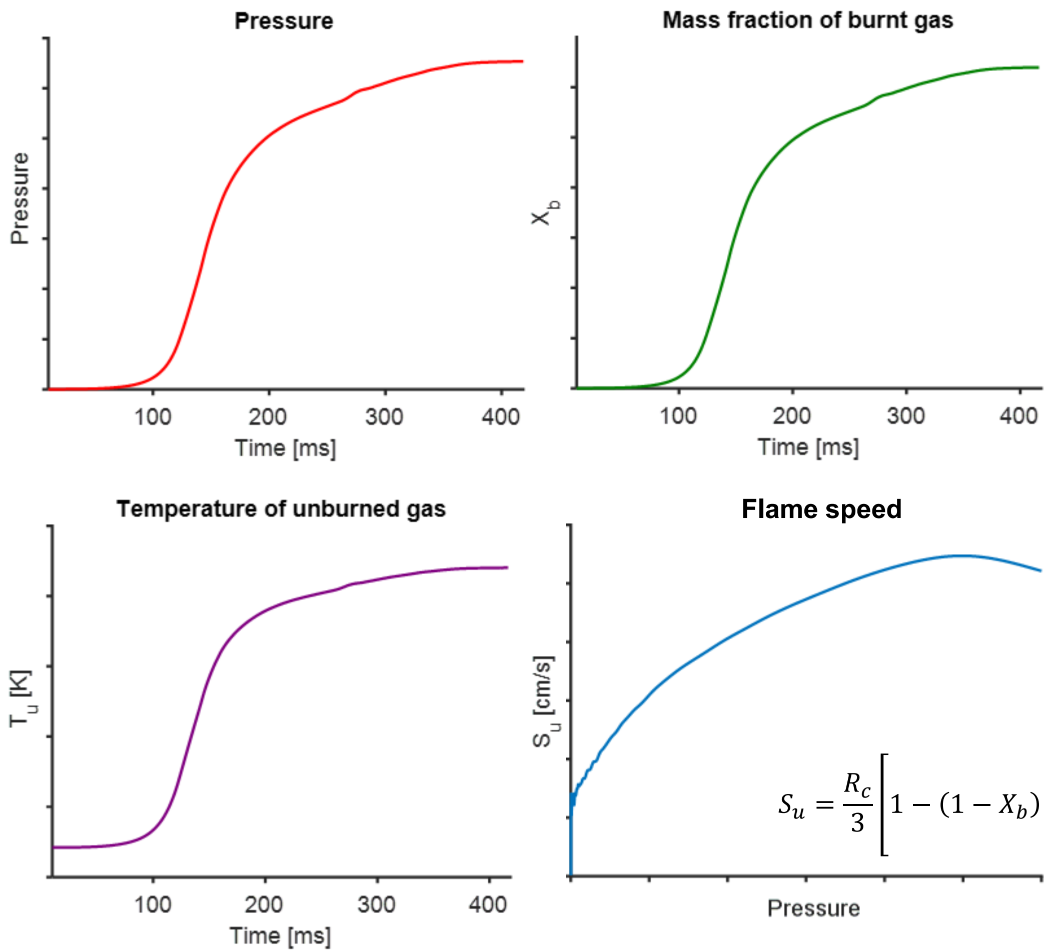


- Peak pressure by initial pressure (left) and normalized peak pressure vs CO_2 ratio (right).

$$\frac{P_{max}}{P_{init}} = -26.46\, X_{CO2} + 12.18$$

R^2: 0.5235
RMSE: 0.9109

Flame speed calculation

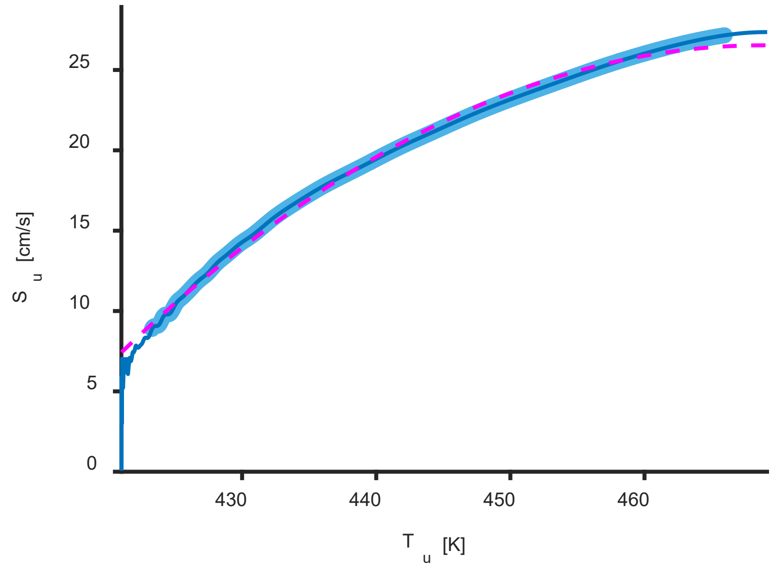


$$S_u = \frac{R_c}{3}\left[1-(1-X_b)\left(\frac{p_i}{p}\right)^{1/\gamma_u}\right]^{-2/3}\left(\frac{p_i}{p}\right)^{1/\gamma_u}\frac{dX_b}{dt}$$

Flame speed curve fitting

Flame speed vs temperature was calculated

- Curve fitting by 2nd order polynomial extrapolation for flame speed at initial condition
- 7.07 cm/s at 20 bar, 429 K and 5.86 cm/s at 26 bar, 422 K.
- Uncertainty of flame speed caused by curve fitting is 0.023 cm/s



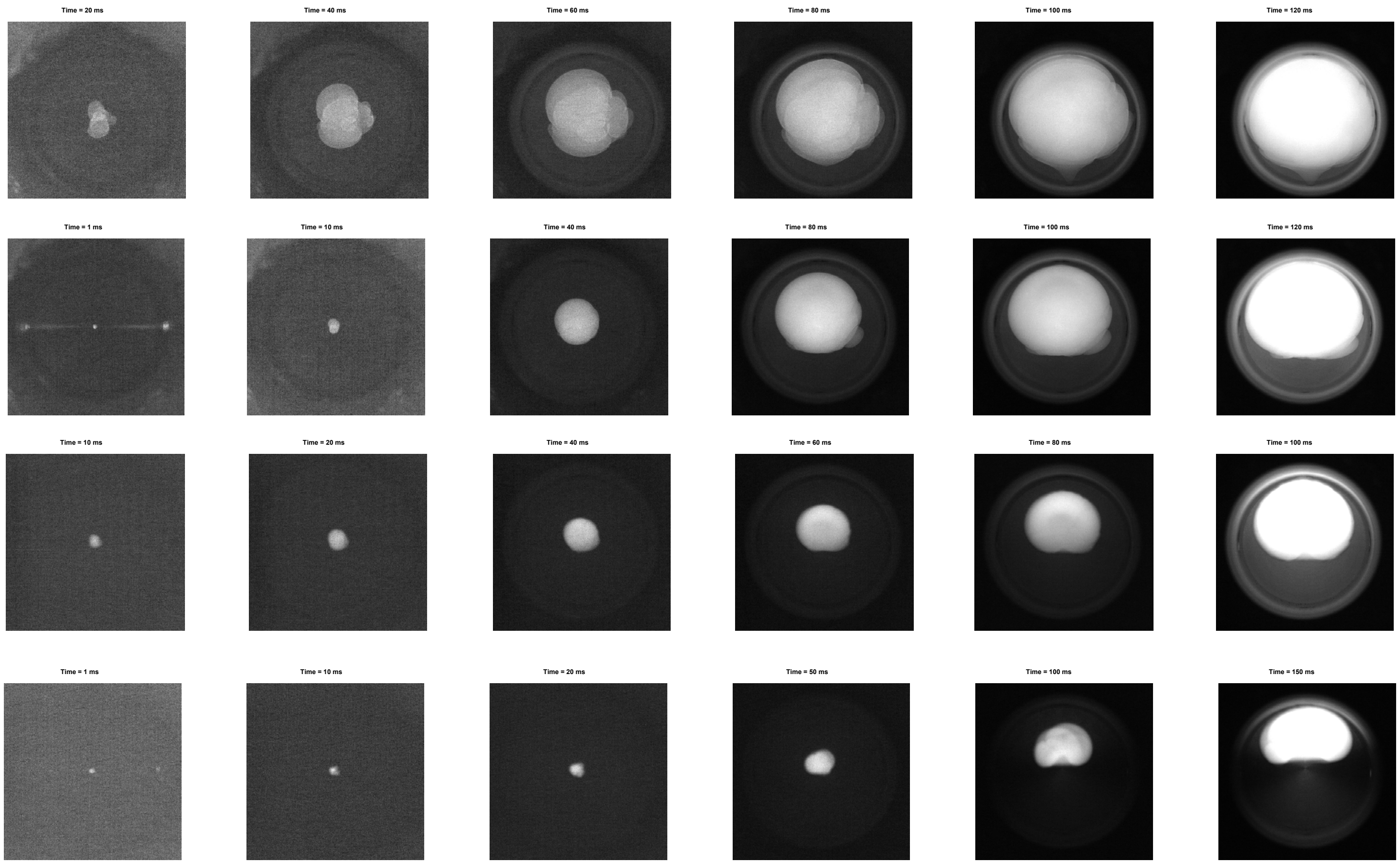
Flame images show buoyant flame

Highly buoyant, cellular surface, non-spherical flames

Initial 29.9 Bar

Initial 43.7 bar

Flame images



Initial 3.1 Bar

Initial 7.0 Bar

Initial 29.9 Bar, Peak 120.2 Bar

Initial 43.7 bar, Peak 171.3 bar

Summary / Conclusion

- Ignition and combustion of CO_2 diluted hydrocarbon mixture were studied at constant volume facility
  - Mixures at high pressure with high amount of CO_2
  - Both high voltage electirical spark and laser ignition system were tested
  - Ignition limit, flame images, and flame speeds are reported
  - Maximum recorded peak pressure after the combustion was 222.5 bar with 43.4 bar initial pressure
- Flame speed measurement
  - The effect of CO_2 reduced the flame speed significantly.
  - Measured flame speeds were 7.07 cm/s at 20 bar, 429 K and 5.86 cm/s at 26 bar, 422 K.
- Flame shape of CO_2 mixture
  - Highly buoyant
  - Cellular flame surface
  - Non-spherical flames

Acknowledgements

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