연소현상의 가시화

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연소현상의 가시화를 위한 몇 가지 레이저 진단기법의 응용 예를 소개한다. 이에는 유동 가시화를 위한 반응성 Mie 산란, 주화학종의 계측을 위한 Rayleigh 및 Raman 산란, 미소화학종 계측을 위한 레이저유도 형광법, 온도 계측을 위한coherent anti-Stokes Raman 산란법 및 매연계측을 위한 광 소멸/산란법 등이 포함된다. 이러한 기법 들이 확산화염, 층류 및 난류 부상화염, 비예혼합 와도 내의 화염전파, 매연생성 등의 연구에 적용되어 물리적 메커니즘을 이해하는데 유용하게 적용된 사례를 보고한다.

연소현상의 가시화

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- **Coflow Diffusion Flame**
- **Counterflow Flame**
- **Bunsen Flame**

- **Axisymmetric CWJ Burner**
- **Lifted Flames in Jets**
- **Oscillating Diffusion Flame**
- **Flame Propagation: Vortex Ring**
- **Soot/PAH Formation**

DIAGNOSTICS

- **(Reactive) Mie scattering**
- **Rayleigh Scattering**
- **Raman Scattering**
- **Chemiluminescence (OH*, CH*)**

- **Laser-Induced Fluorescence (LIF)**
  - **OH, CH, NO, Acetone, PAH**
- **Coherent Anti-Stokes Raman Scattering (CARS)**
- **Laser-Induced Incandescence (LII)**
- **Light Extinction /Light Scattering**

Laser Diagnostics

- Nd:YAG Laser + Dye Laser

CARS → Temperature
LIF → Concentration: OH, CH, NO, PAH, Acetone
LII → Soot volume fraction
Raman (Eximer Laser) → Concentration: O_2, N_2, CH_4
Rayleigh → Concentration : Propane

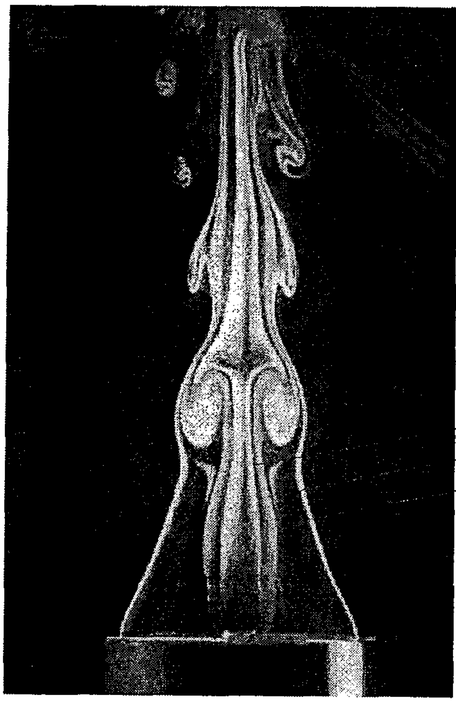
- Argon-ion Laser

LE / LS → Soot diameter, Number density, Volume fraction
LDV → Flow velocity

Reactive Mie Scattering

Flow Visualization

Oscillating Diffusion Flame
Recirculation Zone



Reactive Mie Scattering

Fuel Propane
Coflow Air (dry) w/ trace $TiCl_4$
Ambient air (wet)

$$TiCl_4 + 2H_2O \rightarrow TiO_2 + 4HCl$$

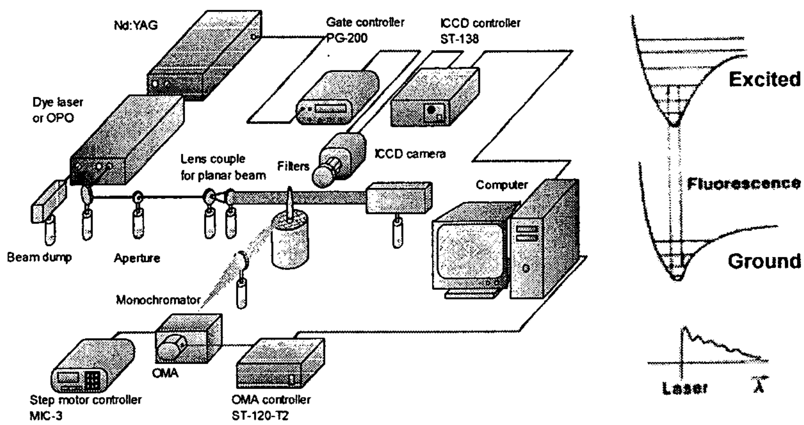
- **Soot**
- **H_2O from combustion product**
- **H_2O from air (wet)**

Hwang et al., 1999

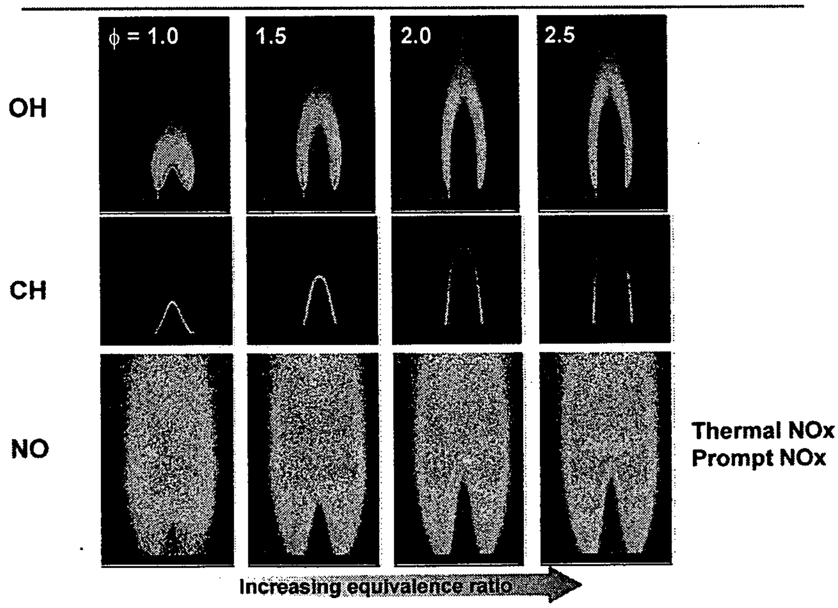
Bunsen Flame :
Laser-Induced Fluorescence

Radials : OH, CH, NO

PLIF SETUP



PLIF : CH_4/Air Premixed Flame

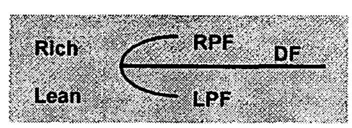


Flame Stabilization

Tribrachial (Triple) Flame
(tri-branched)

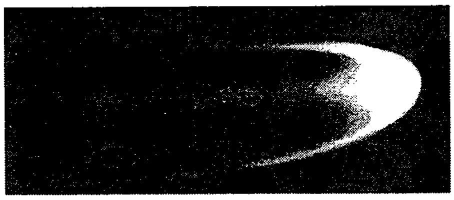
Tribrachial (Triple) Flames

- Flames in mixing layers
  - Tribrachial flame could exist
  - Composed of lean and rich premixed flame wings, and a trailing diffusion flame

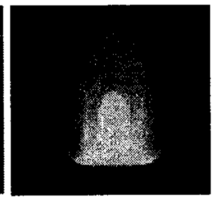


- Unique Characteristics
  - Different from premixed or diffusion flame
- Applications
  - Flame Stabilization in a Jet
  - Flame Spread over Fuel Surface
  - Composite Propellant Combustion
  - Inhomogeneous Charge Preparation: Engine

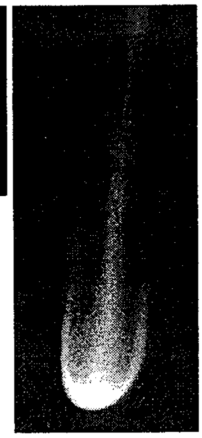
Tribrachial Flames



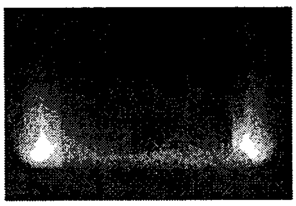
2D Mixing Layer (Phillips, 1965)



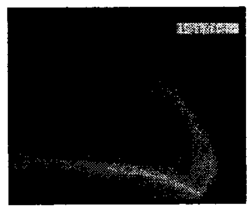
Fuel jet
(Chung & Lee, 1991)



2D Mixing Layer
(Peters, 1995)

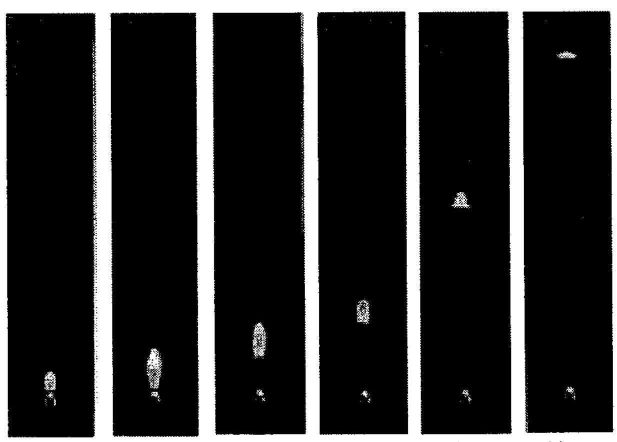


Cylindrical Boundary Layer
(Ko & Chung., 1992)



Flame Spread
(Miller & Easton, 2002)

Attached and Lifted Flames in Propane Jets



(a) (b) (c) (d) (e) (f)

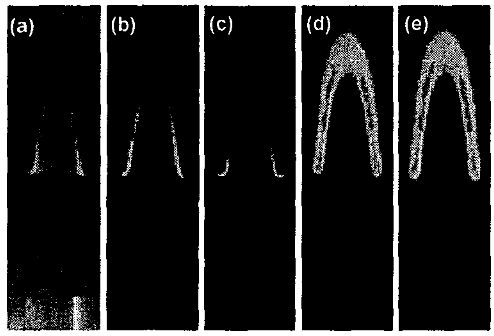
d = 0.195 mm;

(a) Q=0.195 (b)17.3 (c)18.3 (d)20.3 (e)22.3 (f)26.4ml/min

Chung and Lee, C&F, 1991

Laminar Lifted Flame: Flame Marker

($X_{F,o}$ = 0.10, U_o = 7.07 cm/s, V_{co} = 9.4 cm/s)

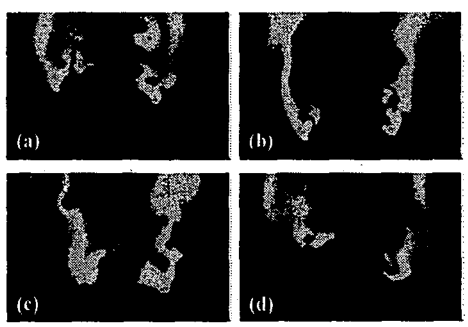


Direct photo | CH PLIF | OH^* | OH PLIF | $OH + OH^*$

Need single image flame marker / or simultaneous measurement to prove tribrachial structure for turbulent flames.

Won et al., Proc. Comb. Inst. 2000

OH PLIF : Lifted Turbulent Free Jet Flame



d = 2.58, Re_d = 26,000

Cannot identify Tribrachial Structure
Flame Marker?

Cha & Chung, 2001

Issues

- Tribrachial Flame Propagation
  - **Along stoichiometric contour?**
- Concentration Measurement
  - **Raman Scattering : Free Jets (free from Mie scattering)**
  - **Rayleigh Scattering : Coflow Jets**

Fuel Concentration: Raman scattering

◈ Raman Scattering :

1. **Species specific**
2. **Linearly proportional to species number density**

◈ Intensity of Raman scattering signal I_i

$$I_i = C I_l n_i \sigma_i$$

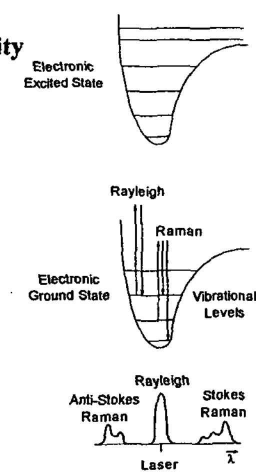
$$\frac{n_{CH_4}}{n_{N_2}} = \frac{I_{CH_4}}{I_{N_2}} \frac{\sigma_{CH_4}}{\sigma_{N_2}}$$

C : optical constant

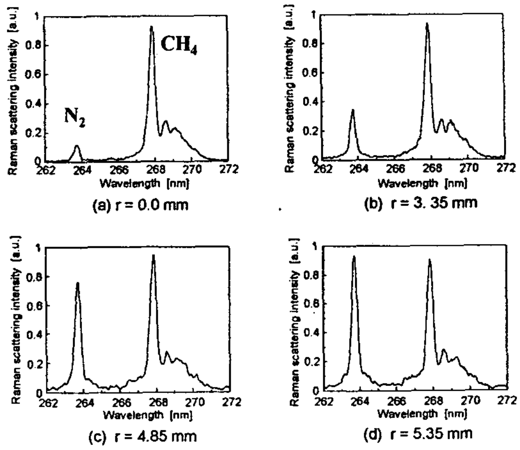
I_l : intensity of incident laser

n_i : mole fraction of species i

σ_i : Raman scattering cross-section of species i



Raman Spectrum with Radial Coordinate

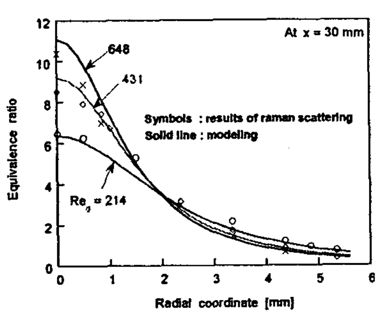


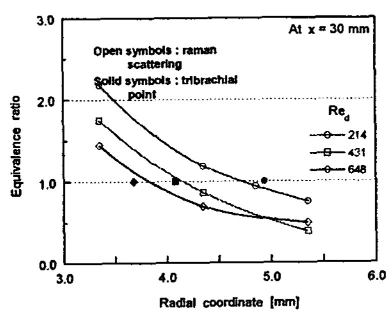
x = 30 mm for $Re_d = 214$

(a) $\phi = 6.25$ (b) $\phi = 2.07$ (c) $\phi = 0.93$ (d) $\phi = 0.72$

Fuel Concentration Field

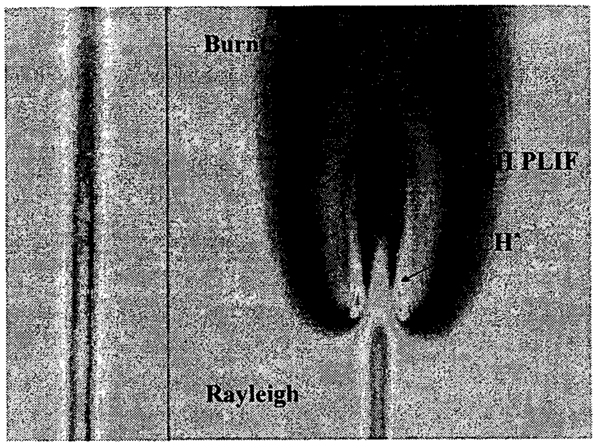
◆ **Radial Profile of Fuel Concentration** ◆ **Stoichiometric Position**





Ko et al., C&F 2000

Rayleigh Scattering for Coflow

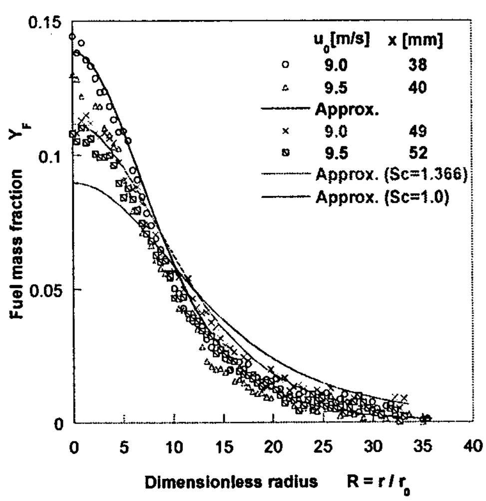


Fuel concentration

Reactive flow

Lee et al., 2001

Radial Profile of Fuel Mass Fraction

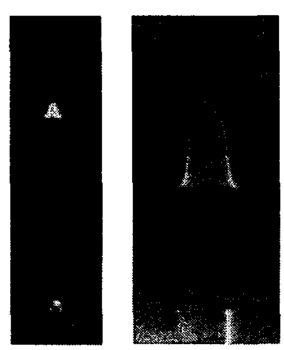


Lifted Flame in Coflow

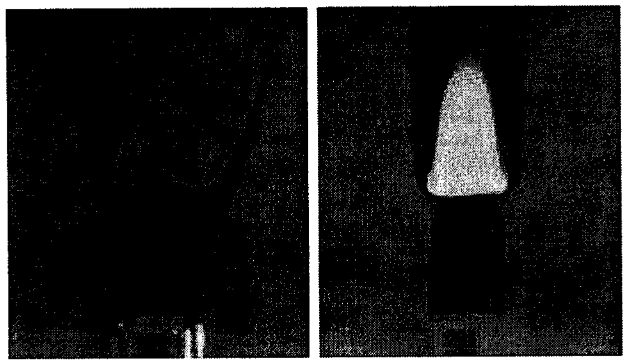
Coflow vs Free Jet

- Oscillating Lifted Flame
  - Not observed for free jets
  - Free Jets : $d = O(0.1\ \mathrm{cm})$, $U_0 = O(100\ \mathrm{cm/s})$
  - Coflow : $d = O(1\ \mathrm{cm})$, $U_0 = O(10\ \mathrm{cm/s})$
  - $Re = U_0 d/\nu$: same order
  - $Fr = U_0^2/gd$: $O(10^3)$ difference
  - Buoyancy can be important for coflow

- Visualization



Mie Scattering : Lifted Flame in Coflow Jet



(a) Cold flow (b) Reacting flow

Buoyancy Force

(a) Heavy propane fuel compared to air

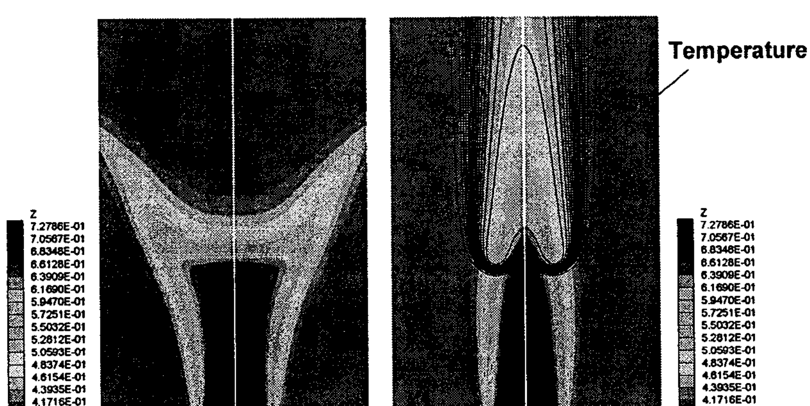
(b) Burnt gas

Won et al. Proc. Combust. Inst (2000)

Cold flow and Reacting flow

(Mixture Fraction Contour)

$U_{F,o}$=7.07 cm/s, $X_{F,o}$=0.1, U_{co}=9.40 cm/s



Cold flow Reacting flow

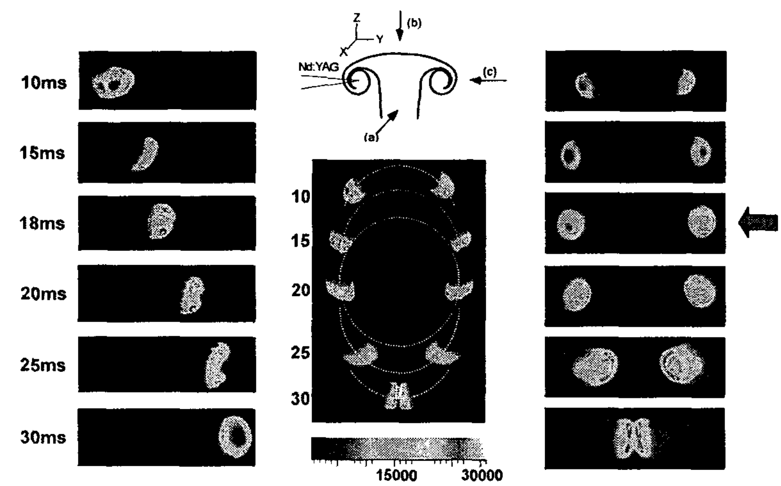
Flame Propagation

Nonpremixed Vortex Ring

Issues

- Nonpremixed Turbulent Flow
  - Wormlike vortex structure
  - Fuel/Air mixing layer : Vortical structures
  - Flame propagation along nonpremixed vortex ring
- Vortex Bursting Mechanism : Premixed flame
  - Chomiak : Acceleration of propagation speed in vortex field
  - Propagation speed $S_d \propto$ Circulation Γ
- Nonpremixed Flame ?

ICCD Images of Flame Propagation

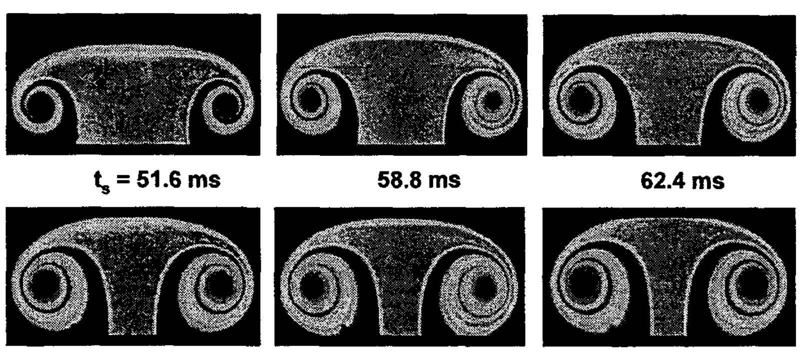


(a) (b) (c)

Choi et al., CST 1998

Vortex Ring : Concentration w/ Time

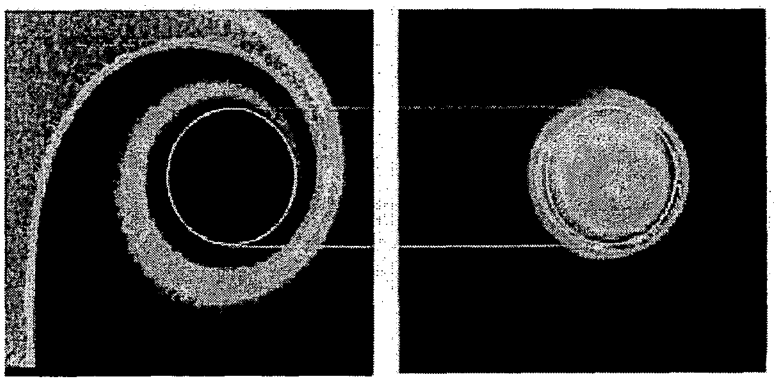
Acetone PLIF



t_s = 51.6 ms 58.8 ms 62.4 ms

69.6 ms 73.2 ms 76.8 ms

Flame Size and Fuel Concentration

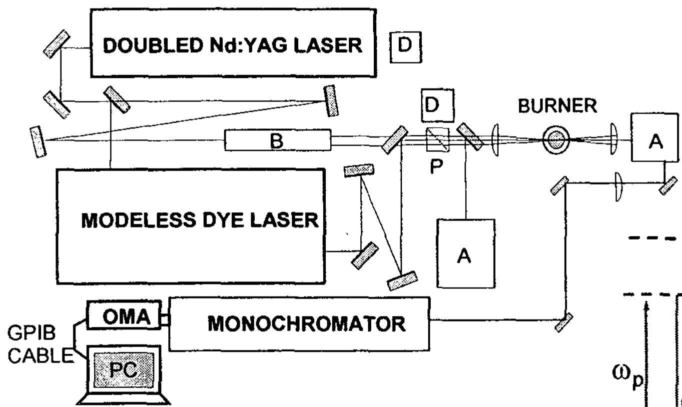


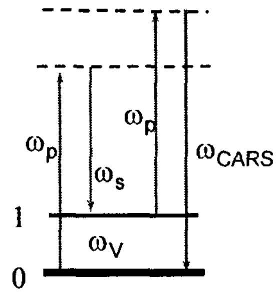
Acetone PLIF image　　　Flame intensity from ICCD

Choi et al., J Visual 2002

CARS : Temperature

CARS Measurement

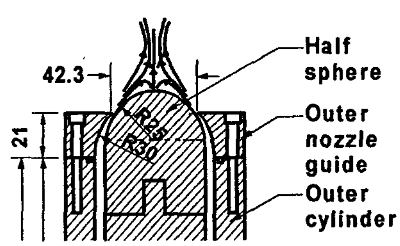




Nonlinear Optical Process
Temperature determined from CARS spectrum

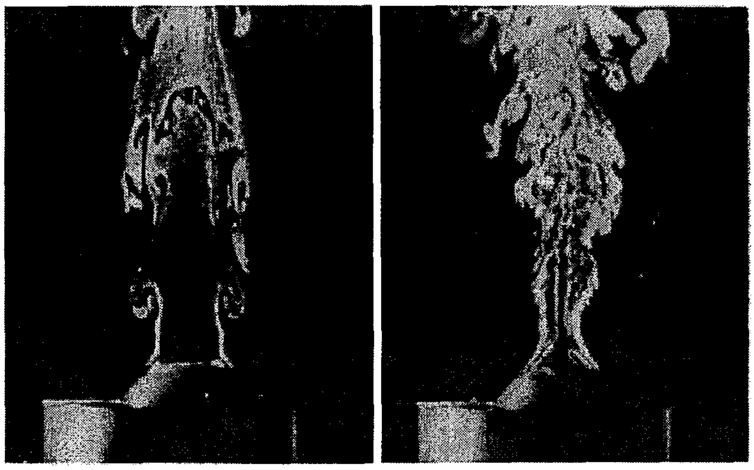
Axisymmetric Curved-Wall Jet (CWJ) Burner

- Axisymmetric radially inward jet
  - **Coanda effect**
- Merits
  - **Large amount of air entrainment**
  - **High level of turbulence intensity**
    - o **Reduce flame length**
  - **Formation of recirculation zone**
    - o **Increase in residence time**
    - o **Enhance flame stabilization**
  - **Control of burner slit width**
    - o **Control of flame length**
    - o **Prevention of flash back (safety)**

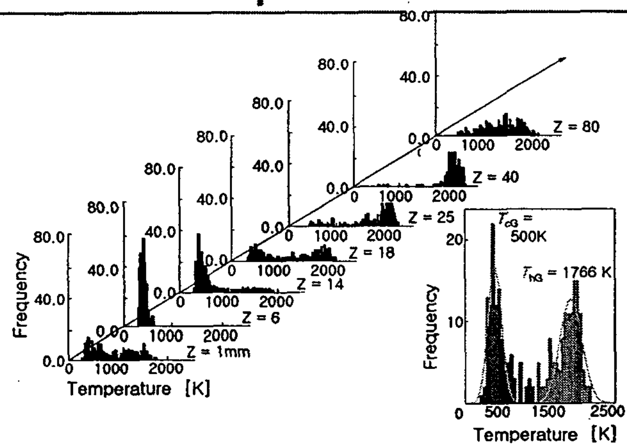


Gil & Chung, CNF 1998

Reactive Mie Scattering: CWJ Burner

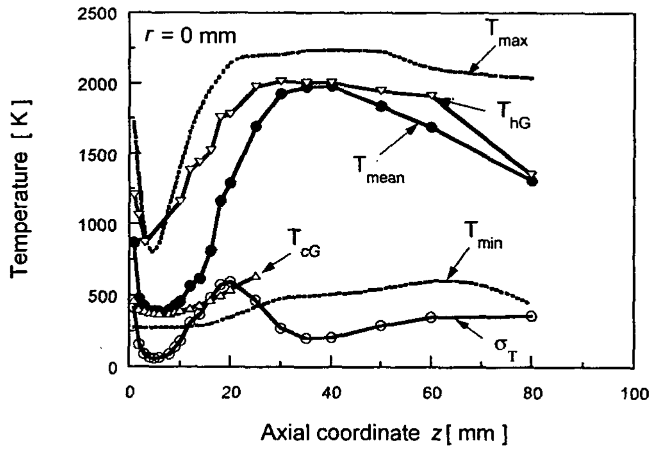


CARS Temperature Measurement



Histograms of temperature along the centerline for $\phi = 1.6$, $U_o = 9.95$ m/s, spherical tip

CARS Results



Stagnation region : Cold Temperature
Recirculation zone exhibited

Soot Studies

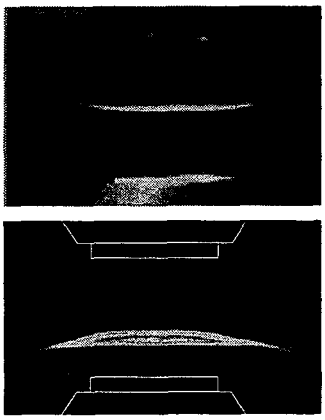
Extinction/ Scattering

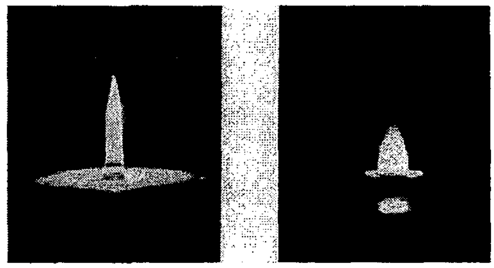
LII

PAH PLIF

Soot Studies

- Soot Zone Structure
  - **Counterflow**
  - **Coflow (normal & inverse)**





NDF **IDF**

Issues

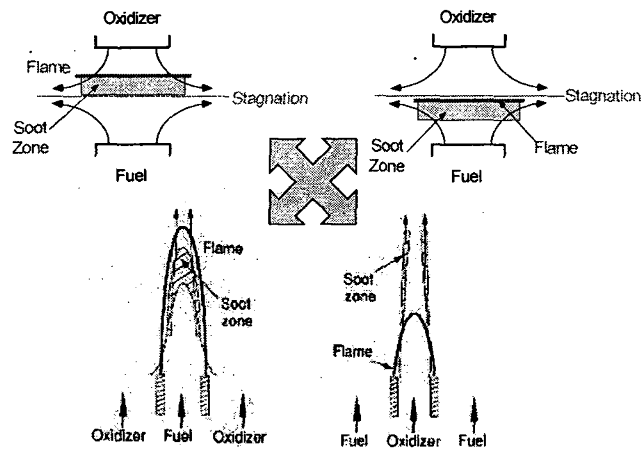
- Soot Model Development
  - **Based on Premixed Flame**
  - **Based on Diffusion Flame (Fuel+Air in coflow)**

- **Inconsistence in Model Prediction**

- Soot & PAH Growth Mechanism
  - **Role of C_2- & C_3- species**
  - **H-abstraction-C_2H_2-addition (HACA)**
  - **C_3H_3 recombination to benzene ring formation**
  - **Role of C_3-species on PAH growth**

Soot Zone Structures in Diffusion Flames

Soot Formation Flame (SF) **Soot Formation/Oxidation Flame (SFO)**

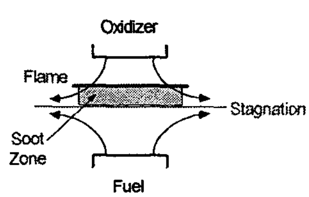


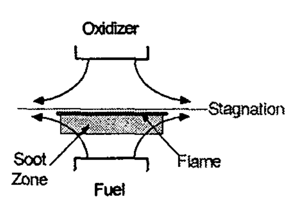
Normal Diffusion Flame (NDF) **Inverse Diffusion Flame (IDF)**

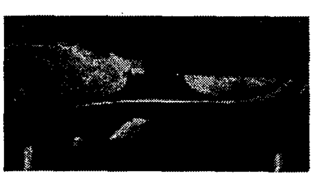
Kang et al., CNF 1997

Sooting Characteristics in CDF

- Soot Formation Flame
- Soot Formation/Oxidation Flame

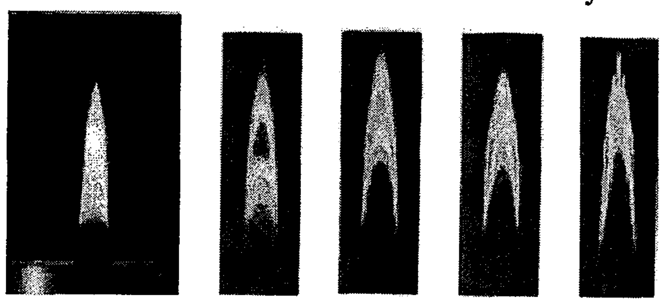






Light Scattering / Extinction

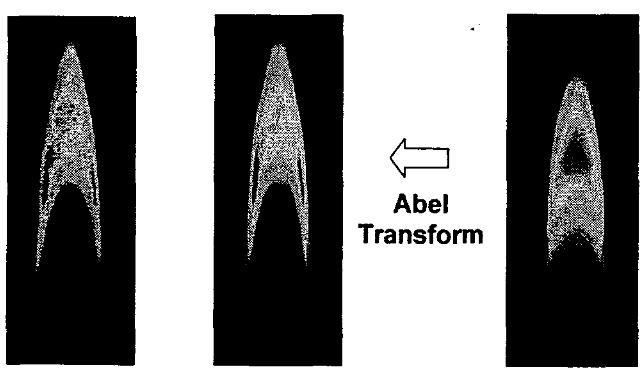
K_e (extinction) $\propto Nd^3$
Q_{vv} (scattering) $\propto Nd^6$ ➡ **Volume fraction, diameter, Number density**



Direct photo | Extinction | Volume fraction (Abel T.) | Scattering (log scale) | Vol. Avg. diameter

LII : Coflow Diffusion Flame

- LII
- Extinction



Soot volume fraction | Line-of-sight Data

Concluding Remarks

- Various diagnostics techniques can be applied to combustion research for visualization.
  - LIF, Raman, Rayleigh, LII, CARS, Laser extinction/scattering

- These techniques are useful in identifying fundamental physical mechanisms.

- Acknowledgment
  - Profs. J.W. Hahn, B.J. Lee, W. Lee, O. Fujita
  - Drs. M.S. Cha, J.W. Hwang, K.T. Kang, Y.S. Ko,
  - J.S. Lee, Y.S. Gil,