Thermal effect of N_2O being oxidizer on combustion characteristics of laminar premixed methane flames

以一氧化二氮作為氧化劑的熱效應對於層流甲烷預混火焰燃燒特性之影響

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Oral Defense

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Background

Spacecraft → 40 mins

Benefits :

- ✓ Earth transportation
- ✓ Long distance trips
- ✓ Large thrust
- ✓ travelling in space
- ✓ Easy payload to low earth orbit
- ✓ Interplanetary transport

https://www.spacex.com

Atmosphere

↓

Greenhouse gases

↓

Pollution emission

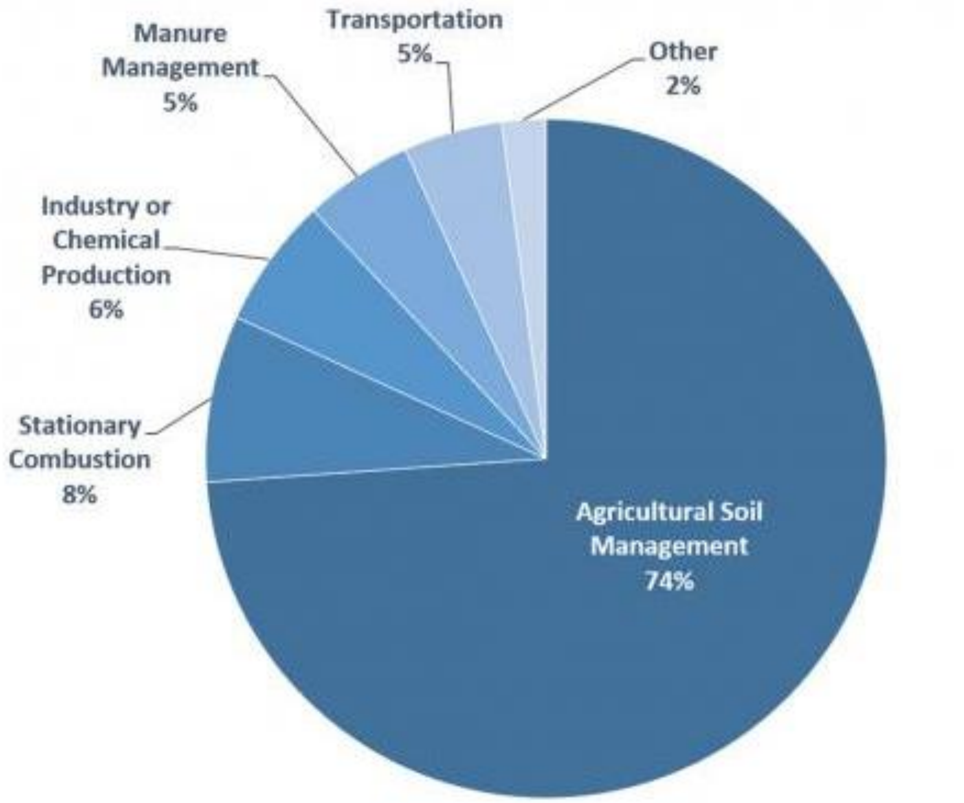
↓

Climate Change

Background

- N_2O is one of the greenhouse gases.
- It is about 6 % emission in GHS.
- It also have higher global warming potential than the CO_2.
- Most of the N_2O come from human activities is 5.6%.

Source of Nitrous oxide



https://www.epa.gov/ghgemissions/overview-greenhouse-gases.

Introduction

❑ Nitrous oxide (N_2O) is often used as the oxidizer propellant for propulsion systems, it is so-called “green propellant”

❑ **Nitrous oxide (N_2O, also called as laughing gas)**

✓ Total reaction step： $N_2O \rightarrow N_2 + \frac{1}{2}O_2 + 82\left(\frac{\mathrm{MJ}}{\mathrm{kmol}}\right)$

✓ Temperature of self-decomposition：≌ 800 K

✓ Temperature of maintained self-decomposition ：≌1273 K

✓ Adiabatic flame temperature ：2900 K

Introduction

N_2O Combustion

Advantages :

- ✓ Strong oxidizer
- ✓ Thermal exothermicity
- ✓ Reduce the volume of oxidizer
- ✓ Improve flame stability
- ✓ Increase flame temperature
- ✓ Positive enthalpy of formation
- ✓ Pathway to NO_x formation
- ✓ Large heat release

Applications:

- ✓ Space propulsion system
- ✓ Heating process
- ✓ Industrial applications
- ✓ Lab-scale burners
- ✓ Glass industry manufacturing
- ✓ Gas-turbine combustion chamber
- ✓ In diesel engines

Literature review

- **T. Newman Lehman et al. 2013 -** Studied the combustion behavior of CH_4/N_2O/Air and C_2H_6/N_2O/Air premixed flames, and found that the burning velocity decreases with increasing mass fraction of N_2O premixed mixture. Therefore, replacing O_2 by N_2O inhibits the flame.

- **Domina Razus et al. 2018 -** Investigated the flame speeds of nitrogen diluted CH_4/N_2O mixture under equivalence ratios of 0.8 and 1.0, results shows that the decrease in the laminar burning velocity and flame temperature along with increase of flame width.

Literature review

- **Vanderhoff et al. 1986 –** They studied the H_2/N_2O premixed flame, the equivalence ratio changed from lean to stoichiometric, temperature distribution and NO, O_2, N_2, and OH concentration distributions were obtained for preliminary results.

- **C.H.Chen et al. 2018** – Investigated dissociated from N_2O combustion under the dilute gases on the combustion characteristics of CH_4/N_2O IDF and reports that the thermal effect is dominated the chemical effect which affects the increase in flame temperature through reaction pathways of diluted N_2O combustion.

Introduction

Oxy-enrich combustion :

- If the oxygen concentration exceed ***21%***, it called as **oxy-enriched combustion**.

- **Advantages**
  - ✓ Reduce the total amount of oxidizer
  - ✓ Increase the flame temperature
  - ✓ Save energy
  - ✓ Reduce pollutant emission

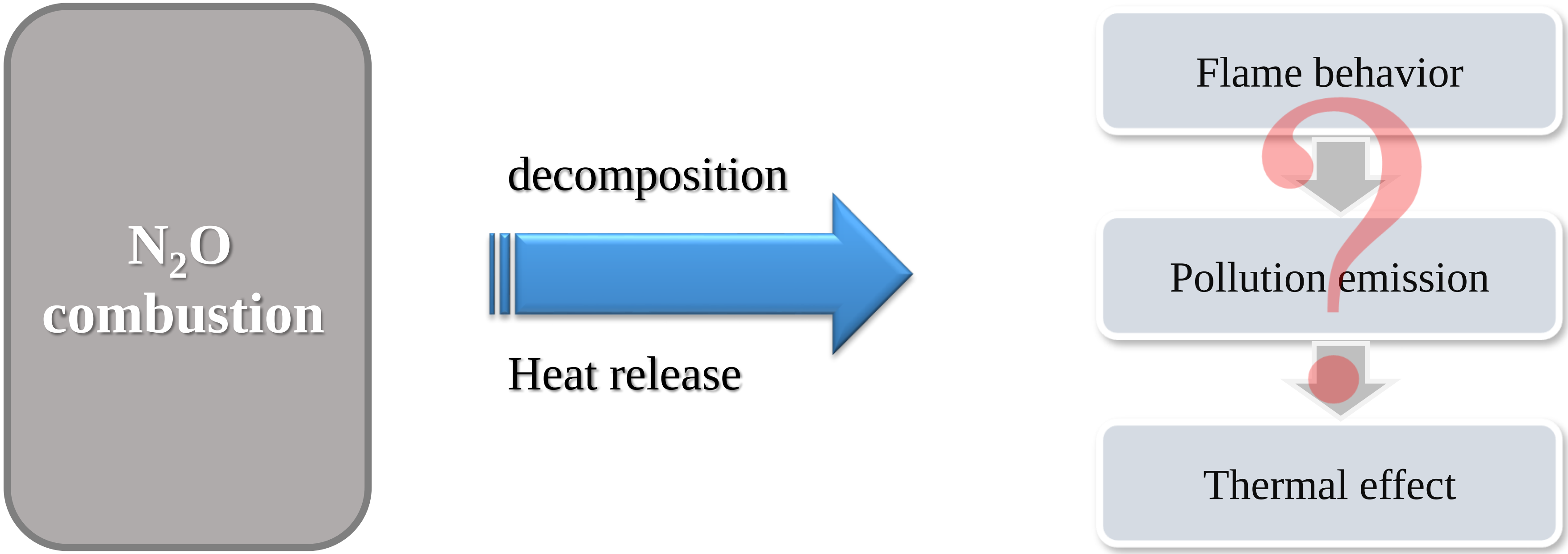
- **Disadvantages**
  - ✓ Higher cost
  - ✓ Low reliability of system

Literature review

- **S.Sharma et al. 2012 -** Investigated the temperature profile in axi-symmetric premixed butane/air flames using the fourier transform digital holographic interferometry, concluded that the flame width increases slightly but the measured temperature decreases as the supply of air induced.

- **Z.N.Ashrafi et al. 2015 -** Investigated the 2D temperature field, flame structure and its isotherm pattern in a slot burner of CH_4/air flames using MZI, and found that the thermal flame height is varied by Reynolds number. MZI measurement data is validated using the K-type thermocouple.

Motivation



N_2O combustion

decomposition

Heat release

Flame behavior

Pollution emission

Thermal effect

?

Objective

N_2O and Oxy-enrich Combustion

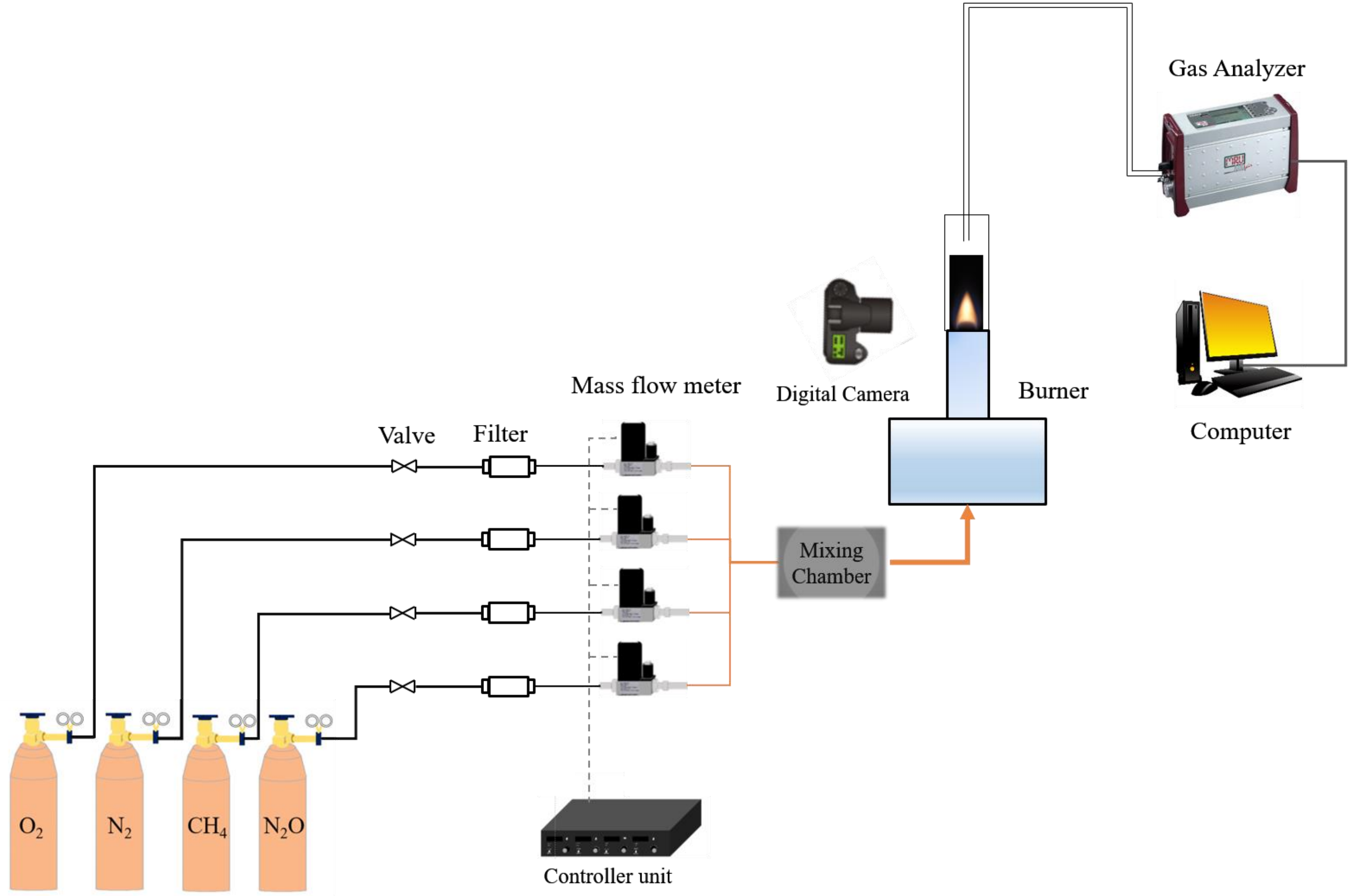
Investigation

- ➢ Flame configuration
- ➢ Pollutant emission
- ➢ Thermal effect
- ➢ Chemical effect

Combustion characteristics

- ✓ Flame height
- ✓ Flame appearance
- ✓ Emission behavior
- ✓ Heat release rate
- ✓ Heat production rate
- ✓ Flame speed
- ✓ Flame temperature

Experimental Methodology



A Schematic diagram of experimental setup.

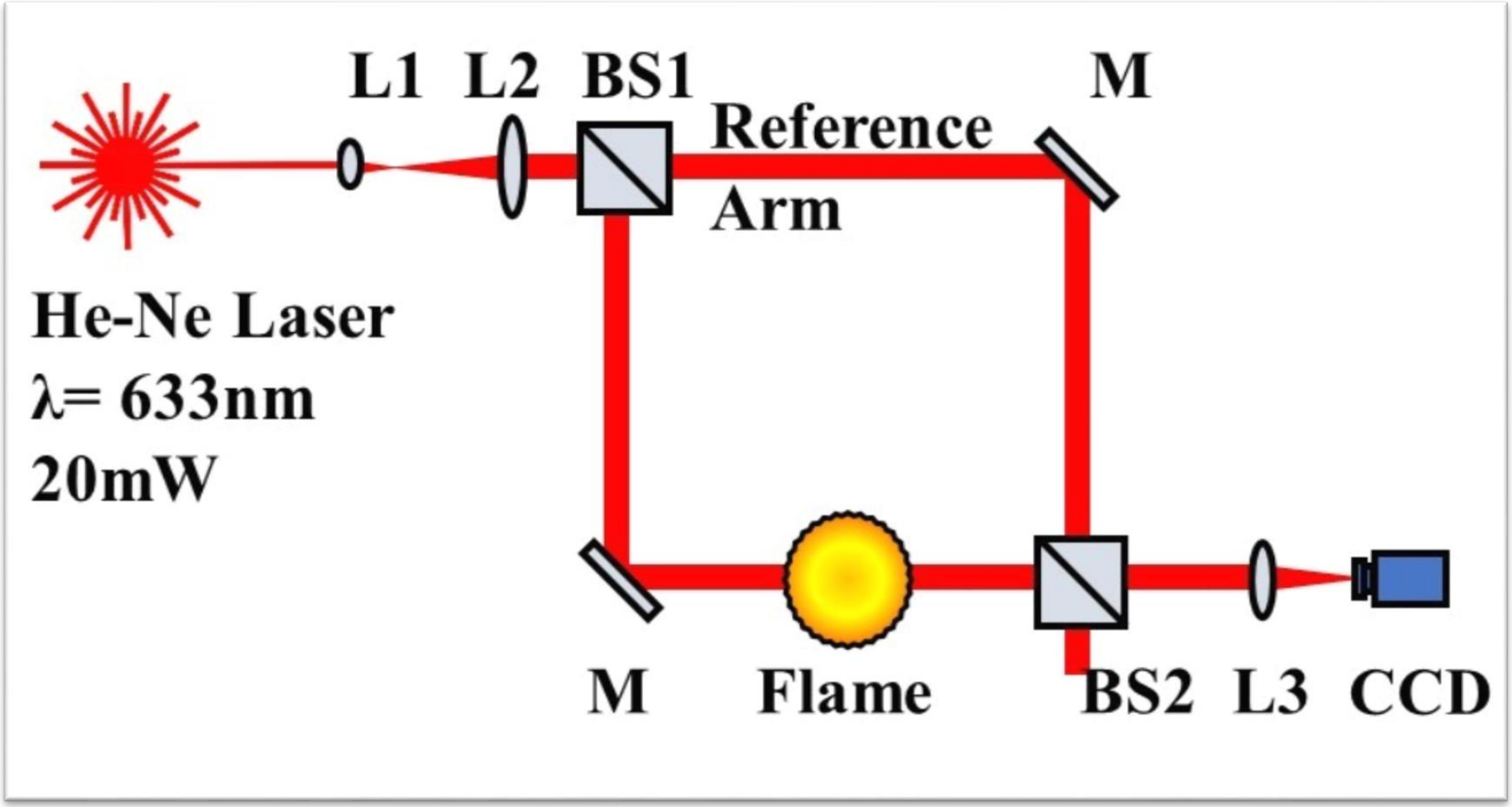
Experimental conditions

Fuel	Oxidizer	Velocity (cm/s)	Equivalence ratio (Φ)
CH_4	N_2O	100	0.8 - 1.2
CH_4	$33\%O_2/67\%N_2$	100	0.8 - 1.2

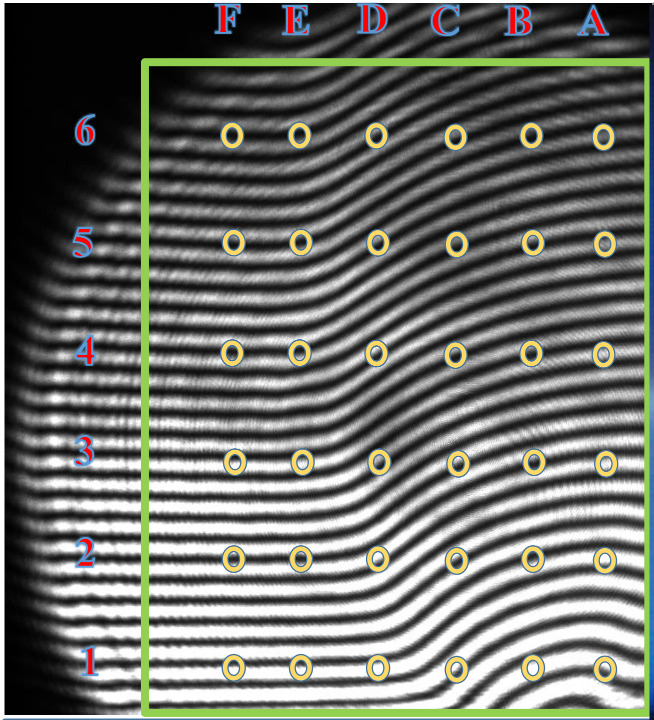
Numerical Simulation

Inlet temperature	300 K
Inlet pressure	1 atm
Inlet Velocity	1 m/s
Reactant mixture	CH_4/N_2O and CH_4/oxy-enrich
Equivalence ratio	1.0
Model	Equil, Oppdif, Freely propagating model

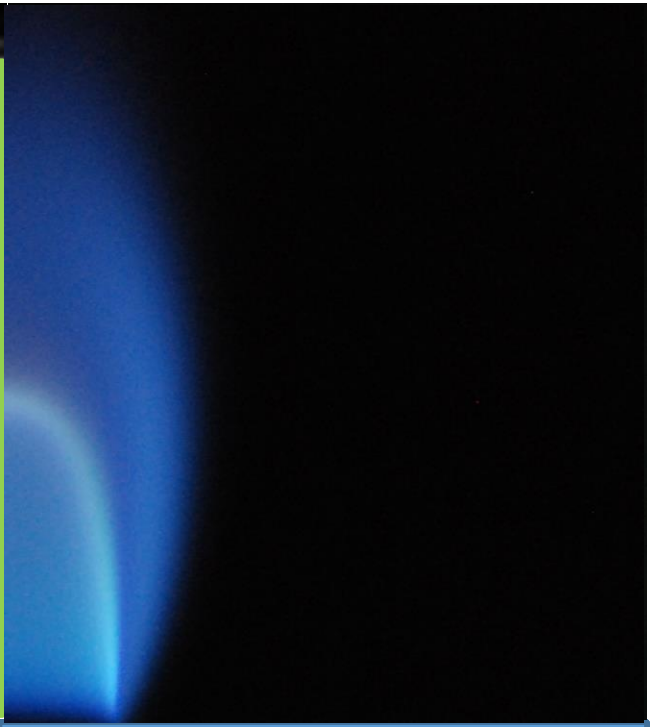
MZI Experimental Setup



Optical Measurement



Fringe pattern



Flame structure

__Flame fringe__

Image 1392 x 1040

Defining the image symmetrical dimensions for data abstraction.

FFT for fringe pattern analysis

Derived equations:

$$g(x,y) = a(x,y) + b(x,y)\cos[2\pi f_0 x + \boldsymbol{\phi(x,y)}]$$

$$= a(x,y) + \frac{1}{2} b(x,y) e^{i\boldsymbol{\phi(x,y)}} e^{2\pi i f_0 x}$$

$$+ \frac{1}{2} b(x,y) e^{-i\phi(x,y)} e^{-2\pi i f_0 x}$$

$$= a(x,y) + c(x,y)\, exp(2\pi i f_0 x) + c^*(x,y)\, exp(-2\pi i f_0 x)$$

$$\mathrm{G}(f,y) = A(f,y) + C(f - f_0, y) + C^*(f + f_0, y)$$

$$\Rightarrow \quad \Delta\phi = \frac{2\pi}{\lambda} \int_0^L \left(\frac{n}{n_0} - 1 \right) n_0 \, ds$$

$$\Rightarrow \quad n - 1 = K\rho$$

$$\Rightarrow \quad T = \left[\frac{n_0 - 1}{n(\Delta\varphi) - 1} \right] T_0$$

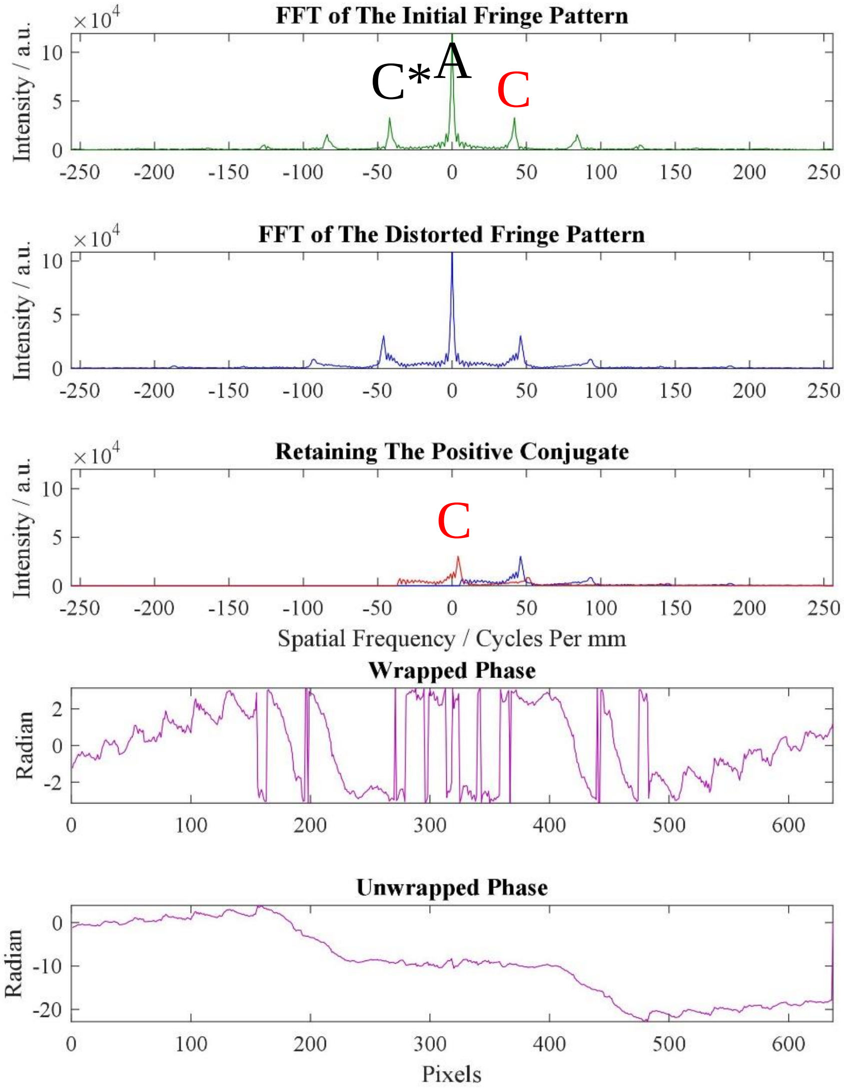
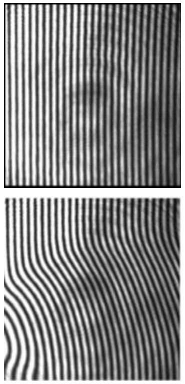
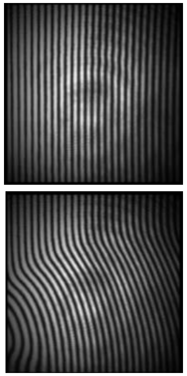


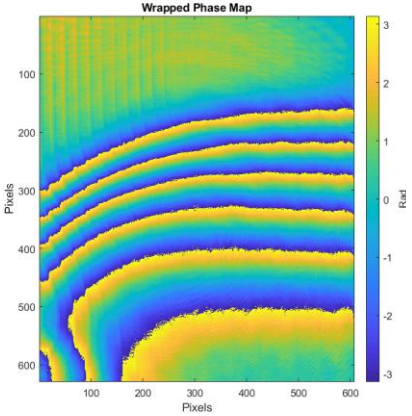
Image Processing [Matlab]



Cropping

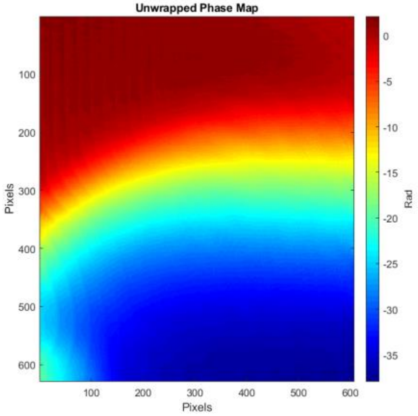


Padding & Hanning



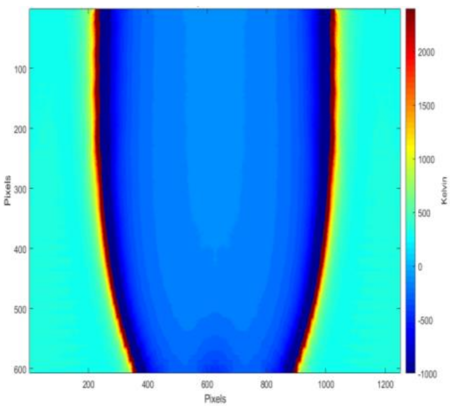
Wrapped Phase Map

Wrapped Phase Map

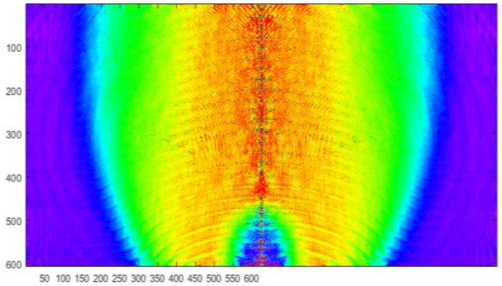


Unwrapped Phase Map

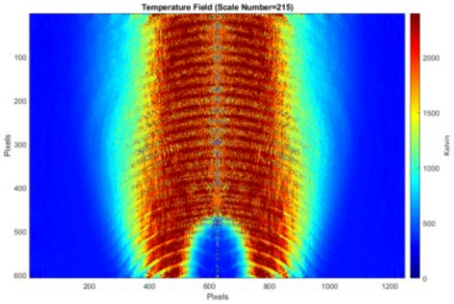
Unwrapped Phase Map



Unfiltered Temperature field

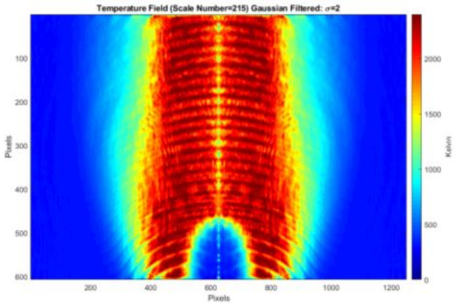


Abel Inversion



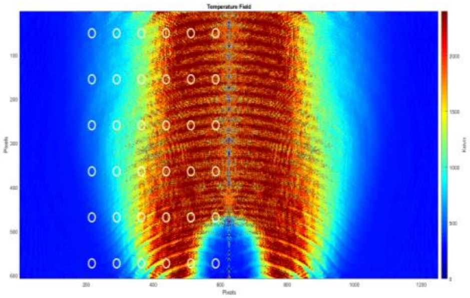
Temperature Field (Scale Number=215)

Filtered Temperature field



Temperature Field (Scale Number=215) Gaussian Filtered: σ=2

Temperature field with Gaussian filter

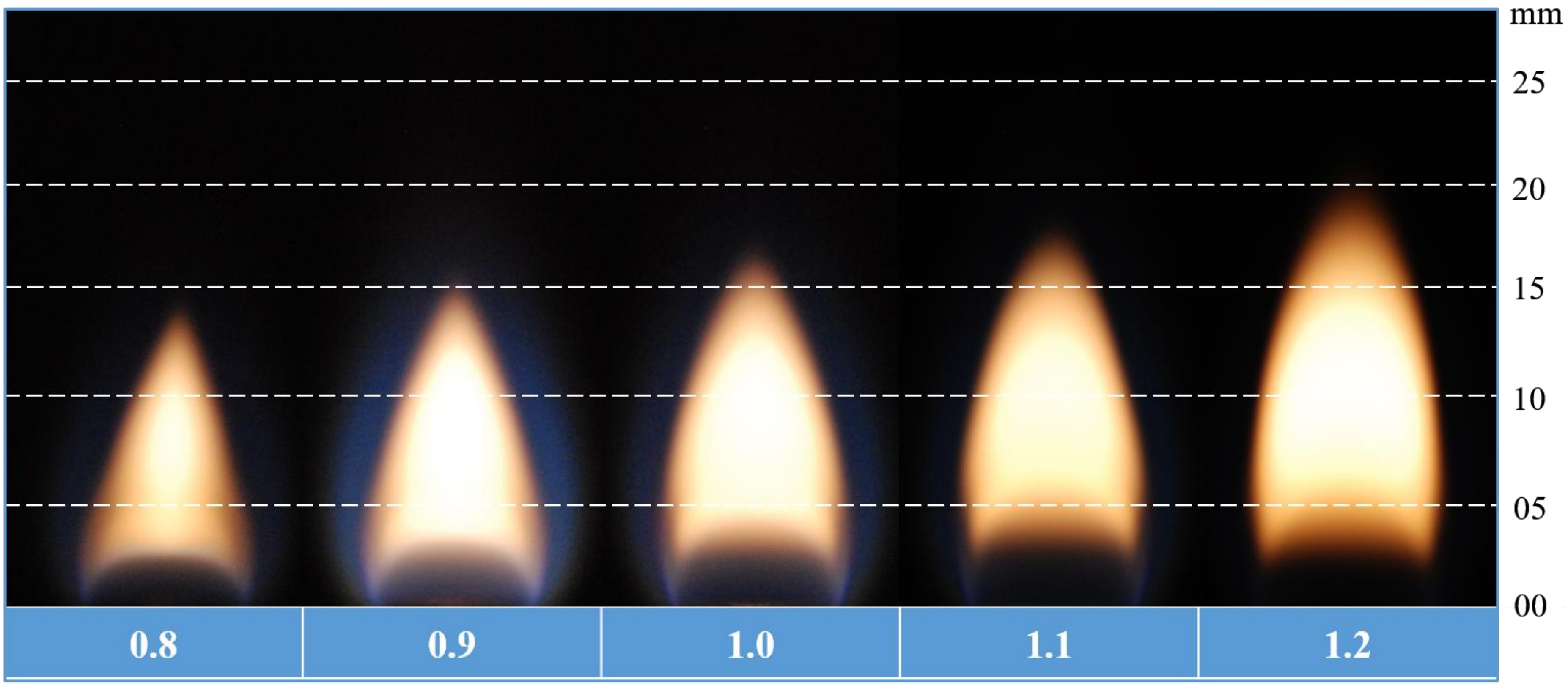


Temperature Field

Data Abstraction

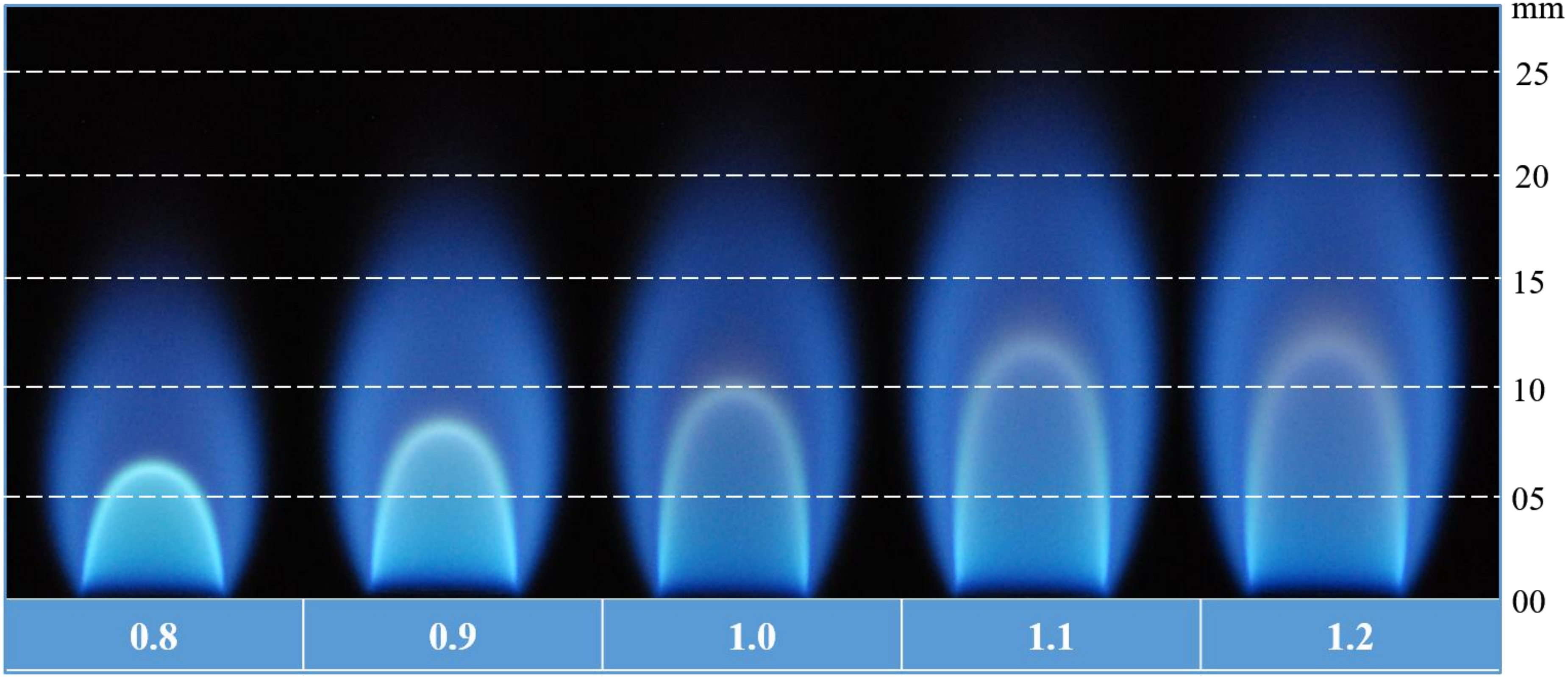
Results & Discussion (1/3)

- Flame Configuration of CH_4/N_2O combustion.



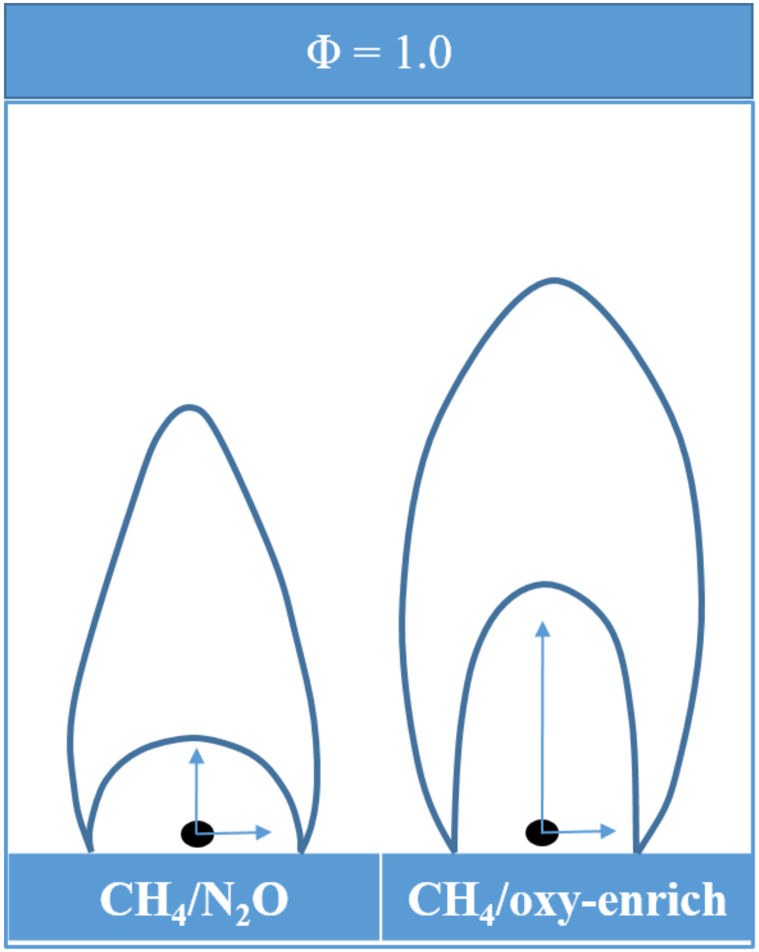
Results & Discussion (1/3)

- ❑ Flame Configuration of CH_4/oxy-enrich combustion.



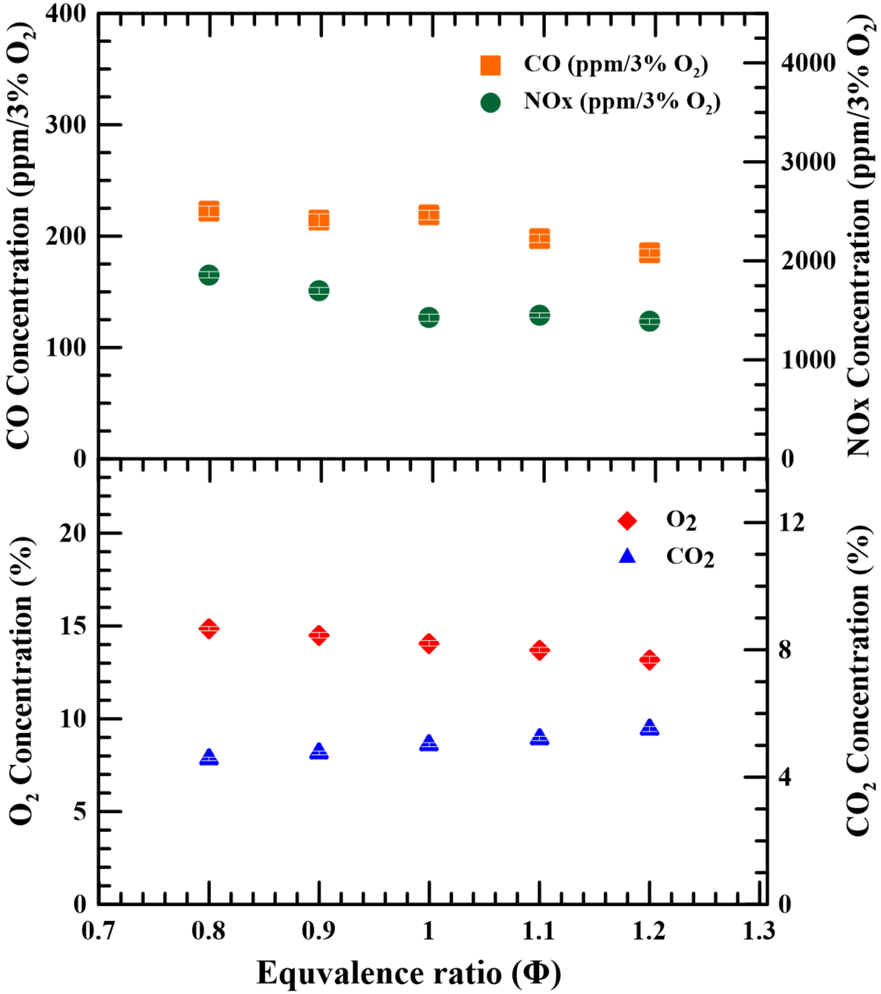
Results & Discussion (1/3)

- Phenomena along the flame.



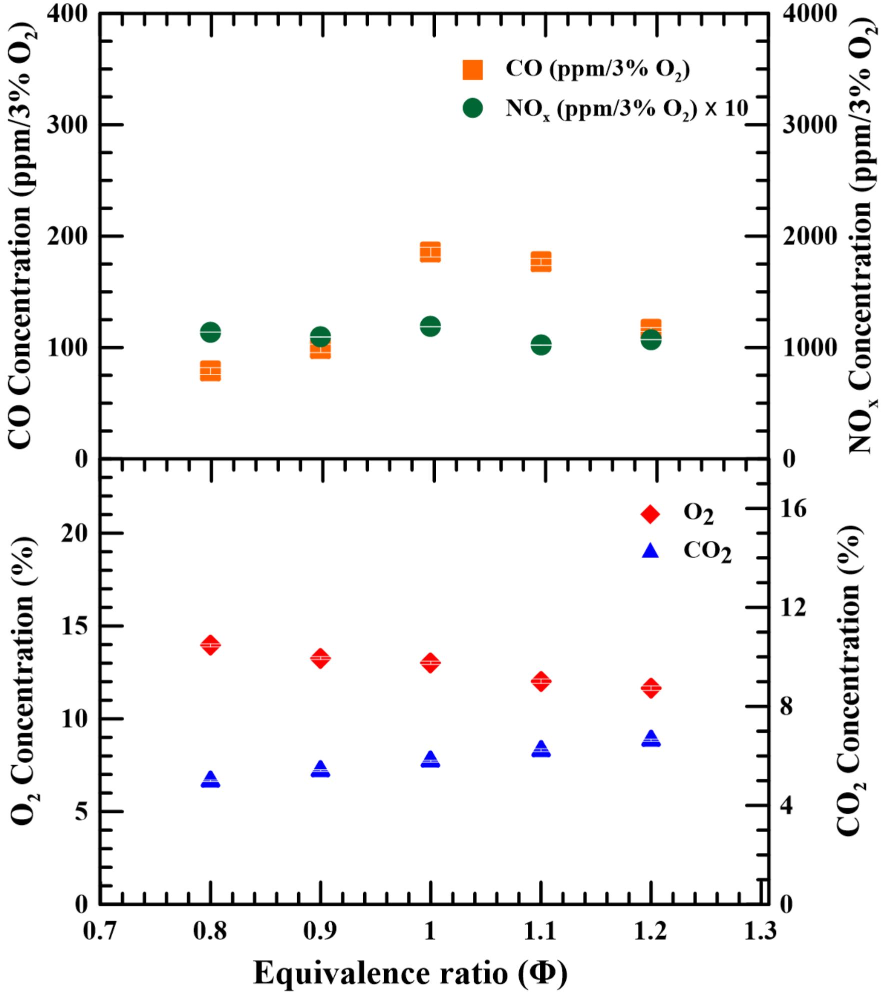
Results & Discussion (1/3)

- Pollution characteristics of N_2O combustion.



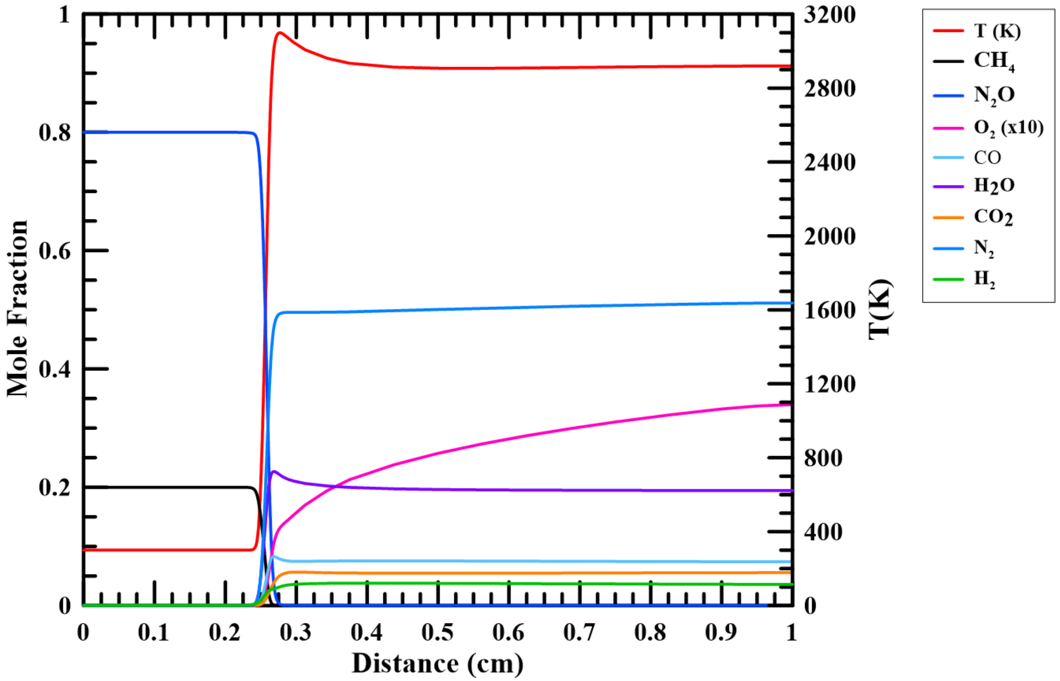
Results & Discussion (1/3)

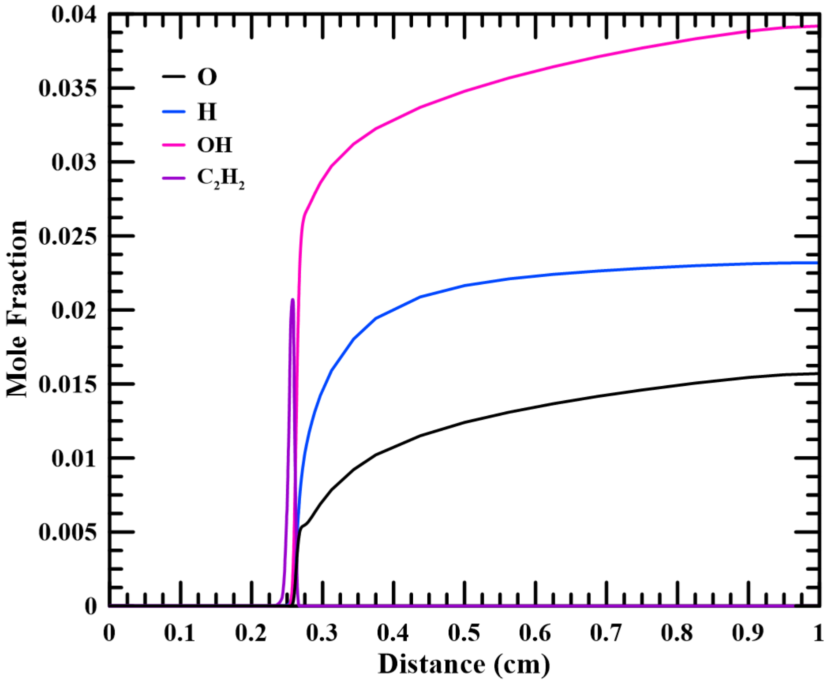
- Pollution characteristics of oxy-enrich combustion.



Results & Discussion (2/3)

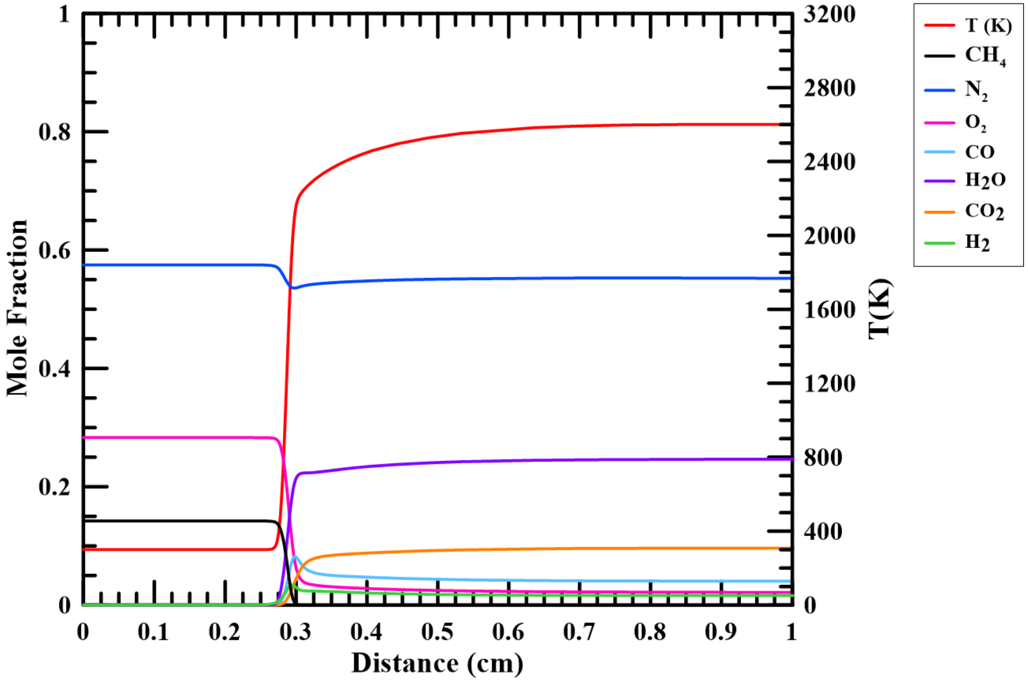
- Flame structure of N_2O combustion.

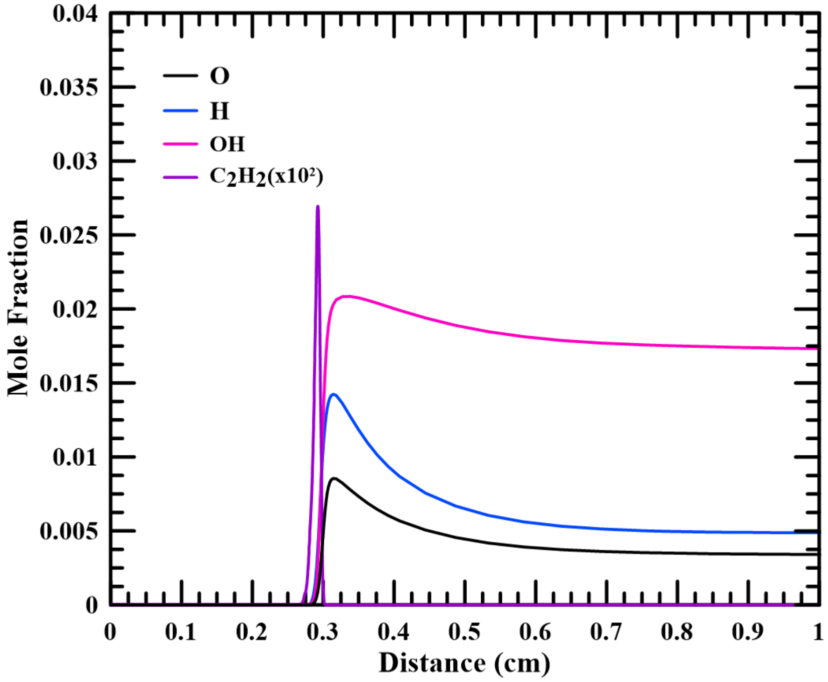




Results & Discussion (2/3)

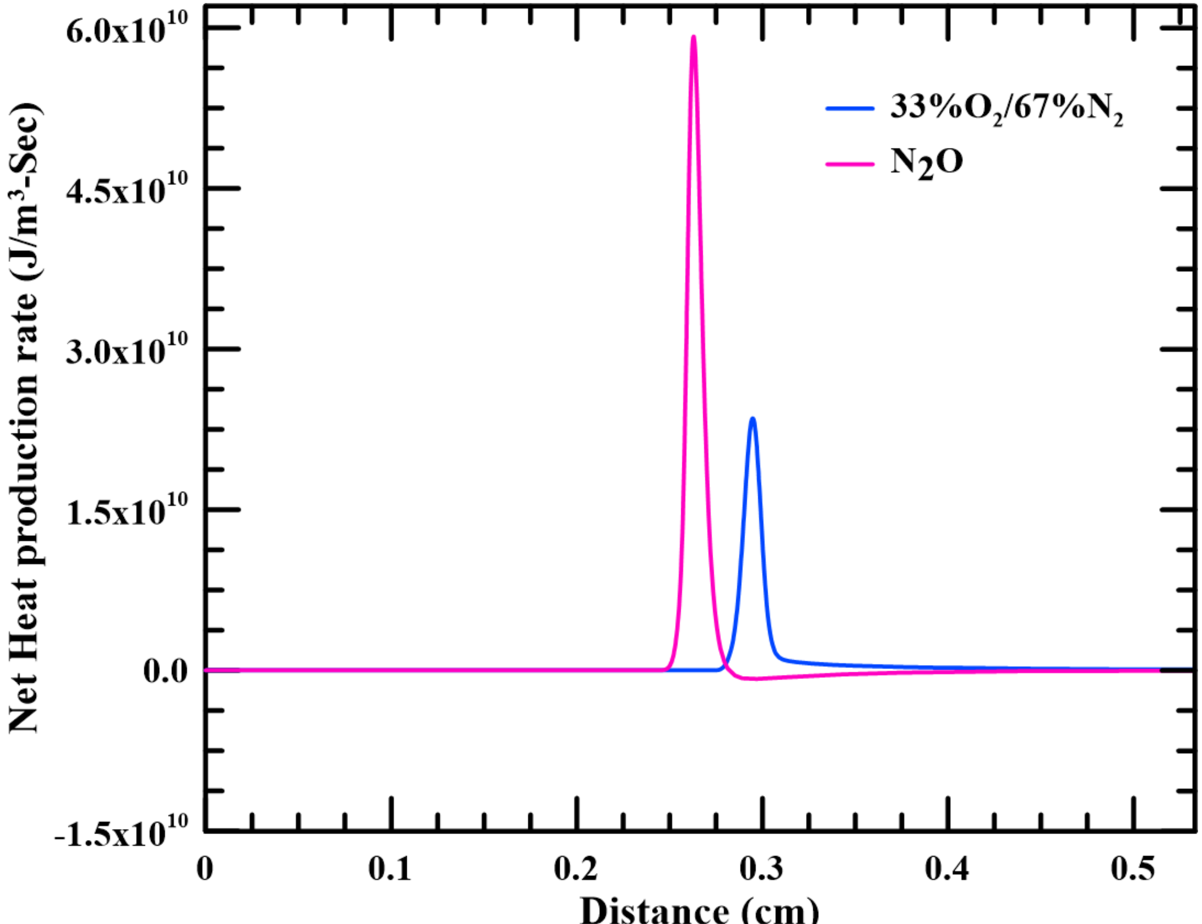
- Flame structure of oxy-enrich combustion.





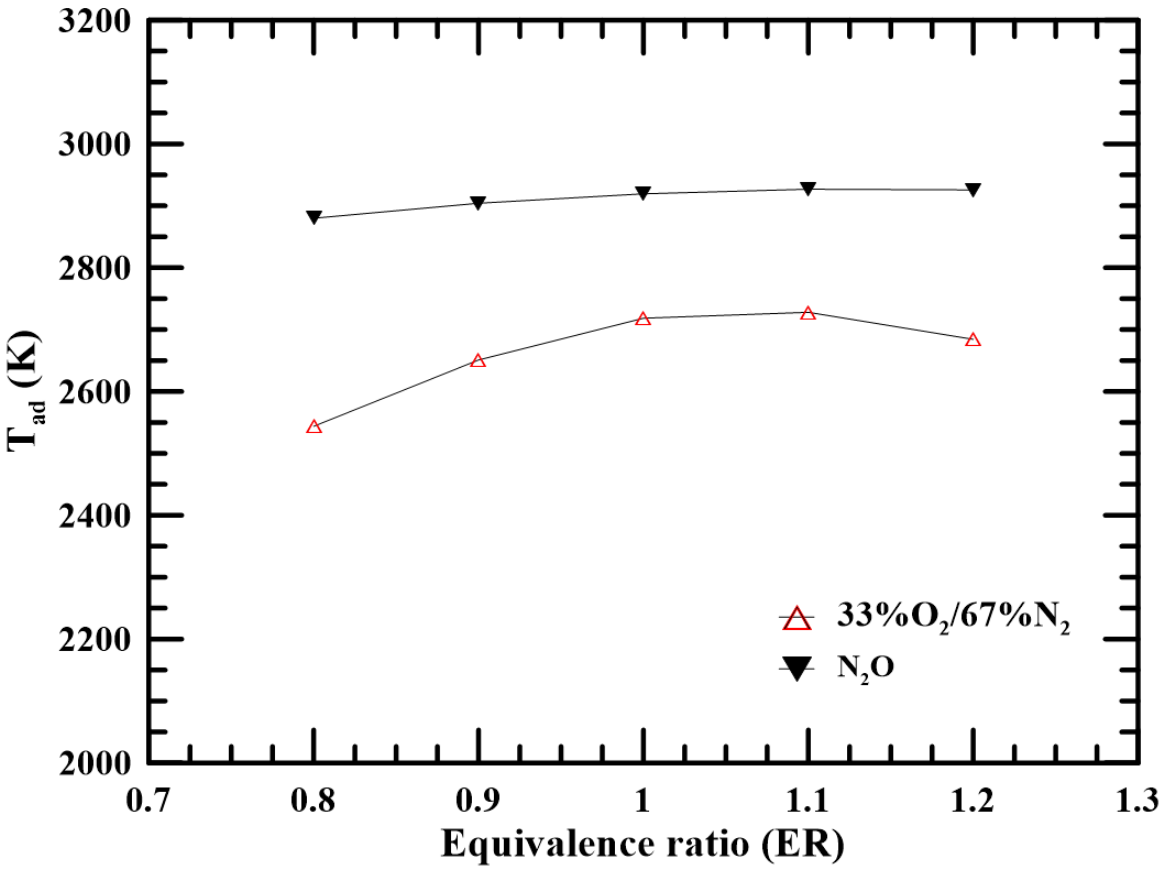
Results & Discussion (2/3)

- Net Heat release rate



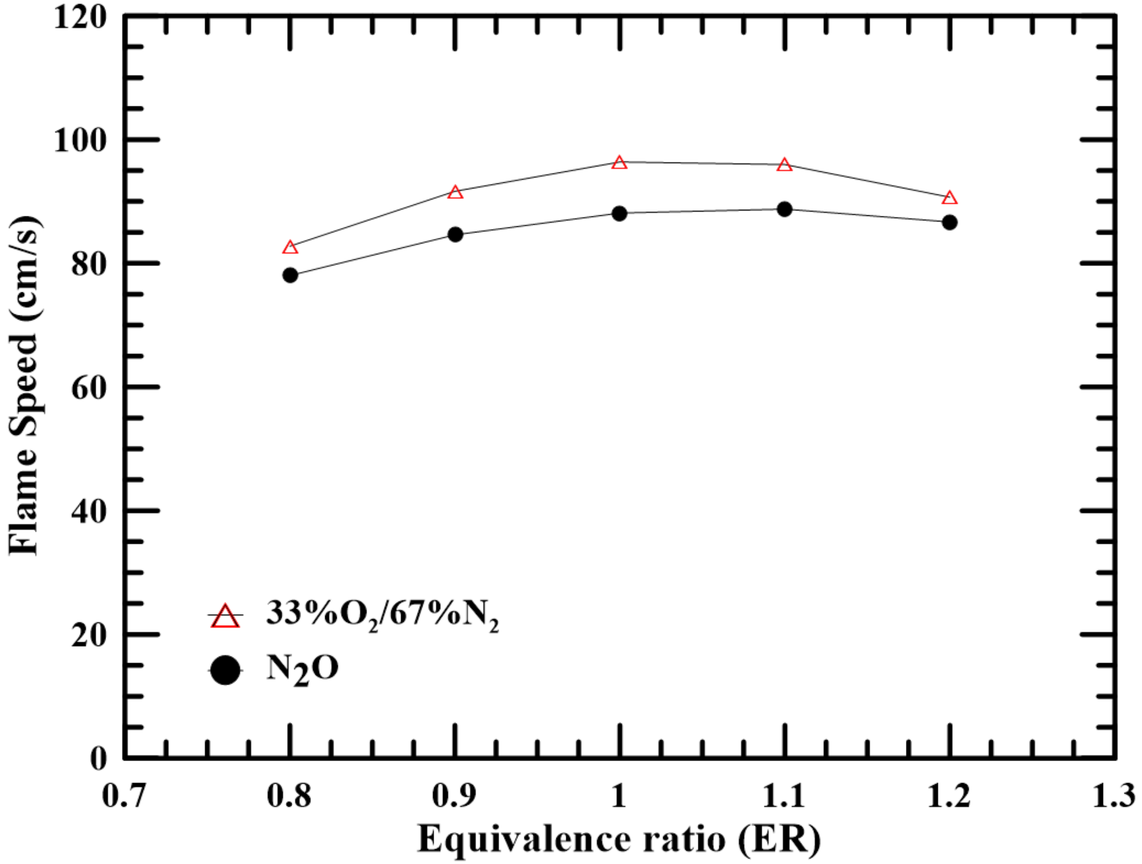
Results & Discussion (2/3)

- ☐ Adiabatic flame temperature



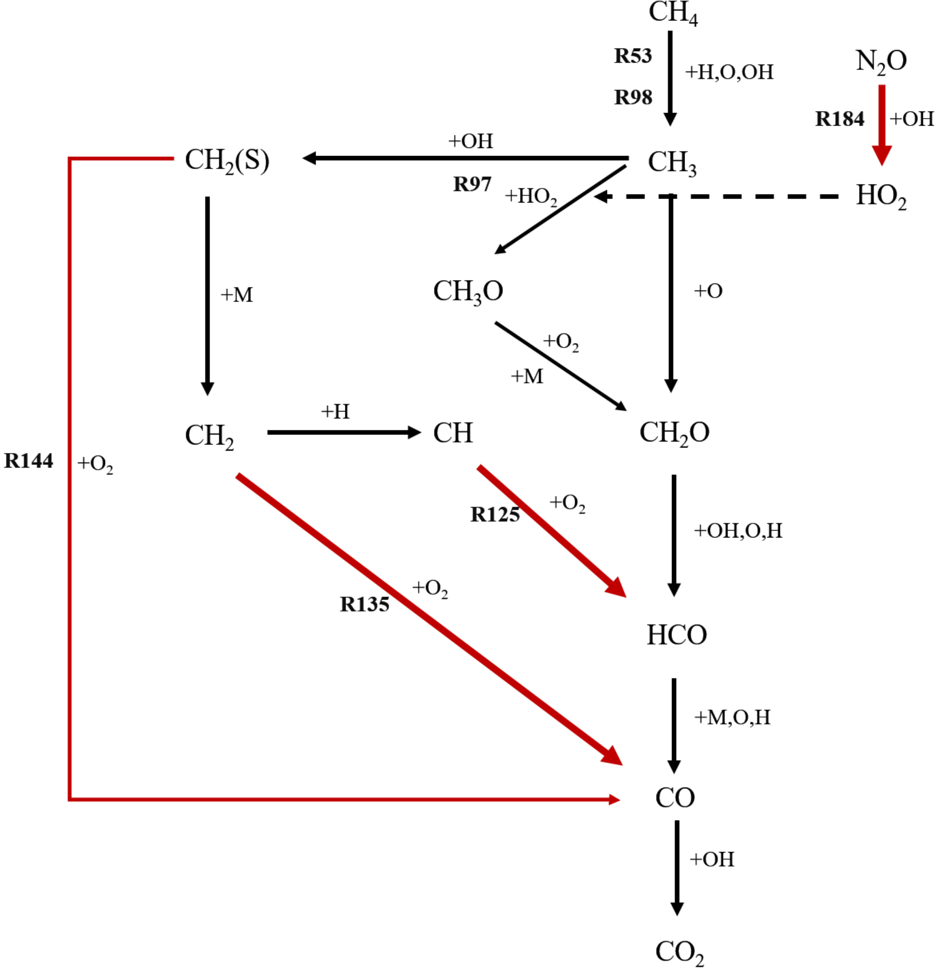
Results & Discussion (2/3)

- Laminar flame speed



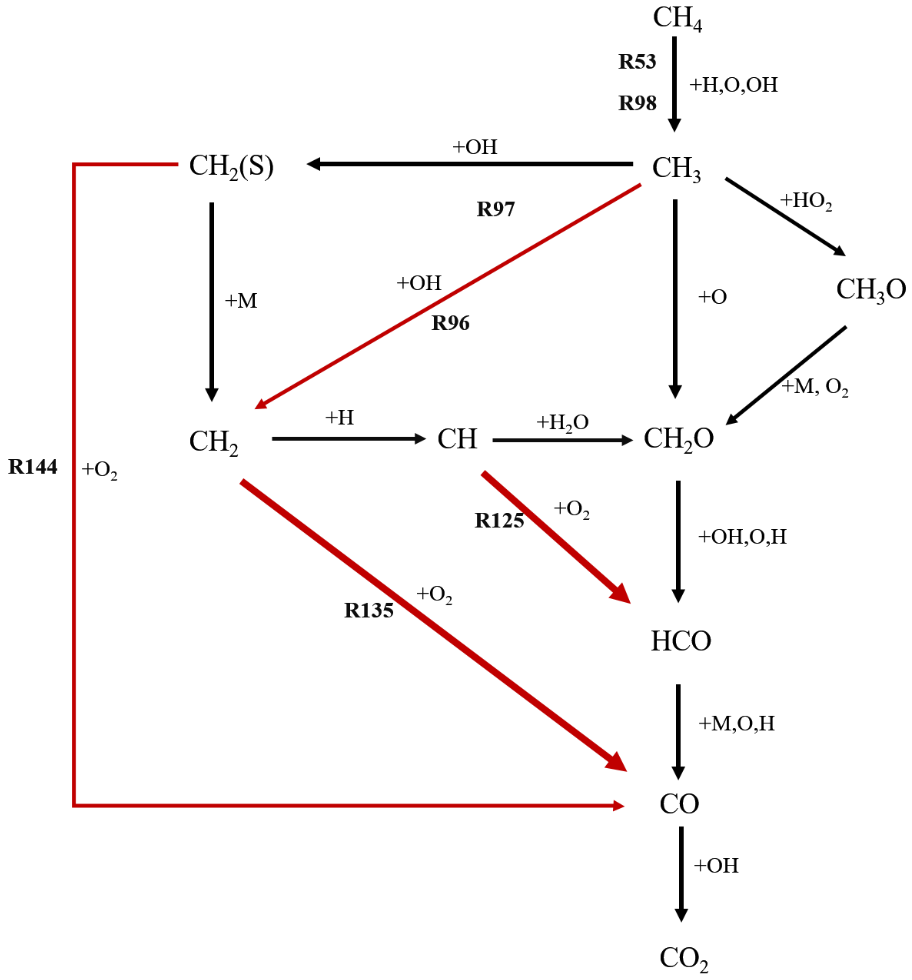
Results & Discussion (2/3)

- Methane oxidation in N_2O combustion.



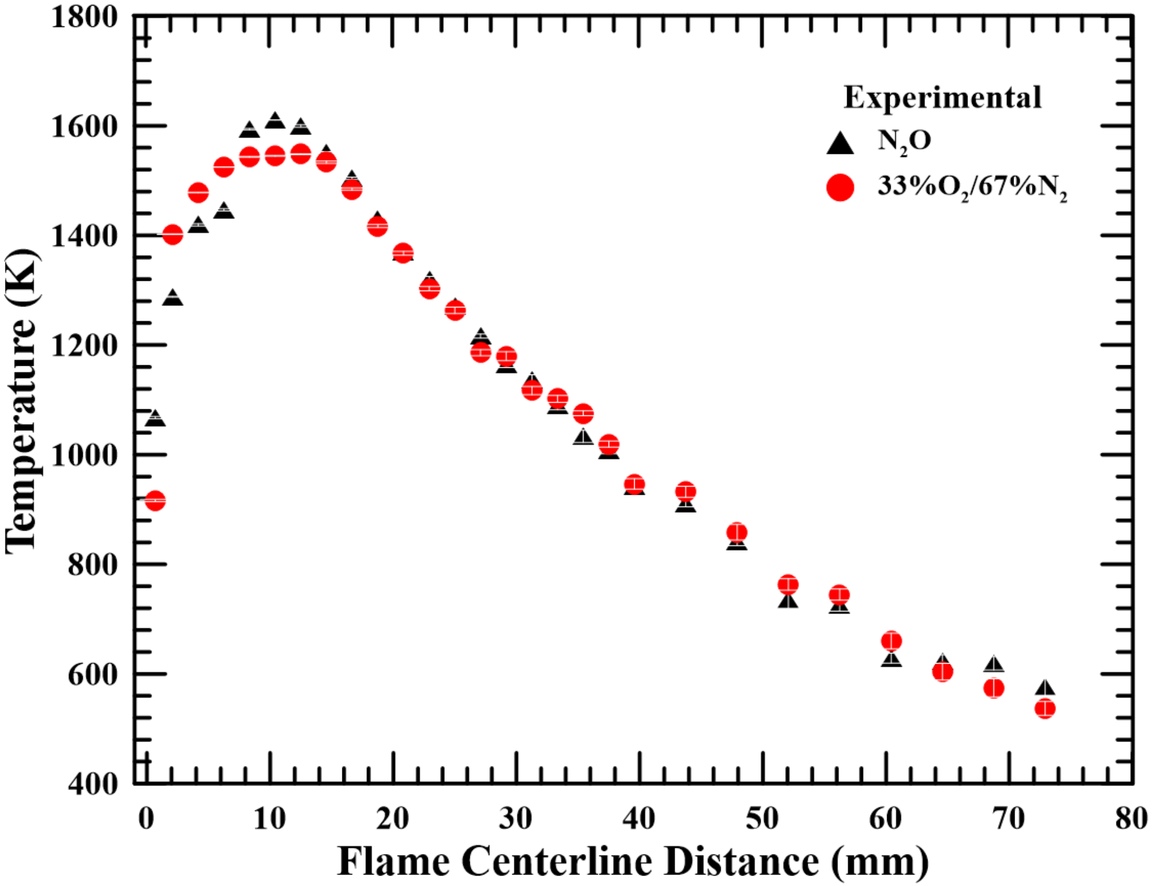
Results & Discussion (2/3)

- Methane oxidation in oxy-enrich combustion.



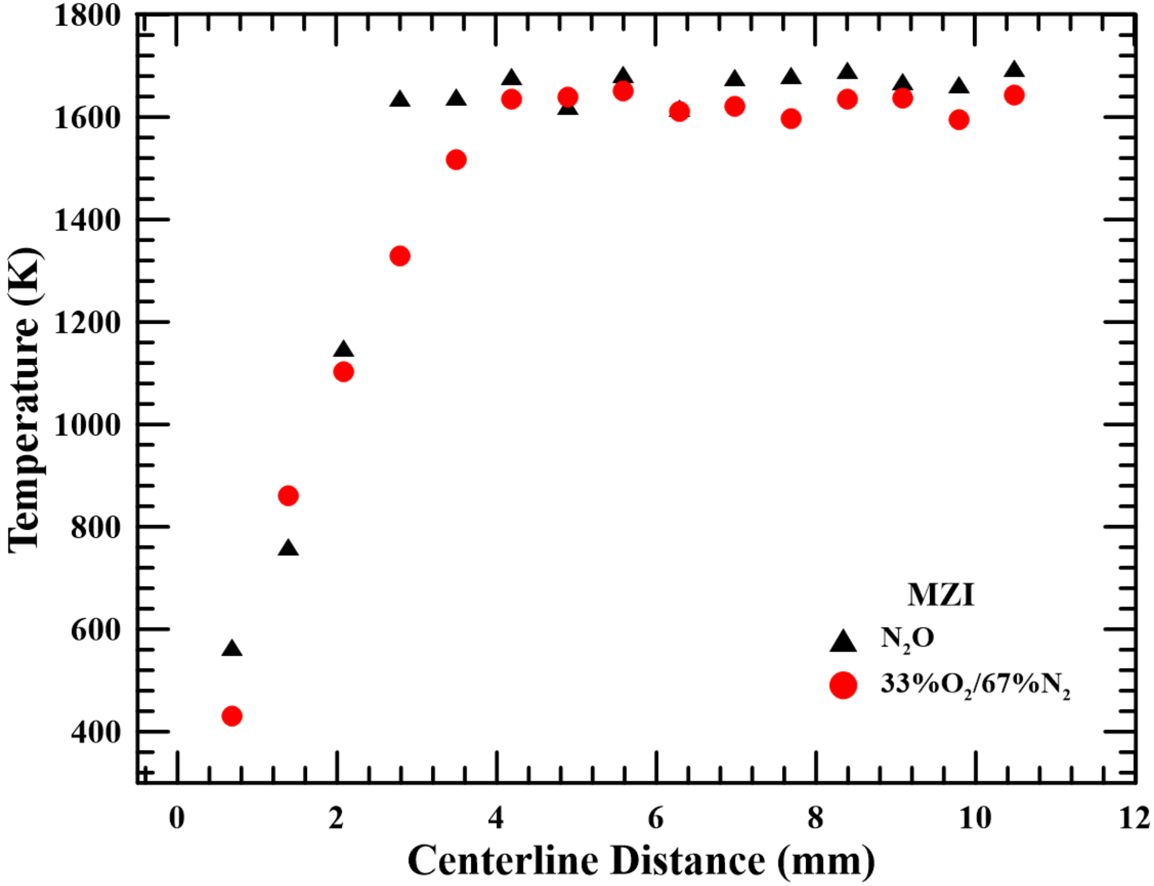
Results & Discussion (3/3)

- Flame temperature at centerline distribution – B-type thermocouple.



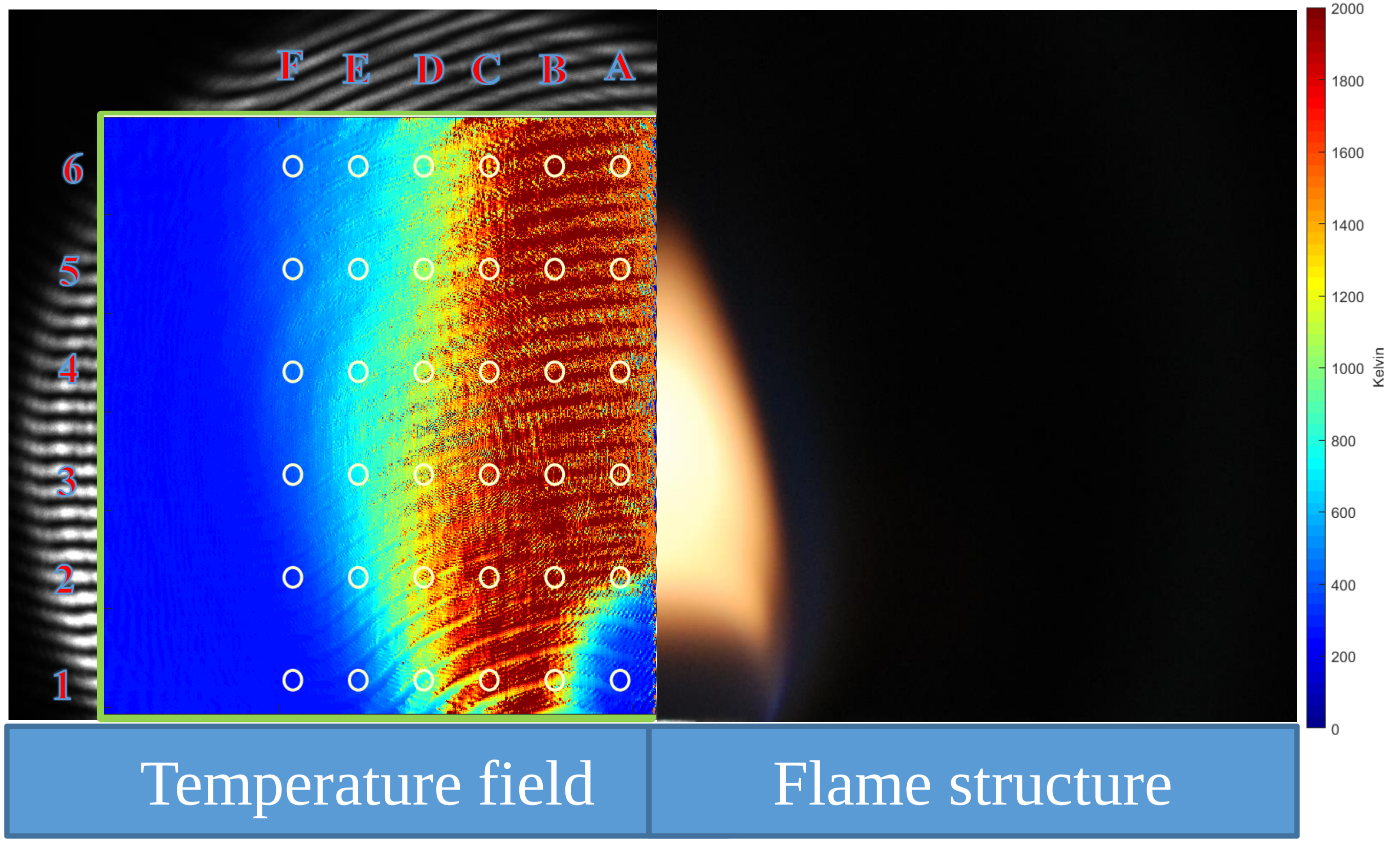
Results & Discussion (3/3)

- Flame temperature at centerline distribution - MZI measurement.



Results & Discussion (3/3)

- MZI measurement of CH_4/N_2O flames



Temperature field

Flame structure

Results & Discussion (3/3)

- ☐ MZI measurement data of CH_4/N_2O flames

Column A x F ↑

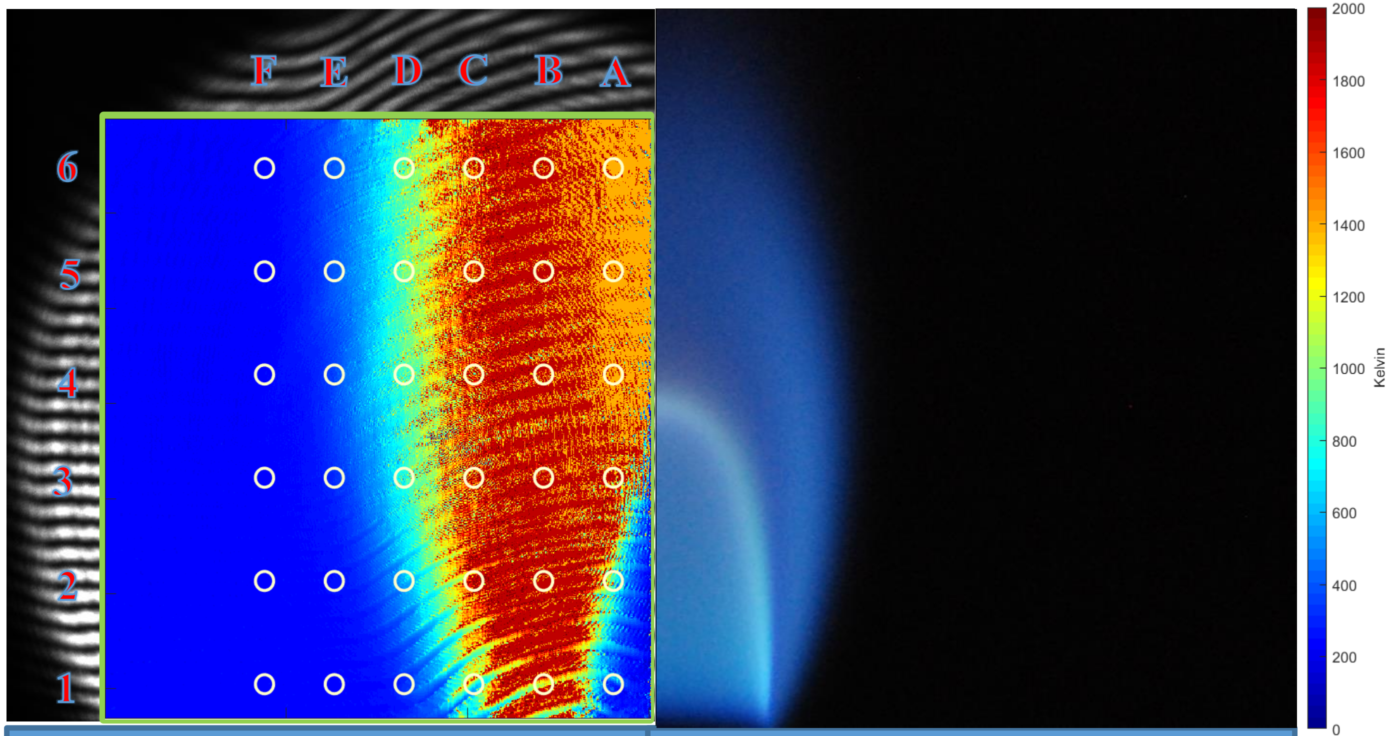
High temperature region : A, B and C

Low temperature region : D, E and F.

	MZI T(K)					
	F	**E**	**D**	**C**	**B**	**A**
6	517	761	1071	1506	1794	1555
5	548	826	1222	1634	1762	1656
4	547	927	1313	1600	1737	1596
3	488	928	1401	1662	1718	1582
2	384	803	1453	1740	1754	1219
1	336	443	1202	1622	1265	389

Results & Discussion (3/3)

- MZI measurement of CH_4/oxy-enrich flames



Temperature field

Flame structure

Results & Discussion (3/3)

- MZI measurement data of CH_4/oxy-enrich flames.

	Oxy-enrich T(K)					
	F	**E**	**D**	**C**	**B**	**A**
6	332	621	1260	1648	1770	1288
5	338	625	1348	1705	1711	1451
4	340	615	1246	1649	1748	1453
3	328	492	1194	1667	1743	1474
2	321	381	894	1720	1785	723
1	320	334	489	1462	1689	362

Results & Discussion (3/3)

- Temperature measurement using the thermocouples

		N_2O T (K)				
	K Type			B Type		
	F	E	D	C	B	A
6	337	783	1133	1350	1520	1583
5	405	925	1149	1427	1546	1582
4	378	924	1245	1450	1529	1551
3	362	919	1282	1455	1486	1428
2	346	820	1245	1391	1361	1266
1	327	594	1073	1307	1193	1040

Results & Discussion (3/3)

- Temperature measurement using the thermocouples

	Oxy-enrich T (K)					
	K Type			B Type		
	F	E	D	C	B	A
6	438	730	1064	1295	1461	1533
5	438	743	1103	1337	1462	1532
4	412	733	1112	1349	1467	1508
3	380	656	1070	1318	1431	1471
2	343	540	949	1212	1390	1124
1	324	384	703	986	1117	906

Results & Discussion (3/3)

- ❑ Comparison of the two measurements.

	N_2O-(%) T(K)					
	F	**E**	**D**	**C**	**B**	**A**
6	-53	2.7	5.5	-11.5	-18	1.8
5	-35	10	-6.3	-14	-13.9	-4.7
4	-45	-0.3	-5.4	-10	-13	-2.9
3	-34	-1	-9	-14	-15	-11
2	-11	2	-16.7	-25	-28.8	3.7
1	-2.8	25	-12	-24	-6	62.5

	Oxy-enrich-(%) T(K)					
	F	**E**	**D**	**C**	**B**	**A**
6	24	14.9	-18	-27	-21	16
5	23	15.9	-22	-27	-17	5.3
4	17.5	16.2	-12	-22	-19	3.6
3	13.8	25	-11.5	-26.4	-21.8	-0.24
2	6.6	29.3	6	-41.8	-28	35.6
1	1.06	13	30	-48	-51	60

Conclusions

- ☐ The flame appearance, flame shape, flame height, flame temperature, flame speed, heat release rate and heat production rate were varied between the N_2O and oxy-enrich flames.

- ☐ The thermal effect dominating in N_2O combustion is due to large heat release from the decomposition of N_2O and cause rise in temperature profiles, CO and NO_x concentrations.

- ☐ In this study, CH_4/N_2O flames was compared to oxy-enrich flames and found that the higher maximum temperatures, broadening reaction zones, significant thermal behavior and exhibit severe flame location shifts.

Conclusions

- ❑ The average and maximum temperature of N_2O combustion along the centerline occurs at inner region of flame.
- ❑ The results of MZI measurement across the flame at selected points are found to be higher temperature region (>1000 K) is observed at *columns A, B and C*, the low-temperature region (<1000 K) at *columns D, E and F* in various oxidizer environments.
- ❑ The comparison of the two measurements approaches show a good agreement at the selected positions.
- ❑ The influence of thermal effect on CH_4/N_2O flames is more prominent than the CH_4/oxy-enrich flames.
- ❑ Therefore, replacing the O_2/N_2 and choosing the N_2O being oxidizer in methane flames is worthy.

Thank you for attention

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