# 레이저를 이용한 분무 가시화

## Spray Visualization Using Laser Diagnostics

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분무를 정량적으로 측정하는 것은 노즐의 설계와 개발을 위해서 뿐만 아니라 연소 시스템 전반의 효율 및 불안정성의 제거, 공해 저감 등의 요구 조건을 만족하기 위해서 중요하다. 이를 위해 이전에는 분무장 내에 수집관을 삽입하는 기계적 패터네이터(Mechanical Patternator)와 같은 삽입식 측정 방식을 이용하여 왔으나, 최근에는 고속카메라, Malvern particle analyzer, PDPA, 광학 패터네이터(Optical Patternator)와 같은 분무장을 교란 시키지 않으면서도 빠른 측정이 가능한 가시화 기술들이 적용되고 있다. 특히 광학 패터네이터는 레이저 평면광을 이용하여 분무를 측정하는 비삽입식 기술로 단시간 내에 분무장 내 액체 연료의 질량 및 액적 크기의 단면 분포를 동시에 얻어낼 수 있는 장점을 갖고 있다. 그러나 분무 액적들의 수밀도가 증가하는 경우에는 이들 액적에 의한 입사광 및 신호 감쇠, 다중 산란 등에 의한 오차가 심하게 발생하여, 기존의 PDPA, PLIF 등의 광학 기법으로는 충분히 신뢰할 만한 결과를 얻기가 어렵게 된다. 이러한 분무를 정량적으로 측정하기 위해서는 입사광의 감쇠뿐만 아니라 분무장 내 액적들에 의한 신호의 감쇠 과정에 대한 고려가 필요하다. 주변 액적들의 영향을 최소한으로 줄이기 위해서는 레이저 평면광을 사용하는 광학 패터네이터와 달리 레이저 광선을 분무장에 조사하여 고압에서 나타날 수 있는 다중 산란에 의한 오차를 최소화할 수 있다. 이러한 이미지 처리 기법을 이용하는 광학 선형 패터네이터(Optical Line Patternator)를 이용하여 기존 레이저 계측기법으로 측정이 곤란하였던 고압 환경 하에서의 스월 동축형 인젝터의 분무 특성을 해석할 수가 있다.

# 레이저 계측법을 이용한 분무 가시화
# Spray Visualization Using Laser Diagnostics

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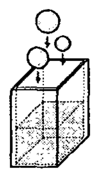
# Part I. Introduction

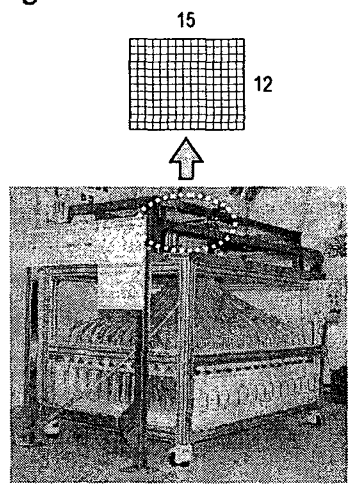
Seoul National University Rocket Propulsion Lab.

## Mechanical Patternator

- measure **mass-flux** collected in each segment



collected mass
*per* unit area & unit time

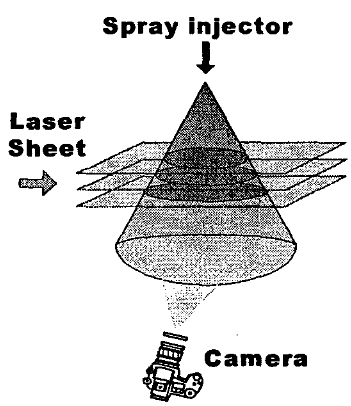


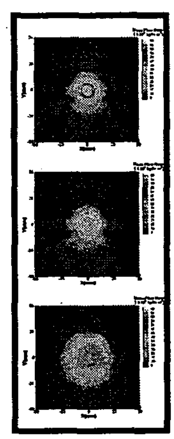

- Disadvantages:
  - ✓ spray-field perturbation
  - ✓ limited spatial resolution
  - ✓ slow measurement and intensive labor



## Optical Patternator

- Non-intrusive method
- Using Mie-scattering or Laser Induced Fluorescence
- 2-D Planar measurement
  - High spatial resolution
  - Rapid characterization



- Measurement parameter
  - Patternation
  - SMD
  - Relative mass distribution
  - Mass flux

# Previous Work

- Planar Laser Techniques
  - Extensively used in gas flows since early 1980s
  - Exiplex(Melton et al.,1985) : both gas and liquid concentrations
- Planar Liquid Laser Induced Fluorescence : UC Irvine (1995)
  - Mass distribution of fuel using the fluorescence signal
  - Experimental correction for the attenuation of the incident beam
- Laser Sheet Dropsizing : Cranfield Univ. (2000)
  - Uncertainty analysis of SMD measurement
- Commercial system
  - TSI : Optical Patternator
  - LaVision : Spray Master
  - En'Urga : SETscan Optical Patternator(*Statistical Extinction Tomography*)

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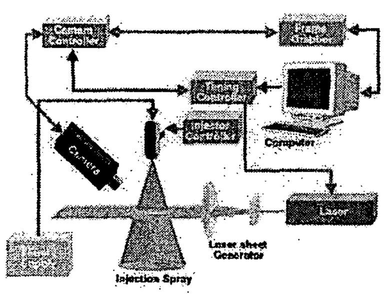
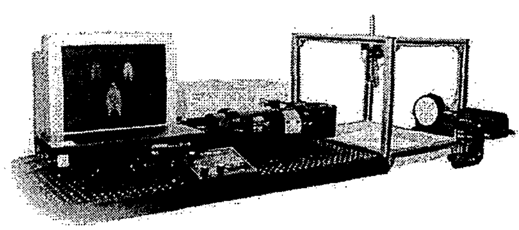
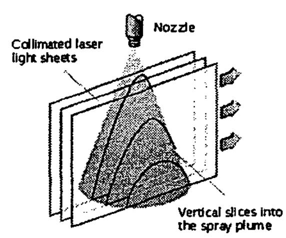
# Optical Patternator (TSI)



Light sheet in the horizontal plane



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# Measurement Principles (1)

**Mie scattered Light Intensity $\propto d^2$**

$$G_s(x,y) = I_o(x,y)c_s\sum N_i(x,y)d_i^2(x,y)$$

- $G_s(x,y)$: scattering signal intensity at (x,y) point
- $I_o(x,y)$: incident laser intensity
- $d_i$: diameter of drops
- $N_i(x,y)$: num. of drops

**Fluorescence Light Intensity $\propto d^3$**

$$G_f(x,y) = I_o(x,y)c_f\sum N_i(x,y)d_i^3(x,y)$$

- $G_f(x,y)$: fluorescence signal intensity at (x,y) point
- $I_o(x,y)$: incident laser intensity
- $d_i$: diameter of drops
- $N_i(x,y)$: num. of drops



# Measurement Principles (2)

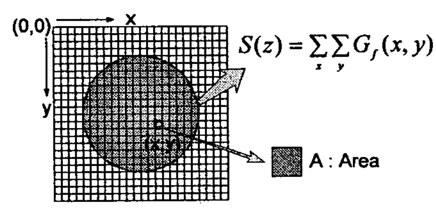
**Mass Distribution**

Proportional to the mass density of the dispersed phase, $\rho$

$$\Rightarrow G_f = C_f' I_o \delta m = C_f I_o \rho$$

Mass Flux, $\dot{m}''$

$$\dot{m}''(x,y) = \frac{G_f(x,y)}{S(z)}\frac{\dot{m}_{nozzle}}{A}$$




**SMD(Sauter Mean Diameter)**

$$\frac{G_f(x,y)}{G_s(x,y)} = \frac{c_f}{c_s}\left[\frac{\sum N_i(x,y)d_i^3(x,y)}{\sum N_i(x,y)d_i^2(x,y)}\right] = KD_{32}(x,y) \Rightarrow D_{32}(x,y) = \frac{1}{K}\left(\frac{G_f(x,y)}{G_s(x,y)}\right)$$

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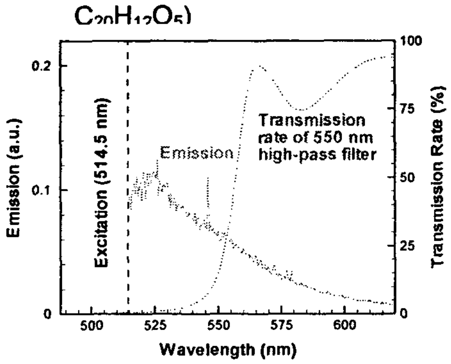
# Characteristic of Dye Material

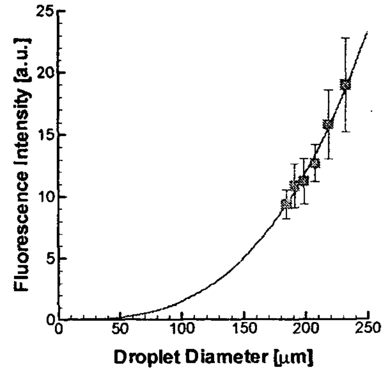
## Emission spectrum

- Ar+ laser (514.5 nm)
- Dye : Fluorescein (Aldrich F245-6, $C_{20}H_{12}O_5$)




## Index of fluorescence

$$G_f = 1.48 \times 10^{-6} \cdot D_p^{3.0006}$$



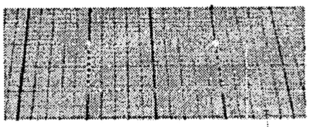



# Error Sources

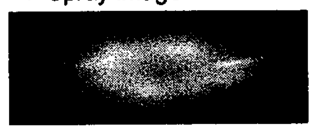
| | |
|---|---|
| ***Laser Sheet Intensity Variation***<br>– Gaussian beam<br>– Sheet beam optics | ***Quartz Cell Calibration*** |
| ***Perspective Error*** | ***Affine Transformation*** |
| ***Laser Sheet Extinction*** | ***Sequential illumination (Talley et al. 1996)*** |
| ***Signal Attenuation*** | ***Objectives of this study!*** |
| ***Secondary Emission***<br>– Emission from molecule(s) outside the plane by scattered energy<br>– Multiple scattering | ***Not Easy to quantify*** |

# Perspective error

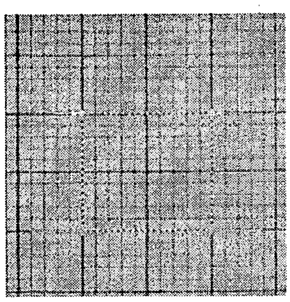
❖ Grid image for calibration

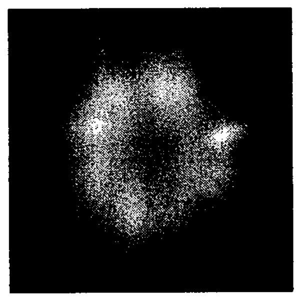


❖ Spray image



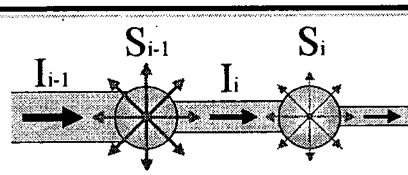
**_Affine Transformation_**





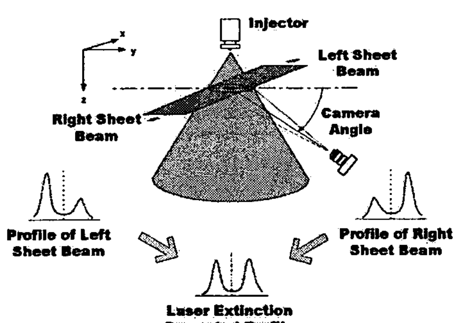


# Laser Sheet Extinction

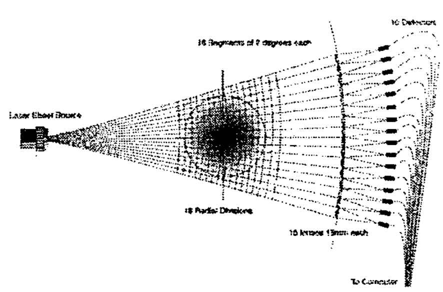



$$I_i < I_{i-1} \ \& \ S_i < S_{i-1}$$

❖ Talley et al. (US Air Force, 1996)




❖ Sellens et al. (Queen's Univ., 2000)



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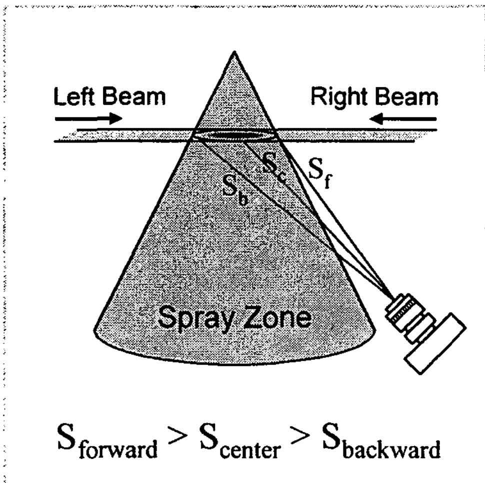
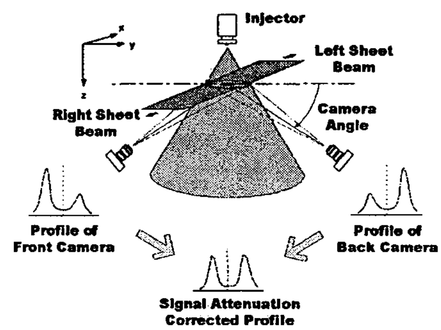
# Signal Attenuation

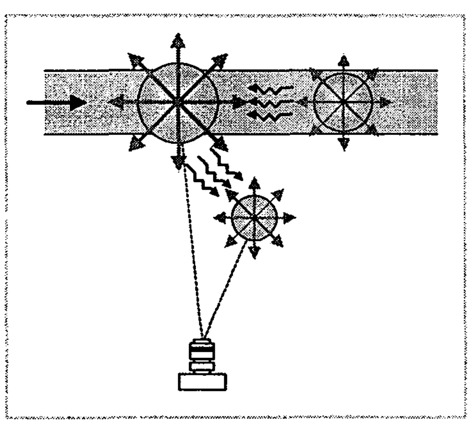



- Sankar et al. (Aerometrics Inc., 1999)
  : SMD is not affected by attenuation
- Present Study (using 2 cameras)

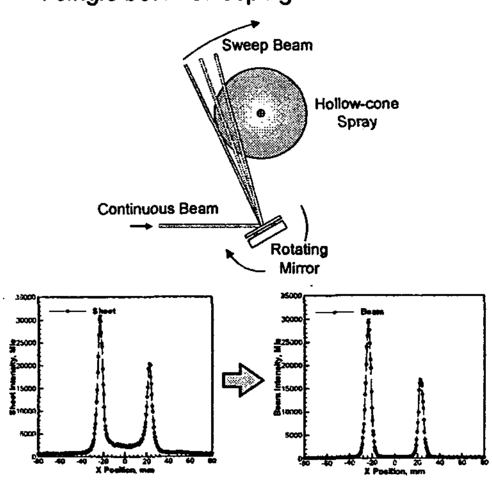





# Secondary Emission



- Brown & Talley (2002)
  : single beam sweeping



# Part II. Correction of Laser/Signal Attenuation in Dense Spray



## Correction of Signal Attenuation

❖ Beer's law

$$G_t = G_0 \exp[-\tau] = G_0 \exp\left[-\int_0^L \gamma(s) ds\right]$$

$G_0$ : original intensity
$G_t$ : transmitted signal
$\tau$ : optical depth
$\gamma$ : attenuation coefficient
$s$ : signal path

❖ If the optical depth ($\tau$) is constant throughout the spray, the attenuated intensity can be restored by ***geometrical average using 2 cameras***.

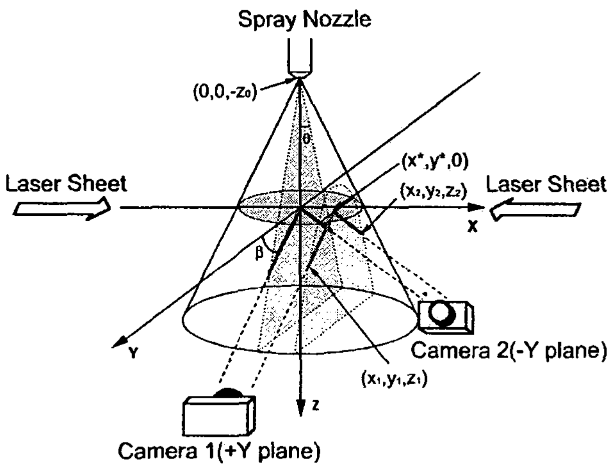
$$\sqrt{G_1 G_2} = G_{real} \exp\left[-\frac{1}{2}\gamma(L_1 + L_2)\right] \approx K_{ext} G_{real}$$

$$G_{real} \approx \frac{1}{K_{ext}} \sqrt{G_1 G_2}$$

❖ Is optical depth $\gamma$ ($L_1$+$L_2$) constant?

➡ ***Errors are dependent on***
**(i) Sum of attenuation length**
**(ii) Inhomogeneity of medium**

# 3-D Geometry for Signal Path




❖ Spray Cone Equation

$$x^2 + y^2 = (z + z_0)^2 \tan^2 \theta$$

❖ Signal Path Equation

- *Meas. Pt. ~ Camera 1*

  $s_1$: $(x^*, y^*, 0) \rightarrow (x_1, y_1, z_1)$

$$\begin{cases} (x^*)^2 + y_1^2 = (z_1 + z_0)^2 \tan^2 \theta \\ z_1 = (y_1 - y^*) \tan \beta \end{cases}$$

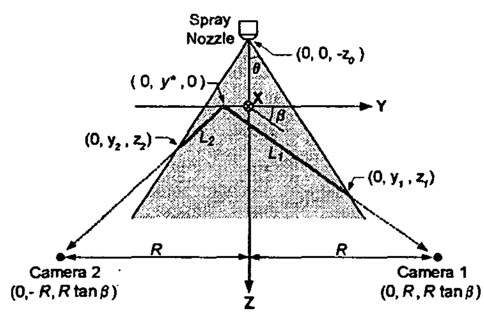
- *Meas. Pt. ~ Camera 2*

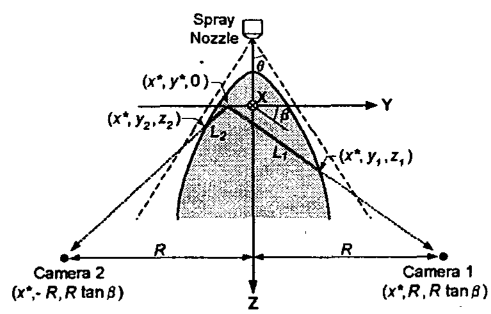
  $s_2$: $(x^*, y^*, 0) \rightarrow (x_2, y_2, z_2)$

$$\begin{cases} (x^*)^2 + y_2^2 = (z_2 + z_0)^2 \tan^2 \theta \\ z_2 = (y_2 - y^*) \tan \beta \end{cases}$$



# Cross-section of Signal Path



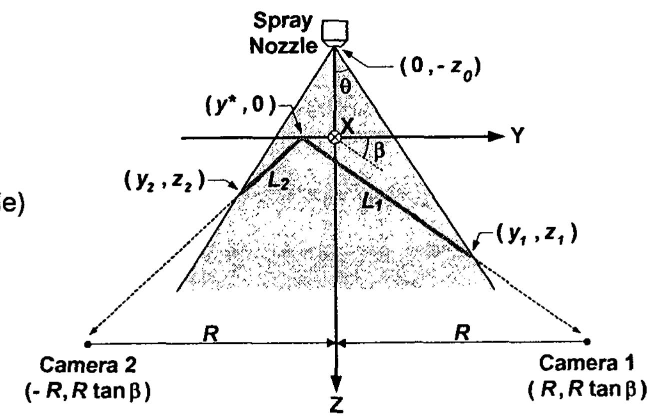




***$x^* = 0$***
***(Straight Line Edge)***

***$x^* \neq 0$***
***(Hyperbola Edge)***

## Signal Path of x=0 plane

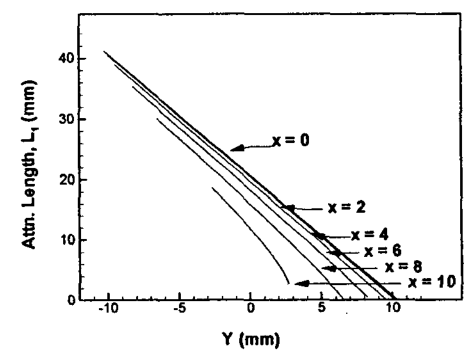
❖ Assumption
- 2-D planar Analysis (X = 0 plane)
- β = const. (camera viewing angle)
- θ = const. (spray cone angle)



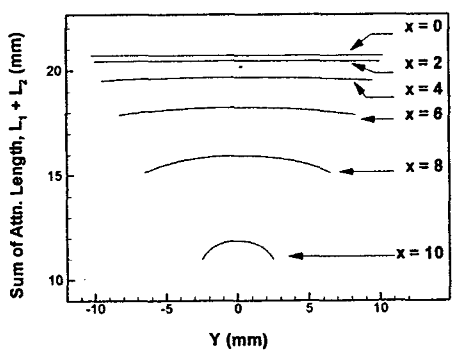

$$\Rightarrow\quad L_1+L_2=\sqrt{(1+\tan^2\beta)}\left(\frac{1-\tan\beta\tan\theta}{2\tan\theta_0}\right)=const$$



## Attenuation Length (Signal Path)



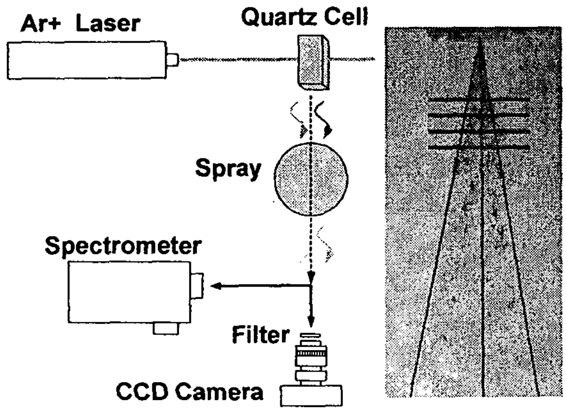

Single camera detection

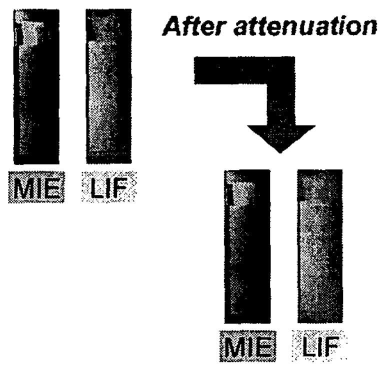



Two cameras detection (Sum of two length of signal path)

# Attenuation Coeff. Measurement

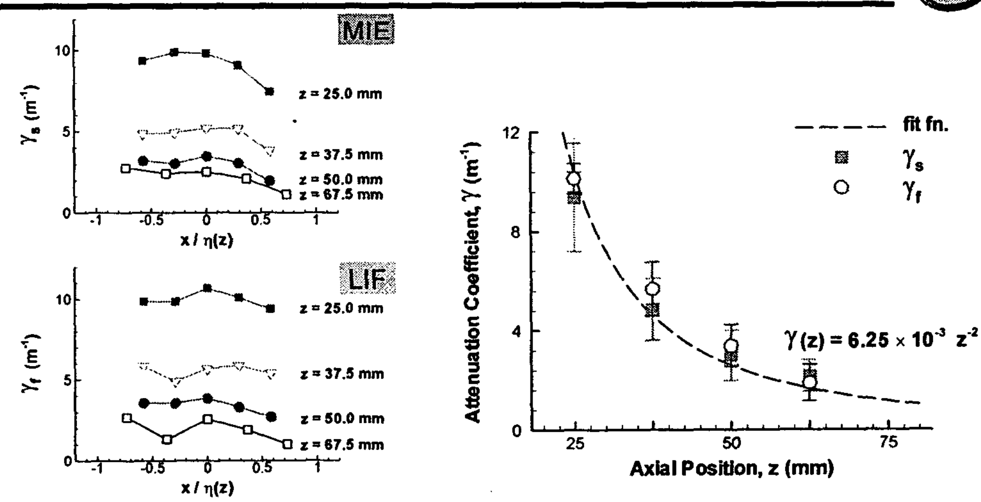
❖ Solid Cone Spray
- Spray cone angle : 45°
- Pressure : 5 bar
- Mass flow rate : 10 g/s





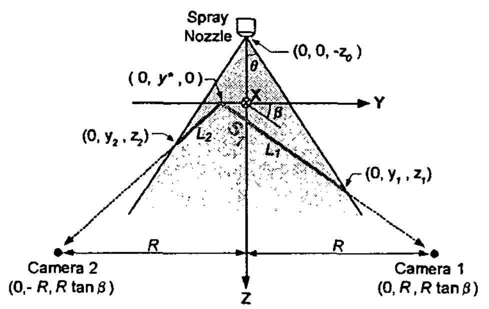

# Attenuation Coefficients ( $\gamma_S$ , $\gamma_f$ )

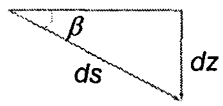



❖ *Radial Variation* : $\gamma = \gamma\,(x,y) \approx$ const. ❖ *Axial Variation* : $\gamma = \gamma\,(z) \neq$ const.

# Calculation of Optical Depth

❖ Optical Depth (τ) = Attenuation Coeff. (γ) × Signal Path (L)




$$\gamma(z) = 6.5\times10^{-3}/(z+z_0)^2$$

$$ds = \frac{dz}{\sin\beta}$$

– Single camera detection

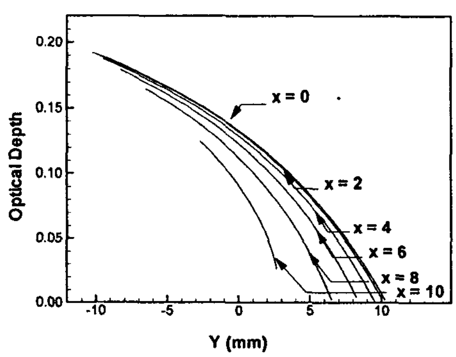
$$\tau = \int \gamma(s)ds$$

– Two camera detection (Geometrical Average)

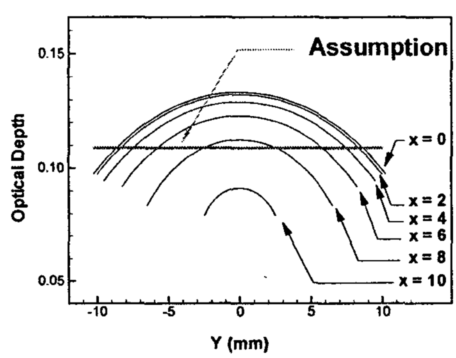
$$\tau = \frac{1}{2}\left\{\int_0^{L_1}\gamma(s_1)ds_1 + \int_0^{L_2}\gamma(s_2)ds_2\right\}$$



# Variation of Optical Depth




❖ *Single camera detection at Z = 25 mm*

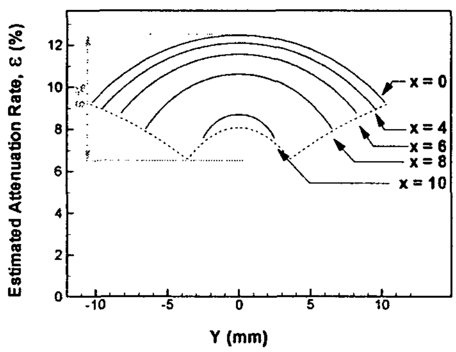



❖ *Two camera detection at Z = 25 mm (Geometrical Average Method)*

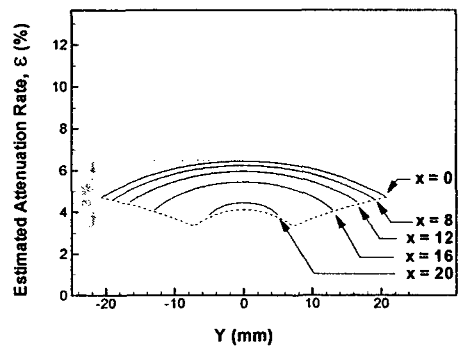
***Optical depth is not constant.*** ➡ **Errors due to Signal Attenuation**

## Estimated Attenuation Rate
### (Two Camera Detection)

The attenuation rate (ε) represents a measurement error due to signal attenuation: $\varepsilon = (G_{real} - G_{meas}) / G_{real}$




❖ *Z = 25 mm*

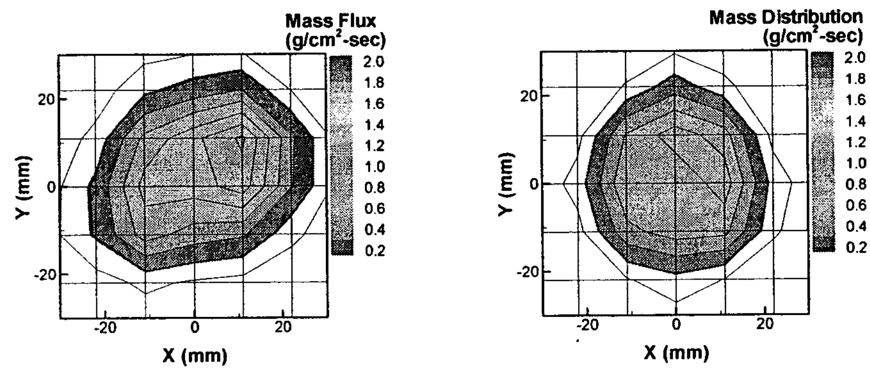



❖ *Z = 50 mm*



# Part III. Spray Visualization Using Optical Patternator

# Patternation (Z=50mm)

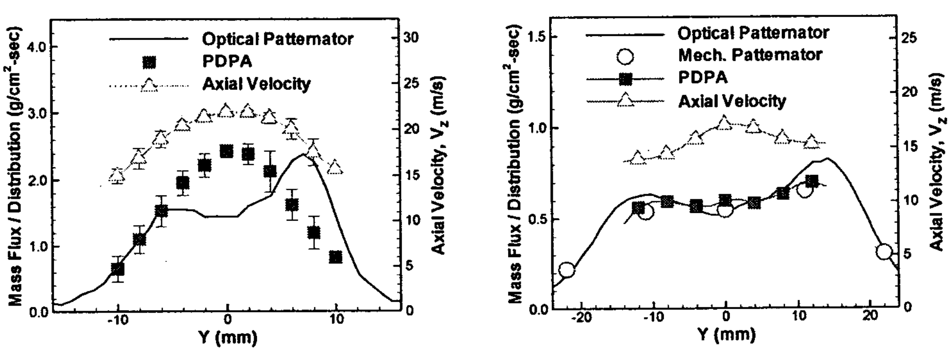



**Mechanical Patternator**

**Optical Patternator**

**Seoul National University Rocket Propulsion Lab.**

# Mass Distribution and Mass Flux




**Z = 25 mm**

**Z = 50 mm**

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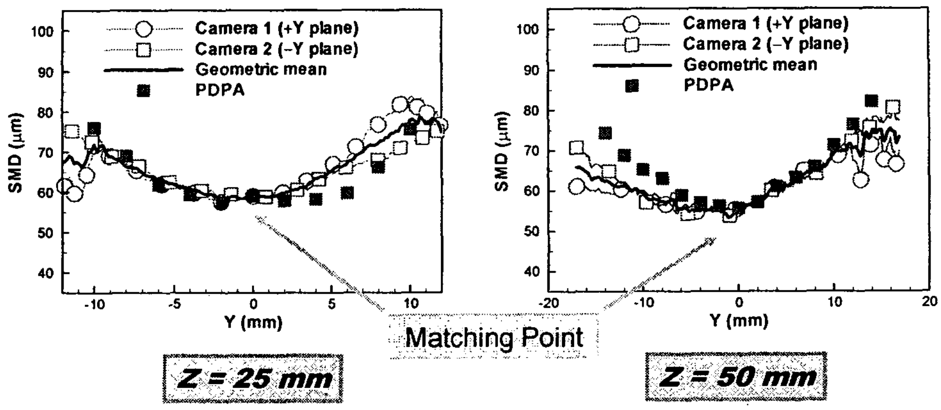
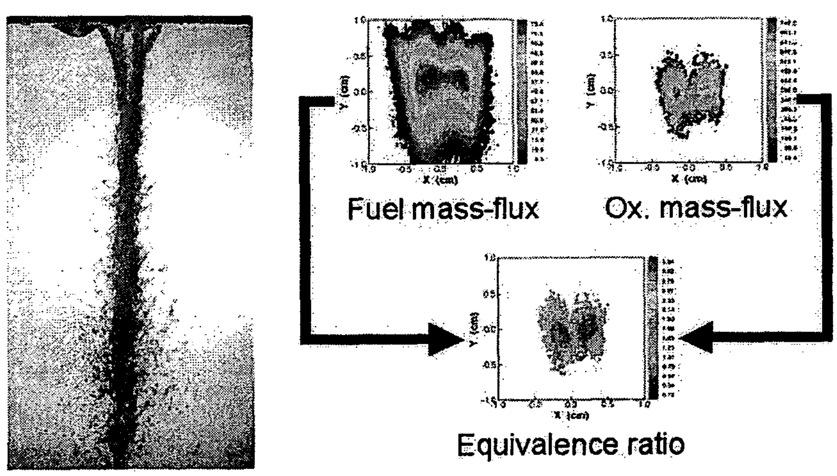
# Comparisons of SMD Meas.



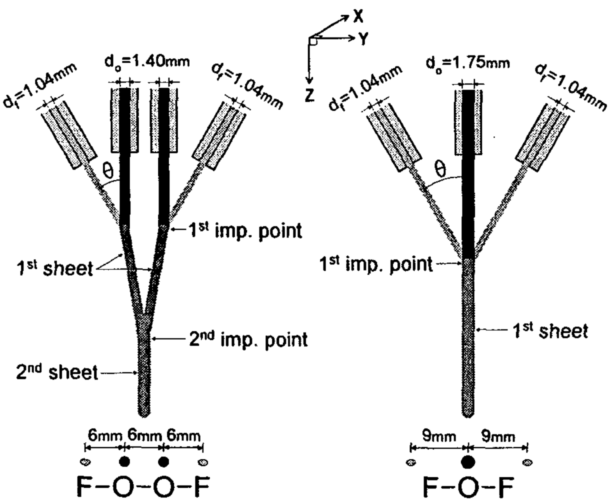

- Correction factor, *K*, was calculated to match a value with PDPA at the spray center (x = 0).

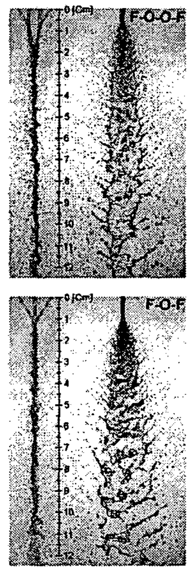


# Measurement of Mixing Rates
## (Rocket Injector: KSR-III)



# FOOF & FOF Injectors

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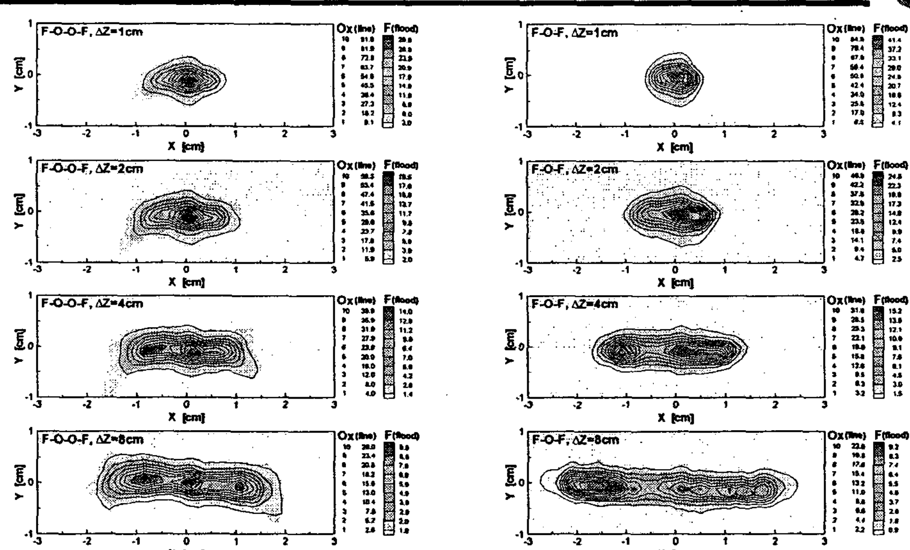
# Mixing Process (F-O-O-F, F-O-F)

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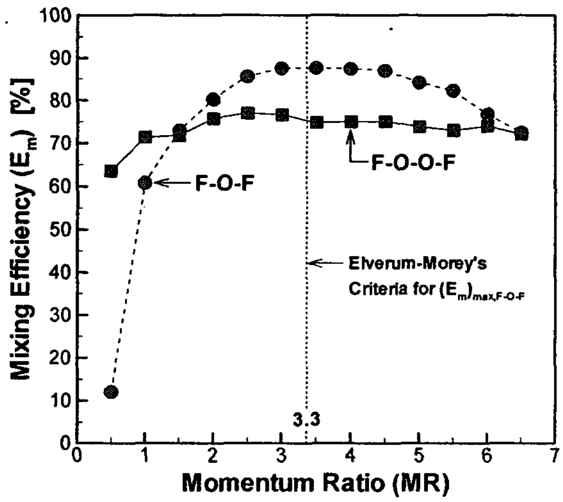
# Mixing Efficiency

$$E_m = 1 - \frac{1}{\dot{m}_o}\left[\sum_{0}^{n}\left(\dot{m}_{o,i} + \dot{m}_{f,i}\right)(R - r)\right] - \frac{1}{\dot{m}_f}\left[\sum_{0}^{\bar{n}}\left(\dot{m}_{o,i} + \dot{m}_{f,i}\right)(\bar{r} - R)\right]$$

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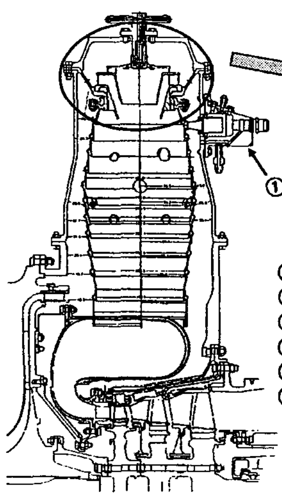
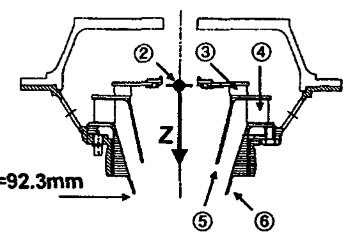
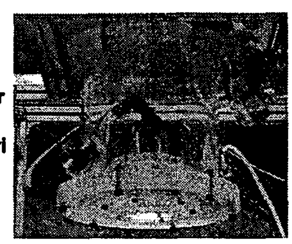
# Model Gas Turbine Combustor




① igniter
② injector
③ primary swirler
④ secondary swirler
⑤ primary venturi
⑥ secondary venturi



Combustor

Swirl cup

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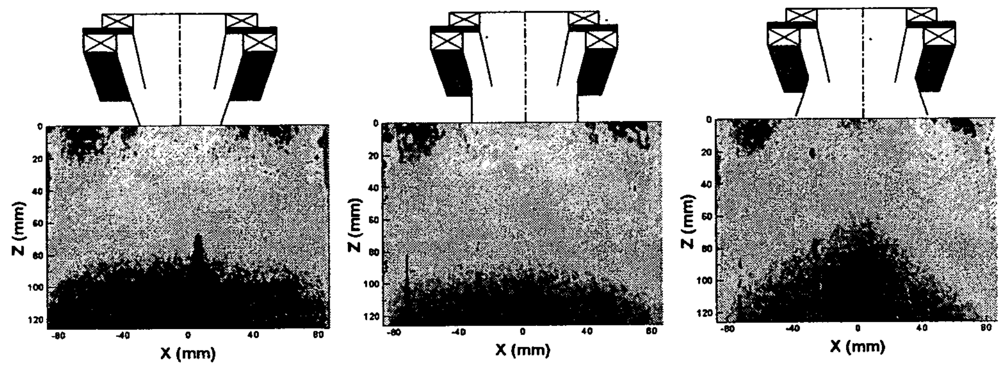
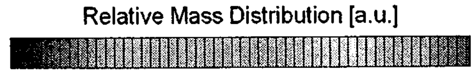
## Relative Axial Mass Distributions

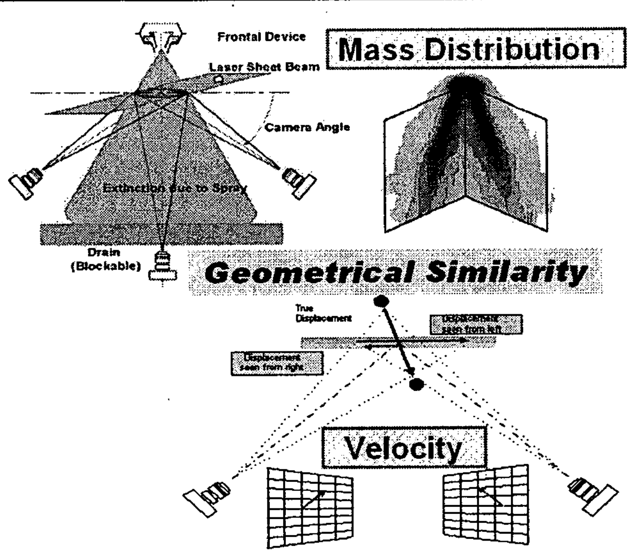



(a) Converging (b) Straight (c) Diverging






## Simultaneous Measurement
### (Mass Distribution & Velocity)

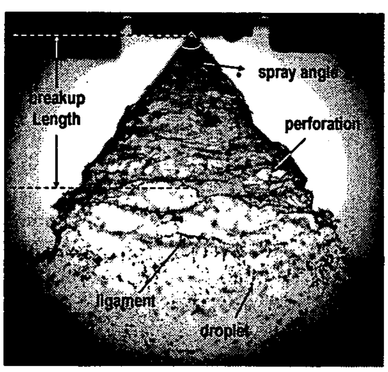


# Part IV. Spray Visualization at High Ambient Pressure



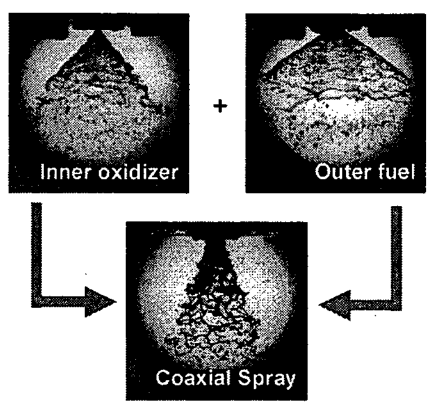
## Swirl Coaxial Injector Spray

❖ **Breakup mechanism of swirl injector**




- Centrifugal force (thinning of sheet)
- Aerodynamic force

❖ **Liquid-liquid swirl coaxial injector**




- Impact force (emulsion injection)

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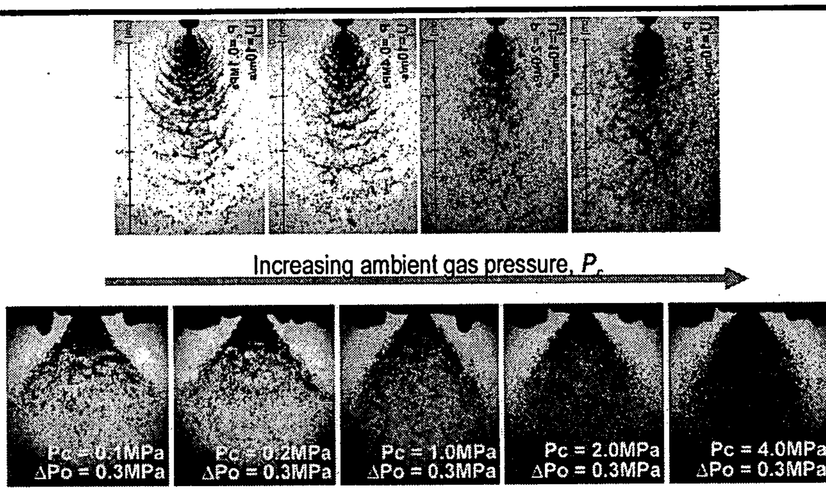
# Spray in High Pressure




⇨ **In high pressure, spray become extremely dense.**
Therefore, noise signals caused by error factors become strong.

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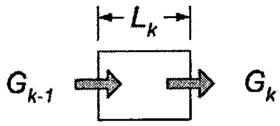
# Beer's Law

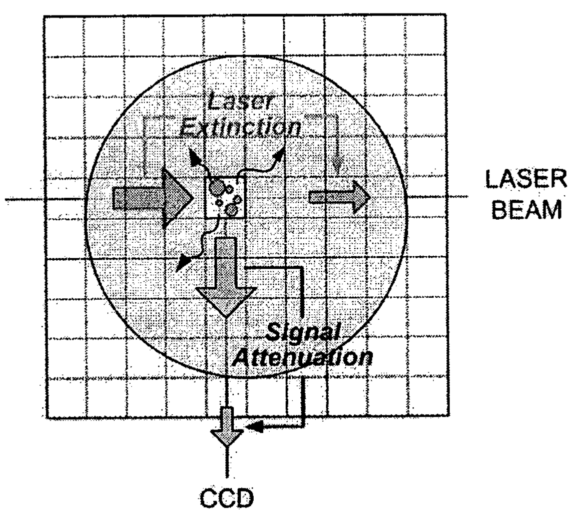
❖ Beer's law

$$G_k = G_{k-1}\exp[-\gamma_k L_k]$$

$$G_n = G_0 \exp[-\tau] = G_0 \exp\left[-\sum_{k=1}^{n}\gamma_k L_k\right]$$

$G_0$ : original intensity
$G_n$ : transmitted signal
$\tau$ : optical depth
$\gamma$ : attenuation coefficient
$L$ : signal path

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# Laser & Signal Attenuation

❖ **Laser Extinction**

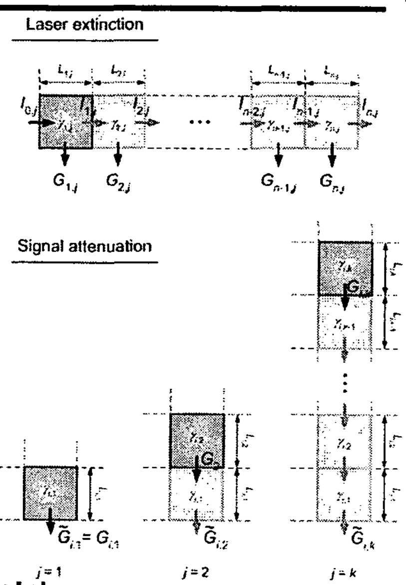
– Transmission (Tx) : measured by a photo detector

$$\mathrm{Tx} = \frac{I_n}{I_0} = \exp\left[\sum_{i=1}^{n} \gamma_i L_i\right]$$

❖ **Signal Attenuation**

$\tilde{G}_k$ : measured intensity by CCD

$$G_k = \tilde{G}_k \exp\left[\sum_{j=1}^{k-1} -\gamma_j L_j\right]$$






# Mie-scattering Signal

❖ **Mie-scattering Signal**

– For large droplets (D >> λ)

Lim and Sivatharu, 2002 (SETScan Optical Patternator)

– $I/I_0 = \tau = \exp(-\kappa\Delta) = \exp(-\pi C_n D_{20}^2 \Delta/2)$

$$\gamma_k \propto N D_{20}^2$$

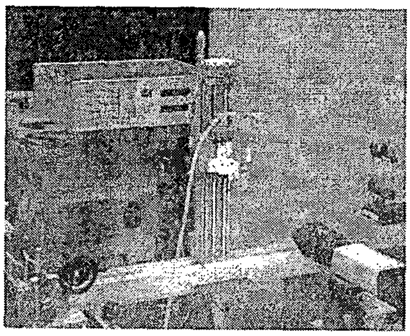
**Mie scattered Light Intensity $\propto d^2$**

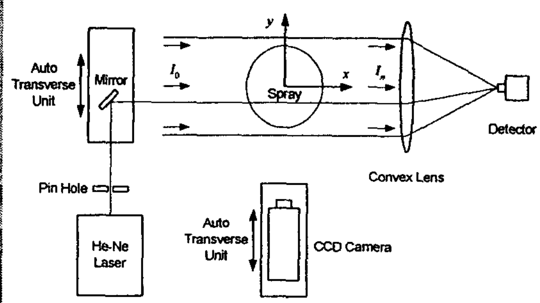
$$G_{k,0} = c_s I_k \sum_i N_i D_i^2 = c_s I_k N D_{20}^2 \quad \text{where,} \quad D_{20} = \left[\sum_i N_i D_i^2\right]^{\frac{1}{2}}$$

# Experimental Setup for Test Experiment

❖ Experimental Setup for the atmospheric pressure circumstances

- Solid cone spray (swirl in inside of injector): Z = 25 mm
- Algebraic Reconstruction Technique (ART) : mentioned at the formal page.

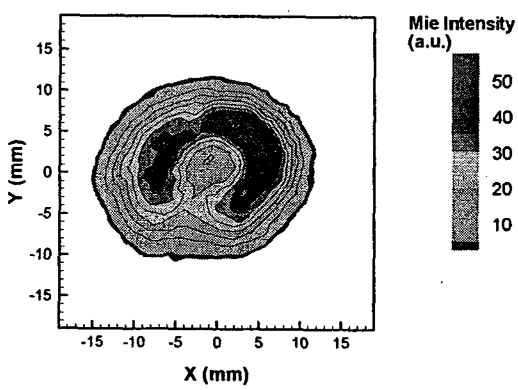




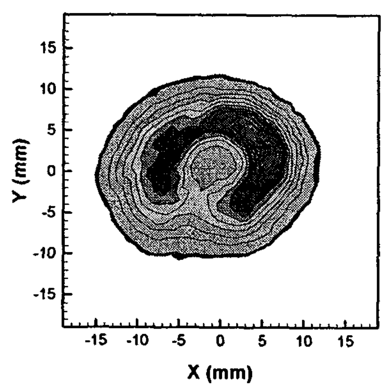



# Mie-scattering Image Correction
## ($Pc$ = 1atm)

❖ Raw image reconstructed from line profile




❖ Processed Image *(attenuation corrected)*



# Patternation Index

❖ Patternation Index (P.I.)

$$\text{P.I.}(\%) = \sum_{i,j} \left| \frac{1}{N} - \frac{m(i,j)}{\sum_{i,j} m(i,j)} \right| \times 100$$

❖ Spray Uniformity Index (S.U.I.)

$$\text{S.U.I.} = \sqrt{\frac{\sum_{i,j} \left( y(i,j) - \bar{y} \right)^2}{N}} \qquad \text{where,} \quad y \equiv \frac{m(i,j)}{\sum_{i,j} m(i,j)}$$

$$\bar{y} \equiv \frac{\sum_{i,j} y(i,j)}{N} = 1$$

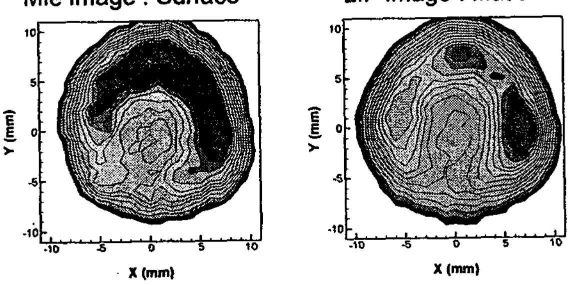
- $N$ : # of grids
- $m$ : mass of liquid or droplets (pixel Intensity in image)



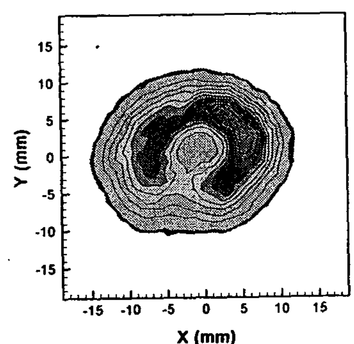
# Test Patternation Result

❖ Optical Patternator

Mie Image : Surface | LIF Image : Mass

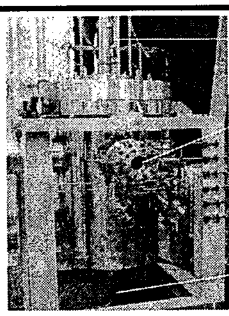


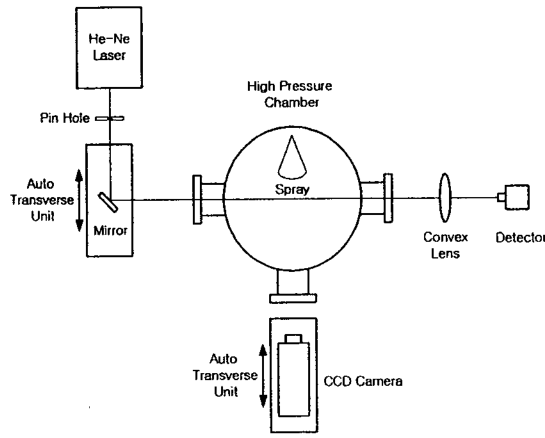

❖ Optical Line Patternator




| | Optical Line Patternator | Optical Patternator | |
|---|---|---|---|
| | | Mie | LIF |
| P.I. (%) | 50.49 | 50.21 | 48.02 |
| S.U.I. | 0.6030 | 0.5593 | 0.5456 |

# Experimental Setup for High Ambient Pressure Condition




| | |
|---|---|
| chamber diameter | 500mm |
| window size | 80mm×4 |
| window material | quartz |
| operating limit pressure | 6MPa |
| spray simulant | water |
| pressurizing gas | nitrogen |

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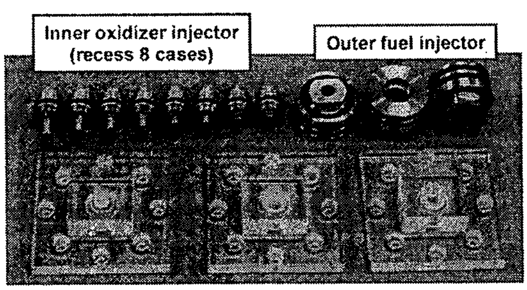
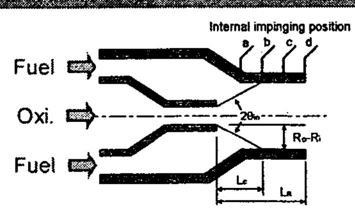
# Experimental Condition

❖ Injector Parts




❖ Operating Conditions

**Swirl Coaxial Injector**
- $d_0$ = 1mm
- Oxidizer flow rate: 25.6 g/s
- Fuel flow rate: 10.76g/s
- $P_c$ = 1,5,10,20,40bar
- Round-edged inlet

**Measurement position :**
***Z = 20 mm*** **downstream**
**From the end of injector**

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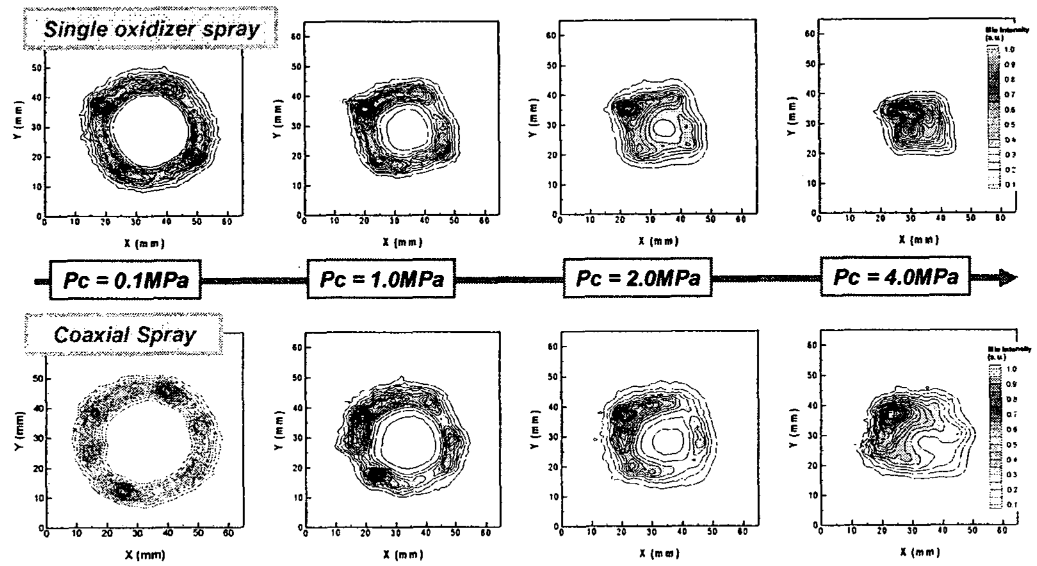
# Patternation Results

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# Conclusion

- **Optical Patternator can measure spray and flow parameters.**
  - Patternation, local mass distribution, drop size(SMD)
- **For quantitative measurement, the method for correcting signal extinction and determining correction factor, *K* must be considered.**
  - In order to correct the signal attenuation on the path through the dense spray, the method to find the geometric mean of the intensities obtained from the two cameras was evaluated.
- **Optical Line Patternator is a reliable diagnostics method for spray.**
  - Major error factors, laser extinction, signal attenuation can be corrected by Optical Line Patternator.

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