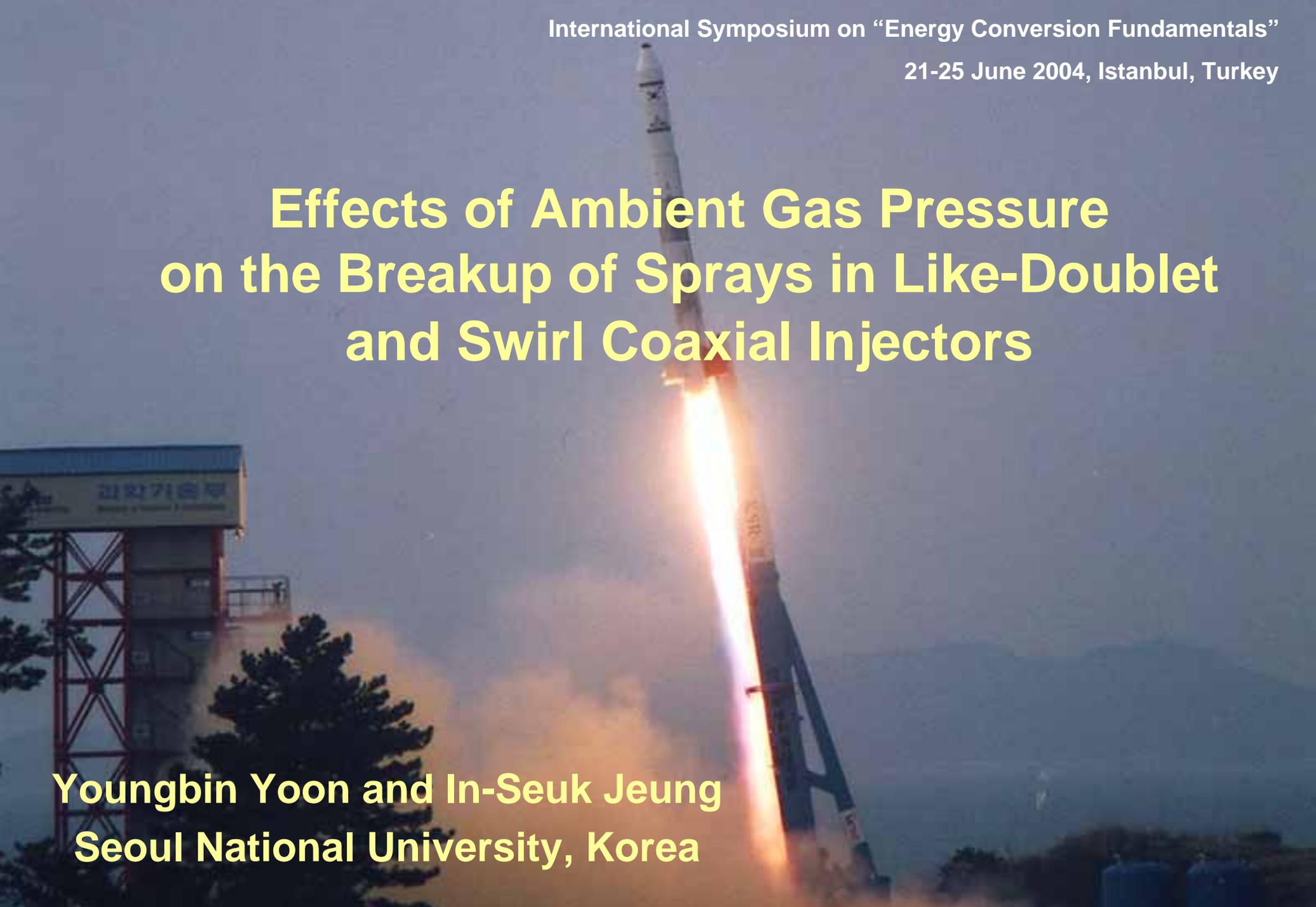


Effects of Ambient Gas Pressure on the Breakup of Sprays in Like-Doublet and Swirl Coaxial Injectors

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Report Documentation Page

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Korean Liquid Rockets



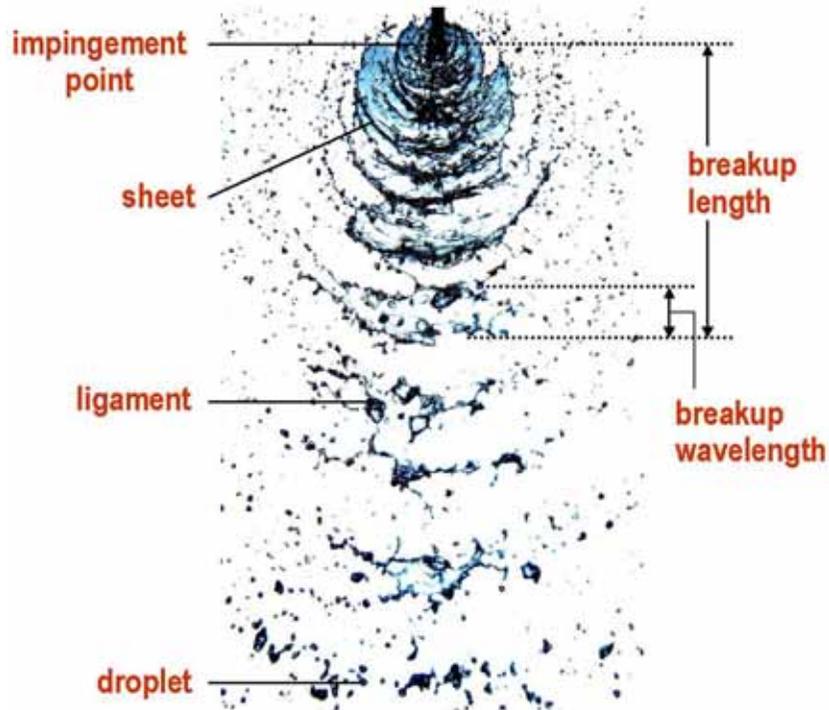
KSR-III

	KSR-III	KSLV-I
Period	1998 ~ 2002	2003 ~ 2007
Budge	\$ 6,800,000	\$ 300,000,000
Target	<ul style="list-style-type: none"> • Science Observation • 1st Liquid Rocket 	<ul style="list-style-type: none"> • Launch of Small Satellite (100kgf)
Injector	Impinging Type (Kerosene/LOX)	Swirl Coaxial Type (Kerosene/LOX)
System	Non-staged	2 stage (1st: liquid, 2nd: solid)
Supply	Pressure Type	Tubopump
Cooling	Ablative Cooling	Regenerative Cooling
Engine Development	Independent Development	Co-development with Russia
Specification		
Total Weight	5.6 ton	140 ton
Thrust	13 ton	150~170 ton
P@chamber	200 psi	5.25 MPa
T@chamber	3200 K	3616 K
Burning time	59 sec	about 120 sec

Breakup Mechanism

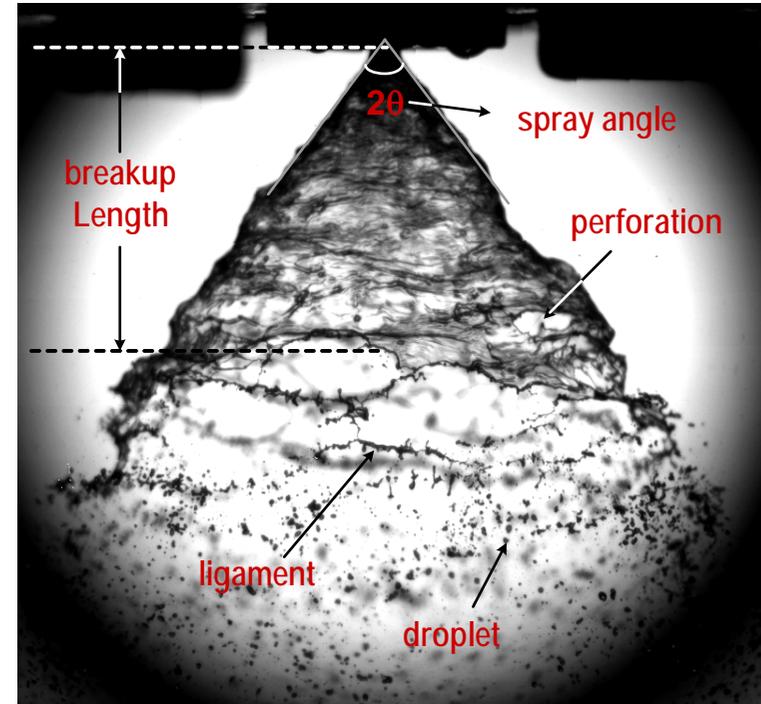


➤ Impinging type injector (Like-Doublet)



- Impact force
- Aerodynamic force

➤ Coaxial type injector (Swirl-Coaxial)



- Centrifugal force (thinning of sheet)
- Aerodynamic force
- Impact force (emulsion injection)

Linear Instability Theory

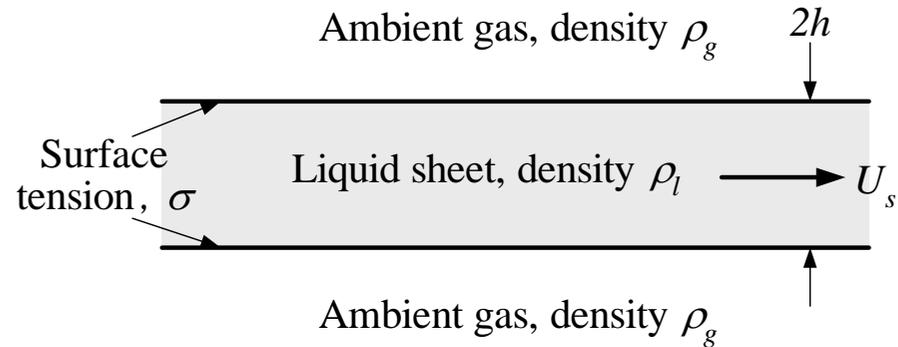


➡ Modeling sheet breakup length and droplet size

Huang [1970]

$$\frac{x_b}{d_o} = 7.1 \rho^{-2/3} We_j^{-1/3}$$

$$\text{where } \rho = \frac{\rho_g}{\rho_l}, We_j = \frac{\rho_l U_j^2 d_o}{\sigma}$$



Ryan et al. [1995]

$$\frac{x_b}{d_o} = 10.4 \rho^{-2/3} We_j^{-1/3}$$

$$\frac{d_D}{d_o} = 1.25 \rho^{-1/6} We_j^{-1/3}$$

$$x_b \propto \rho^{-2/3} We_j^{-1/3}$$

$$d_D \propto \rho^{-1/6} We_j^{-1/3}$$

Objectives



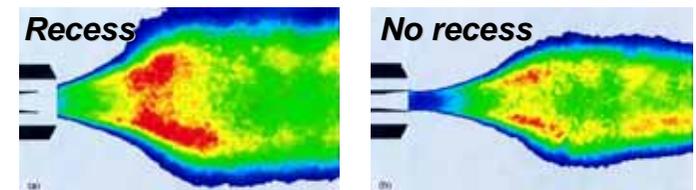
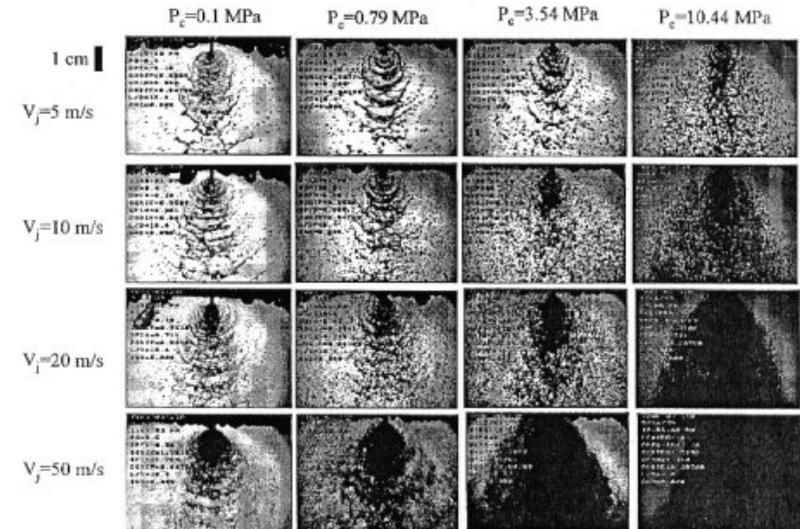
➤ Impinging type injector (Like-Doublet)

Find the breakup characteristics of laminar and turbulent sheets in high pressure environments.

➤ Coaxial type injector (Swirl-Coaxial)

Find the effect of recess on the spray characteristics of liquid-liquid swirl coaxial sprays in high pressure environments.

Strakey & Talley (2000)



D. Kendrick et al.
(ONERA, FRANCE, 1999)

High Pressure Chamber



Traversing device

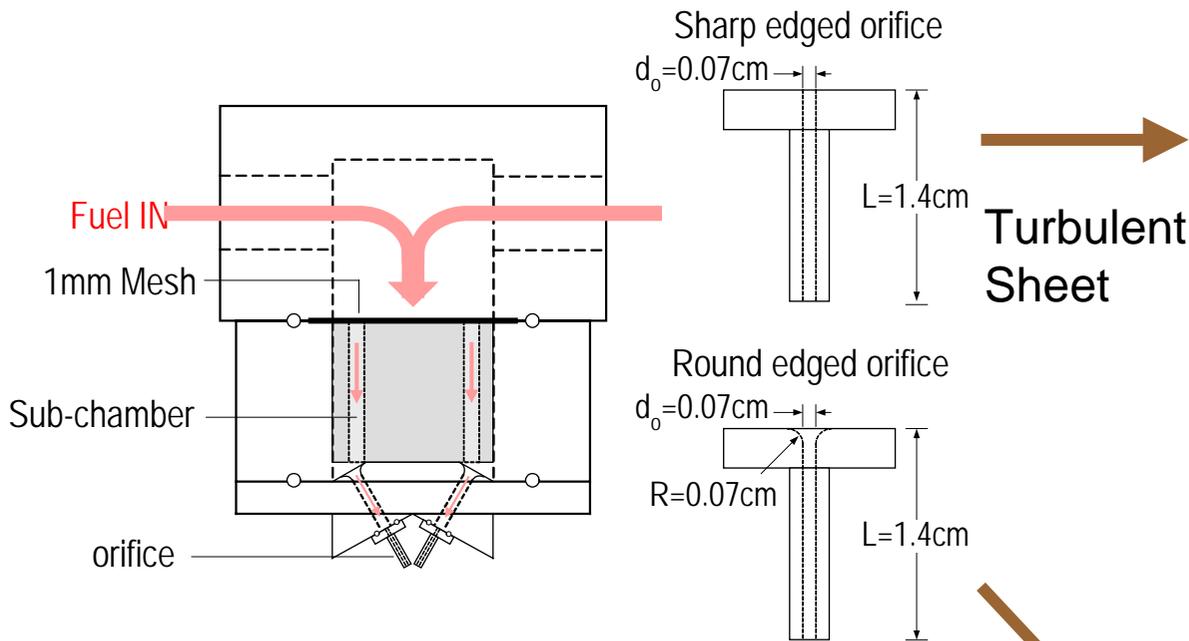
Quartz window

Air-curtain system

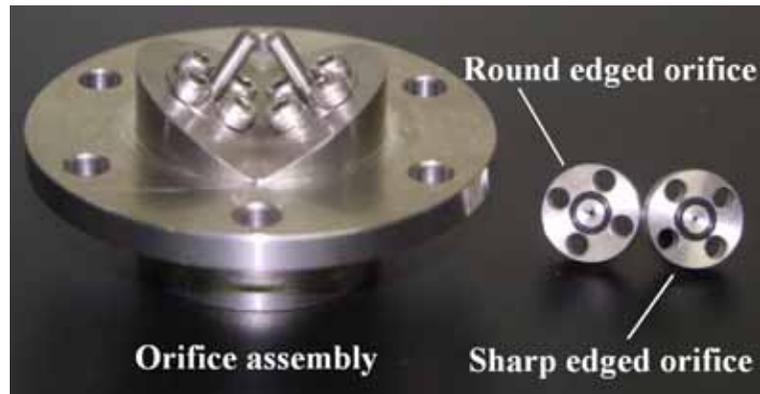
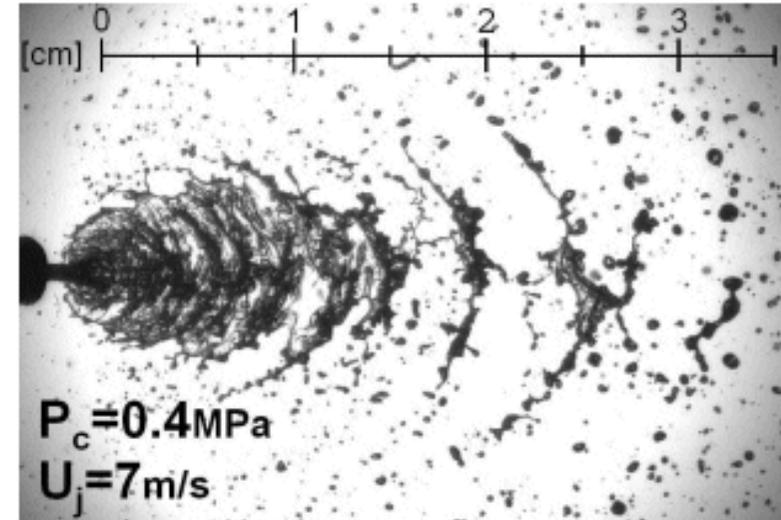
Drain

	Present	AFRL (USA)
Chamber Diameter	500mm	500mm
Window Size	80mm×4	50mm×3 120mm×1
Window Material	quartz	sapphire
Max. Pressure	6MPa	about 10MPa
Spray Simulant	water	water
Pressurizing Gas	nitrogen	nitrogen

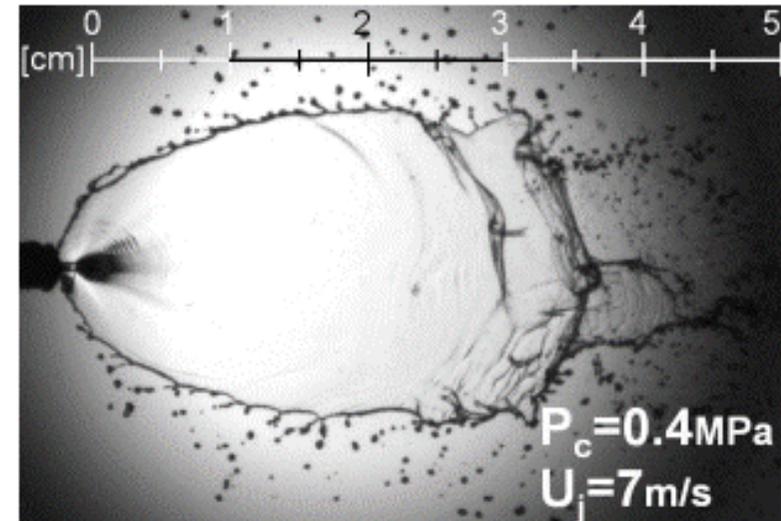
Like-Doublet Injector Design



Turbulent Sheet



Laminar Sheet

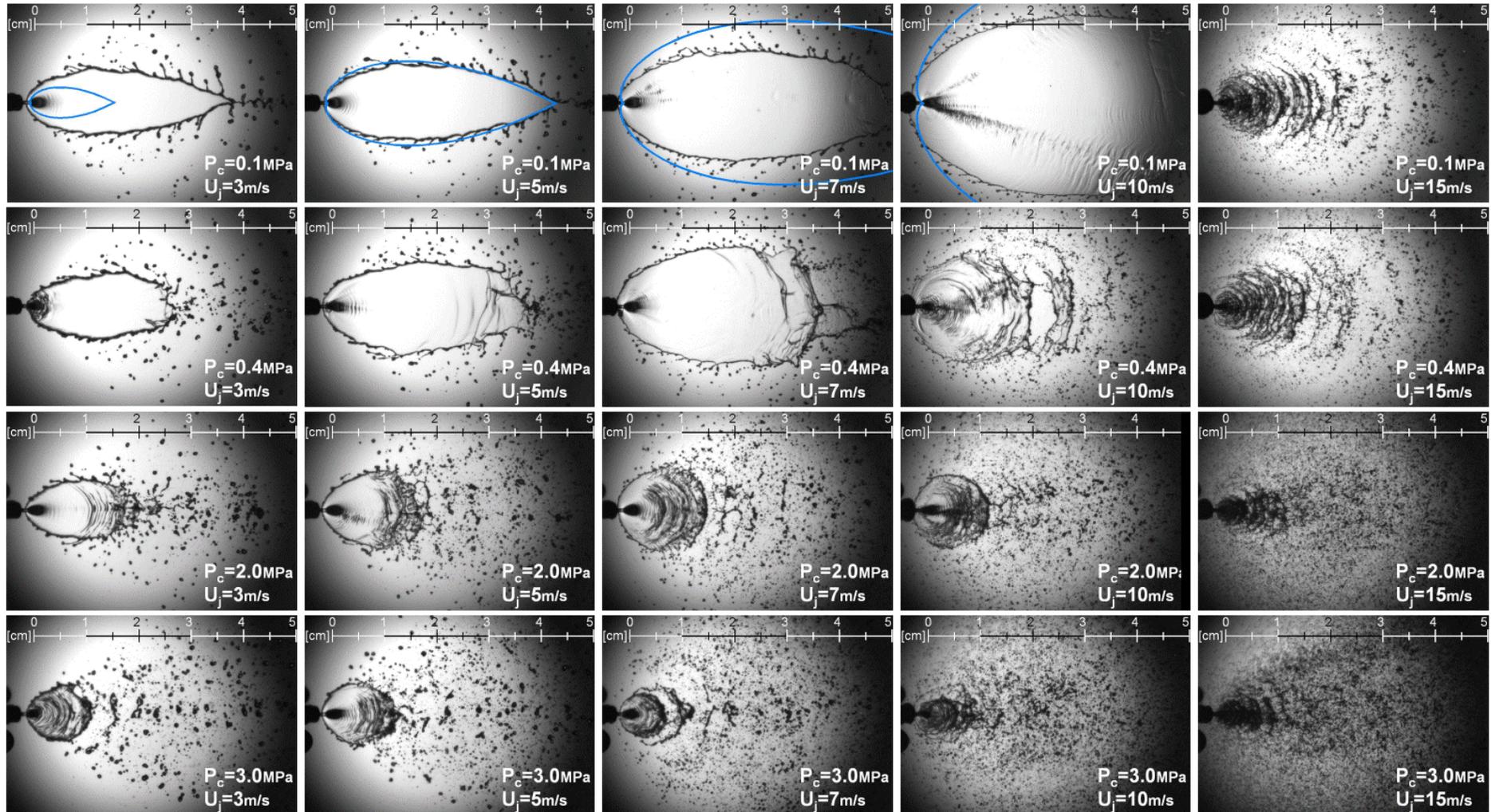


Changes of Sheet Shapes

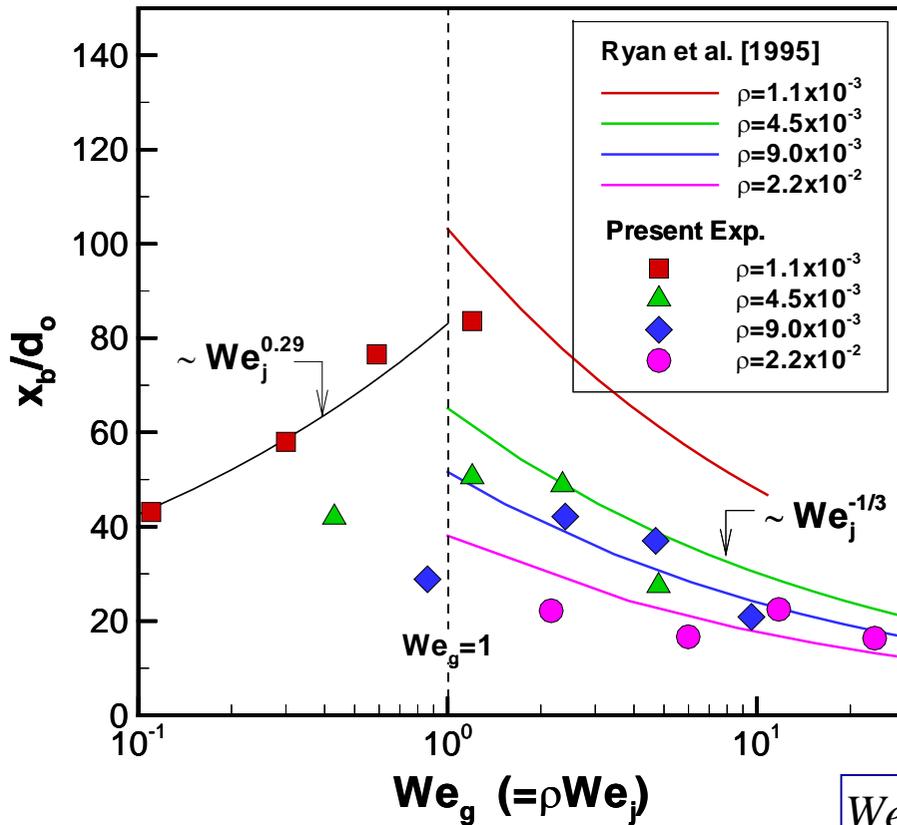


Increasing injection velocity, U_j →

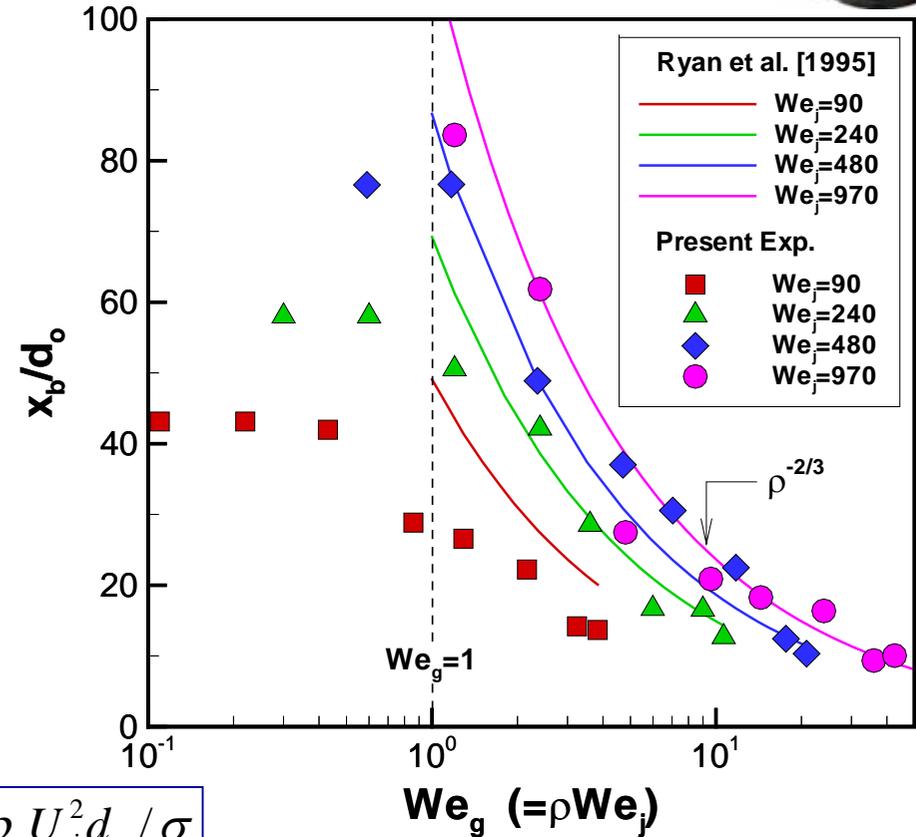
Increasing ambient gas pressure, P_c ↓



Sheet Breakup Length

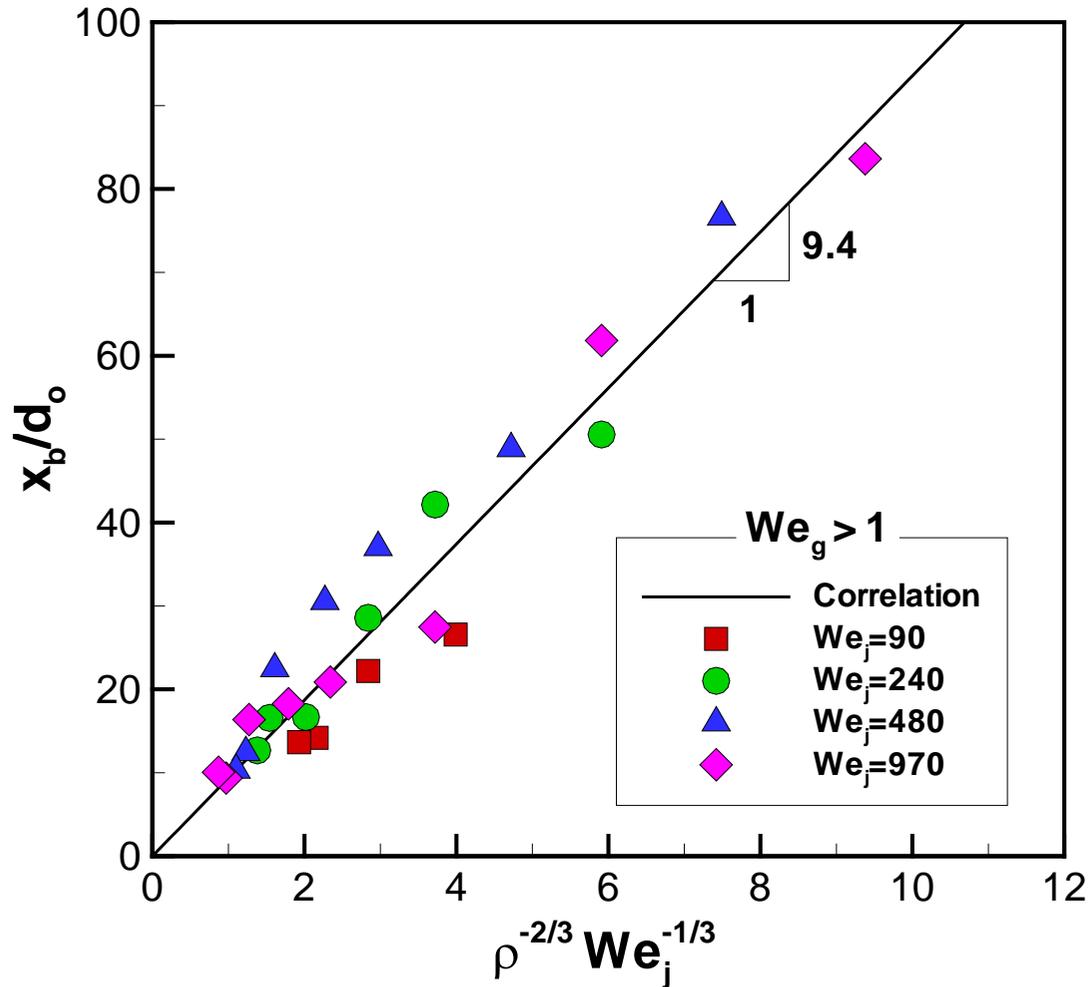


$$We_g = \rho_g U_j^2 d_o / \sigma$$



- When $We_g < 1$, laminar sheets expand as increasing mass flow rate and aerodynamic force does not affect the sheet breakup.
- When $We_g > 1$, laminar sheets are broken by aerodynamic force.

Breakup Length Modeling



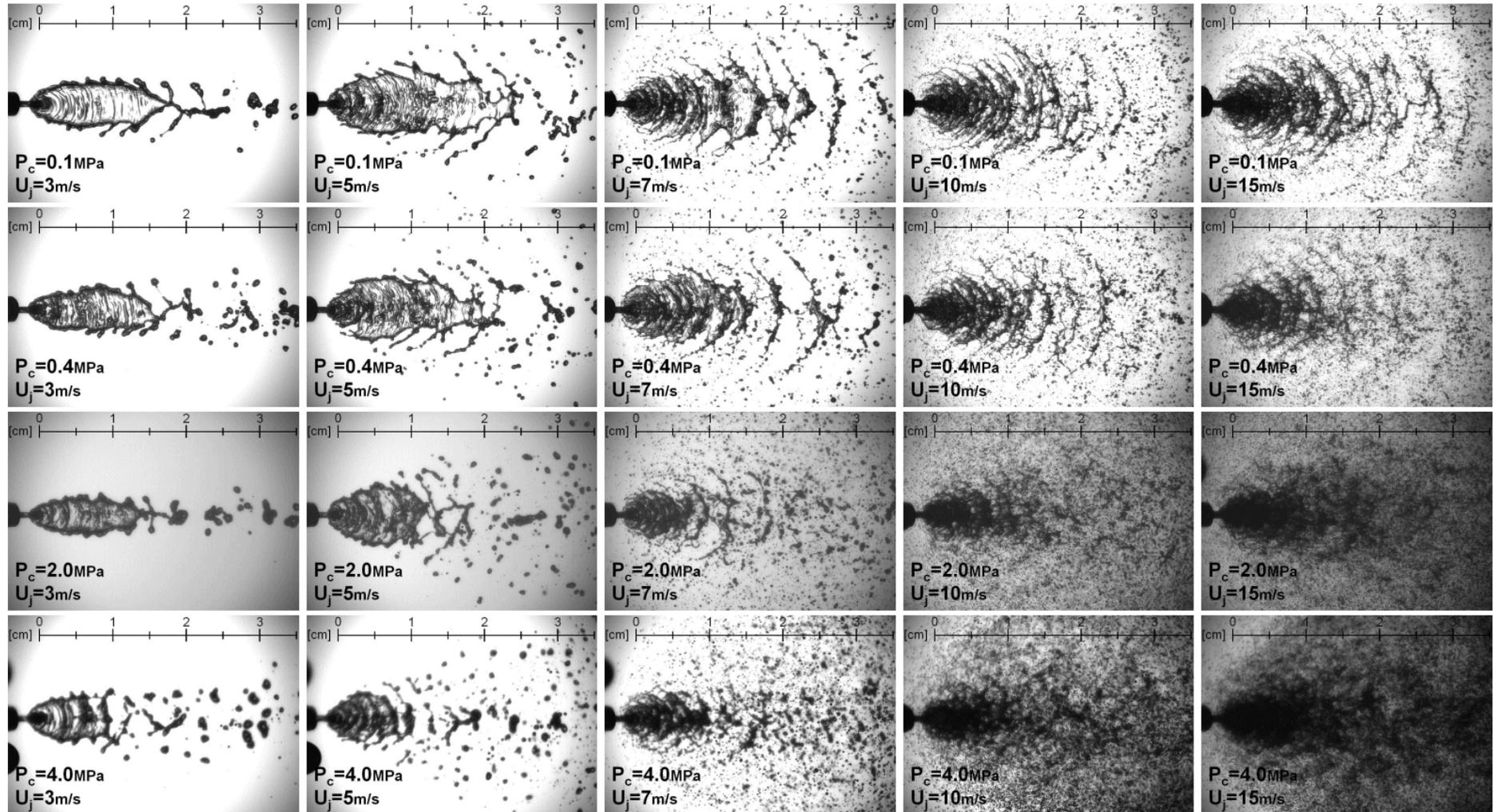
- Huang [1970] :
 $x_b/d_o = 7.1 \rho^{-2/3} We_j^{-1/3}$
- Ryan et al. [1995] :
 $x_b/d_o = 10.4 \rho^{-2/3} We_j^{-1/3}$
- Present :
 $x_b/d_o = 9.4 \rho^{-2/3} We_j^{-1/3}$

Changes of Sheet Shapes

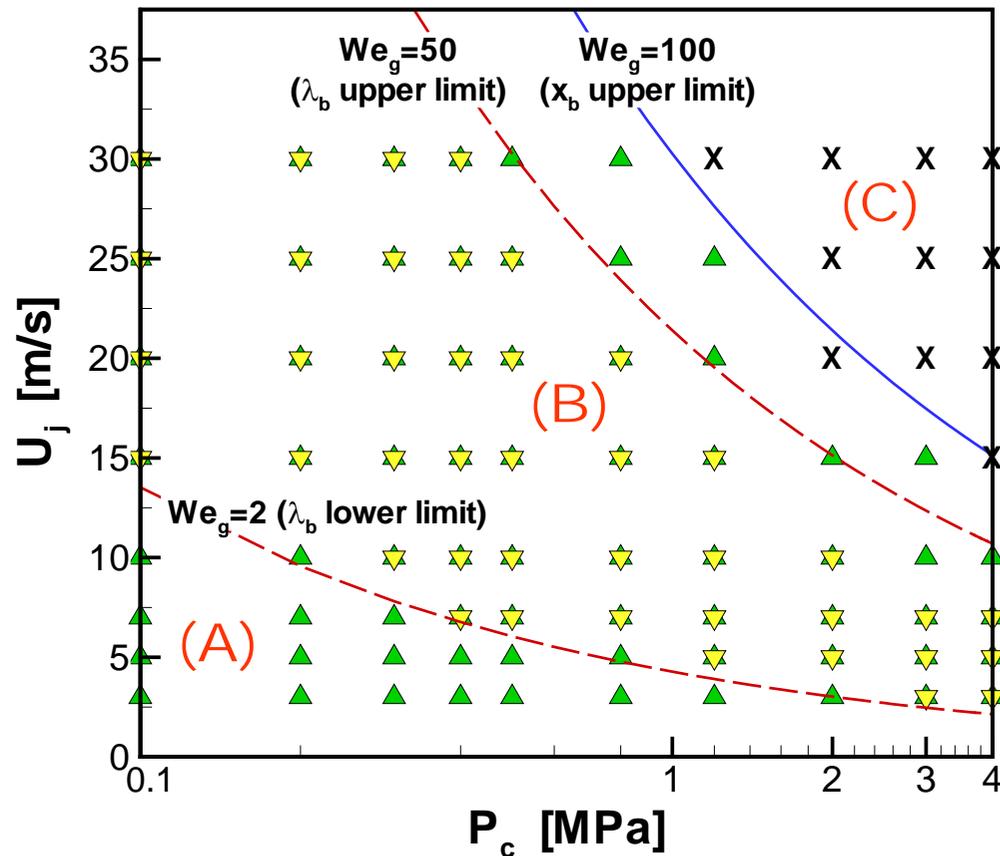


Increasing injection velocity, U_j →

Increasing ambient gas pressure, P_c ↓

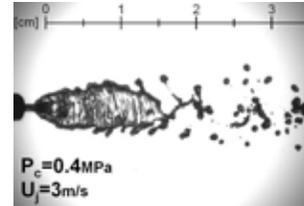


Sheet Breakup Criteria



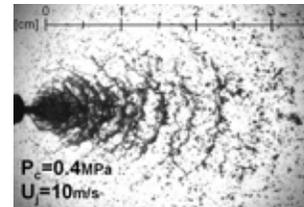
(A) Expansion Regime ($We_g < 2$)

- Sheet breakup is not controlled by waves.
- Breakup periodicity does not appear.



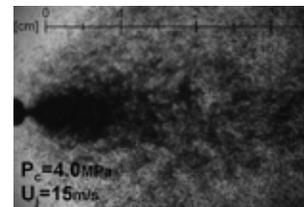
(B) Wave Breakup Regime ($2 < We_g < 100$)

- Sheets are broken by waves.
- Breakup periodicity appears.
- It is difficult to measure breakup wavelength when $We_g > 50$.

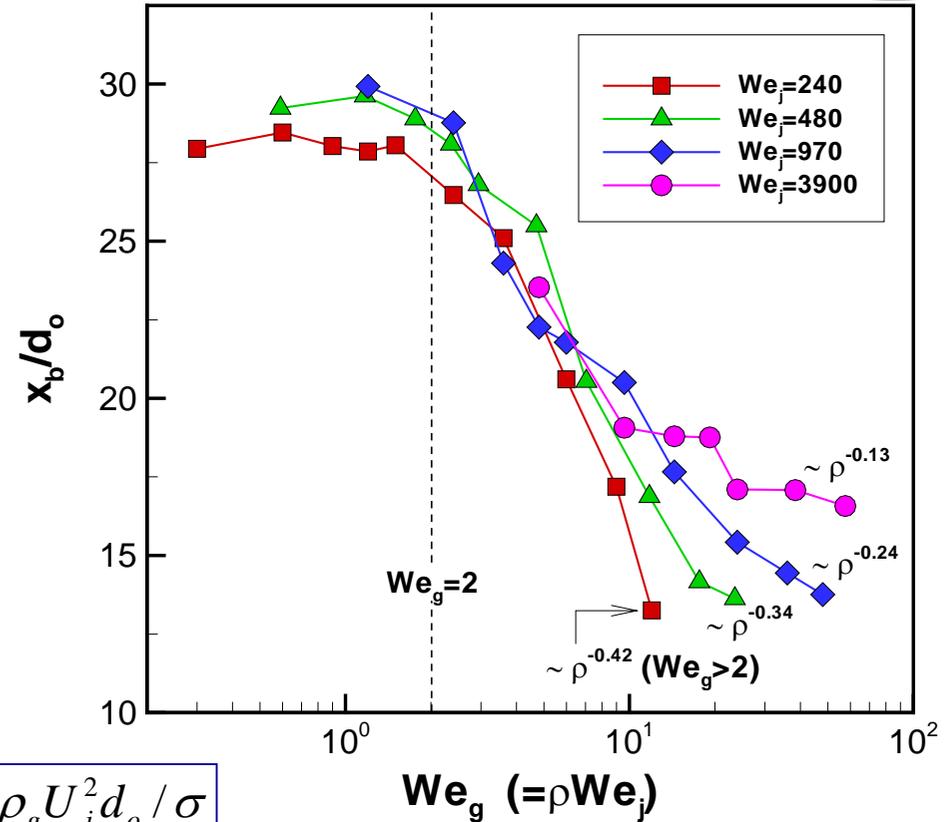
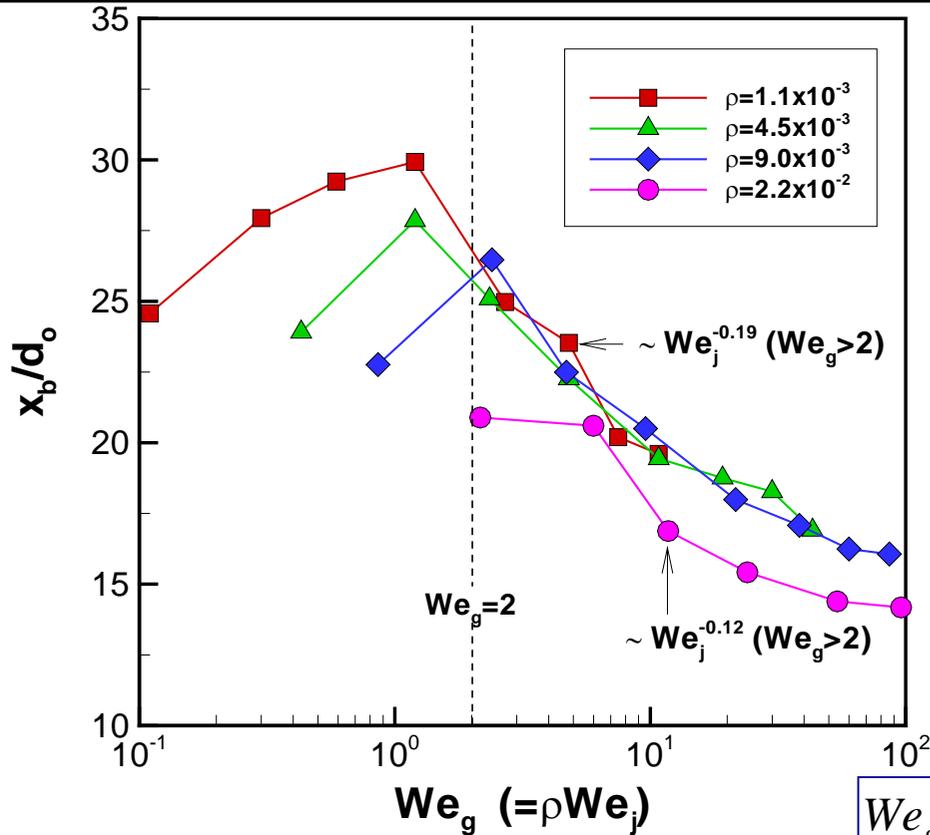


(C) Catastrophic Breakup Regime ($We_g > 100$)

- Sheets are broken just after injection.
- x_b as well as λ_b can not be discriminated.

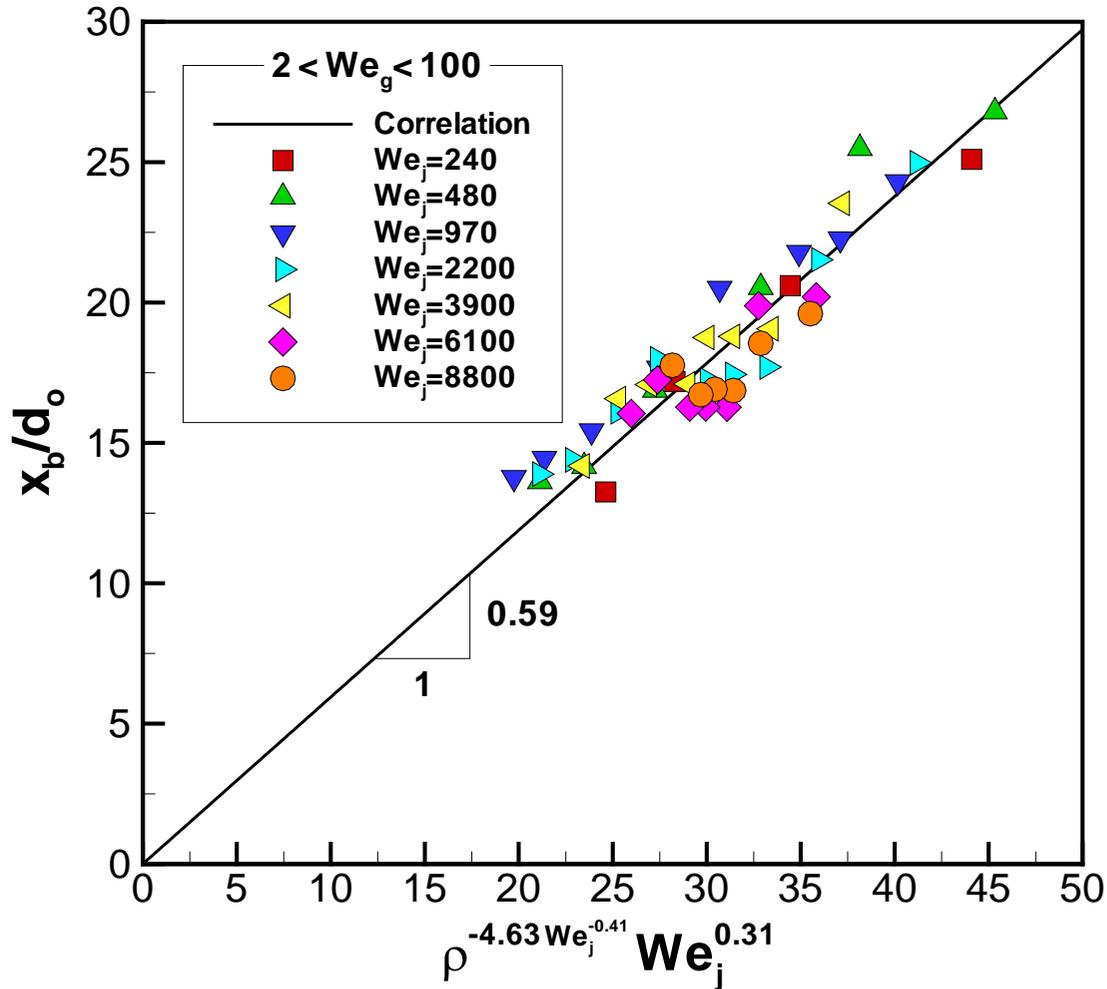


Sheet Breakup Length



- When $We_g < 2$, turbulent sheets expand as increasing mass flow rate; aerodynamic force does not affect the sheet breakup.
- When $2 < We_g < 100$, turbulent sheets are broken by waves generated by aerodynamic force and impact force.

Breakup Length Modeling



- When $2 < We_g < 100$,

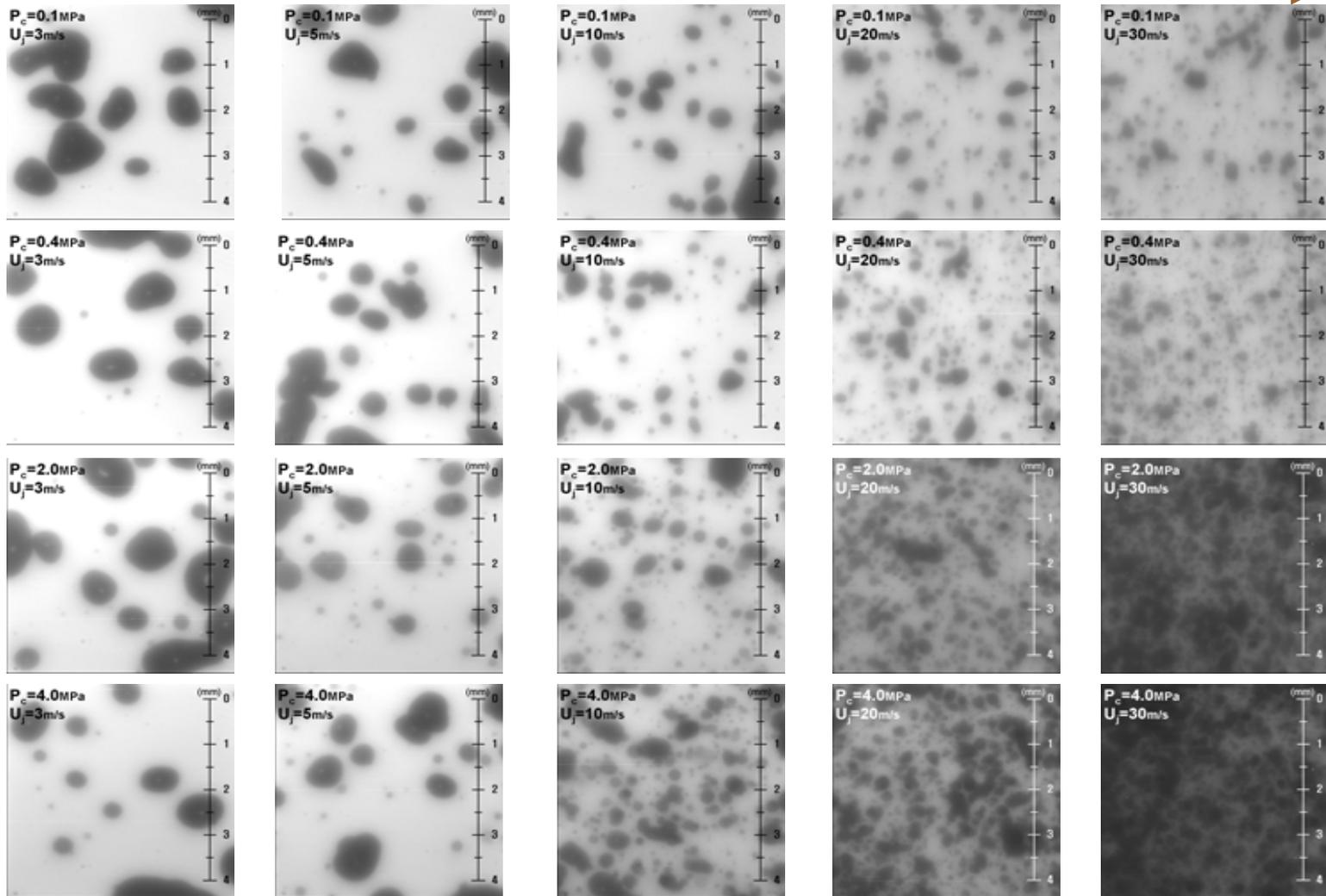
$$x_b/d_o = 0.59 \rho^{-4.63 We_j^{-0.41}} We_j^{0.31}$$
- The effect of ambient density is mitigated as increasing jet Weber number (i.e., impact force).

Changes of Drop Images



Increasing injection velocity, U_j

Increasing ambient gas pressure, P_c

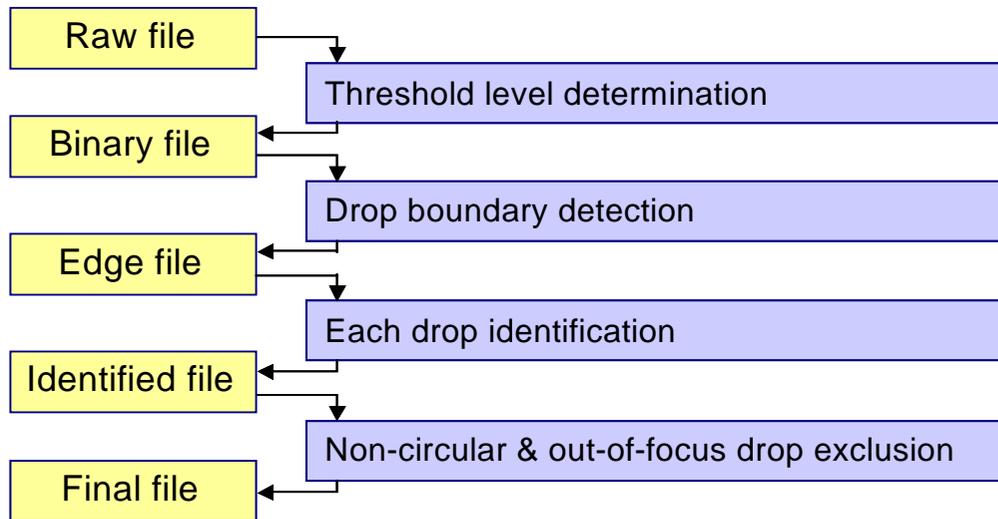




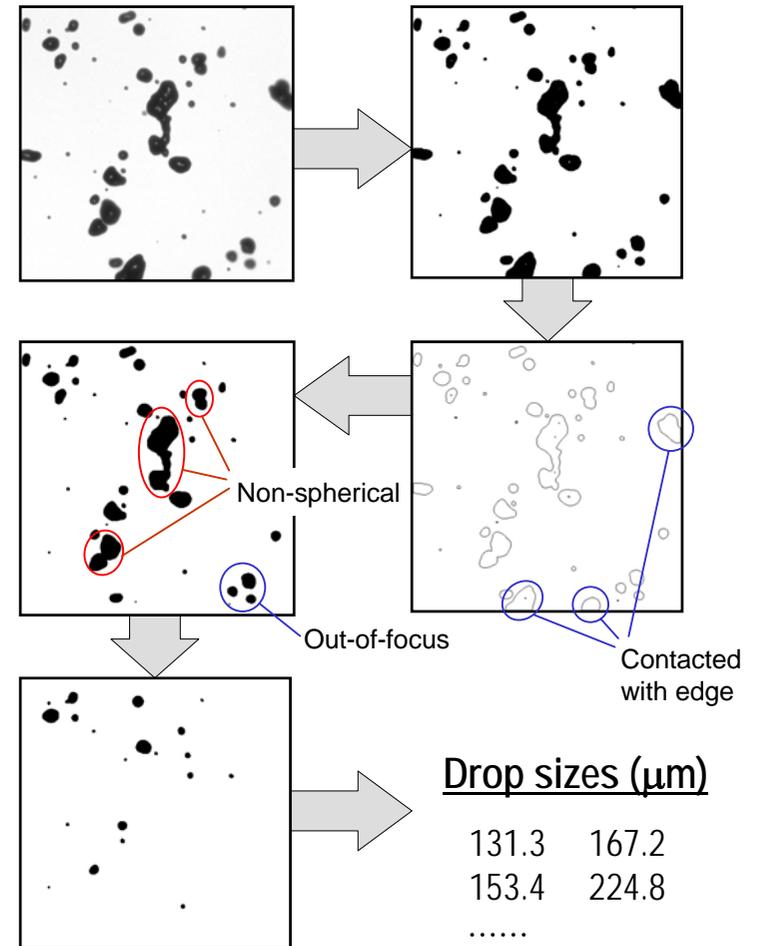
Dropsizing Method

Characteristics of this method

- Convenience to setup and handle, capability to treat the non-spherical and overlapped drops
- Direct visualization of drops, and relatively cheap method
- Hard to select in focus drops and a proper threshold
- Need a algorithm to recognize the pattern



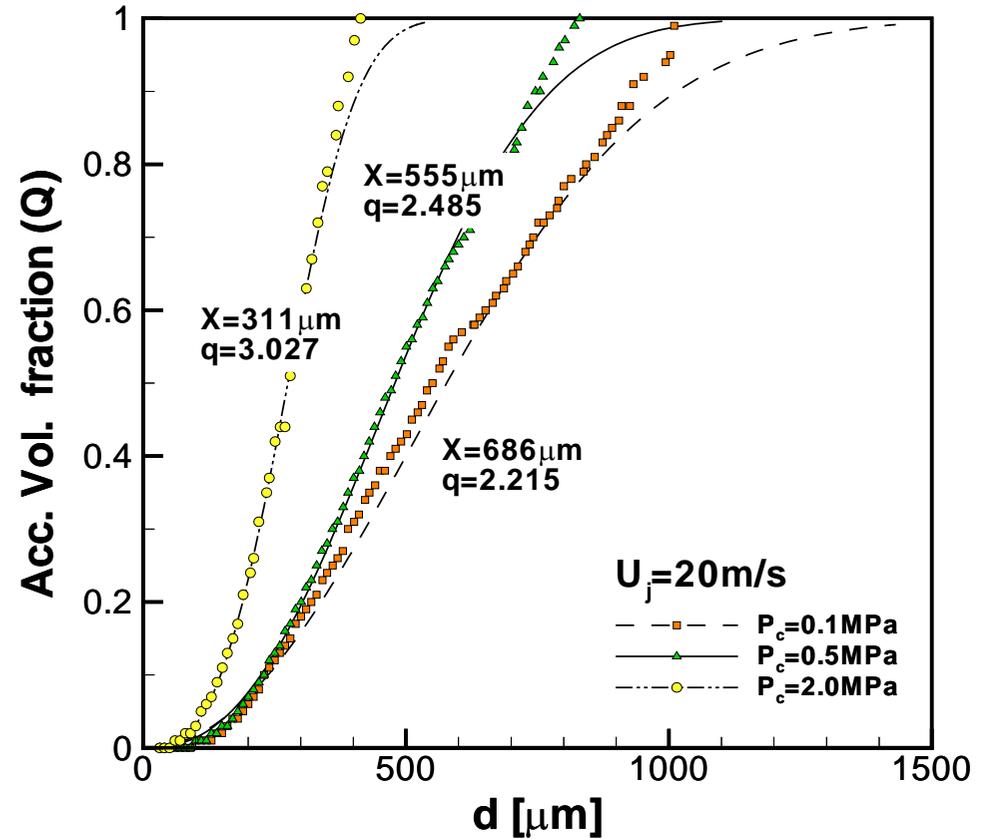
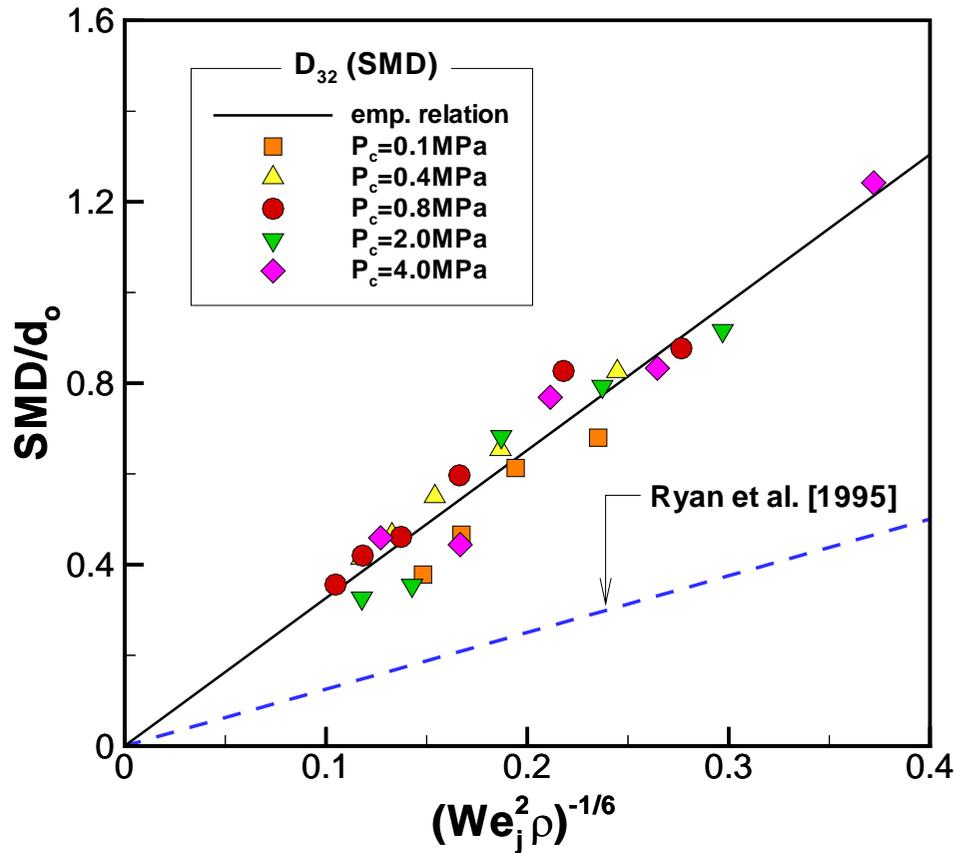
Overall procedure of image processing method



Intermediate images



Drop Size & Distribution



Ryan et al. [1995]

$$\frac{d_D}{d_o} = 1.25 \rho^{-1/6} We_j^{-1/3}$$

Present

$$\frac{d_D}{d_o} = 1.64 \rho^{-1/6} We_j^{-1/3}$$

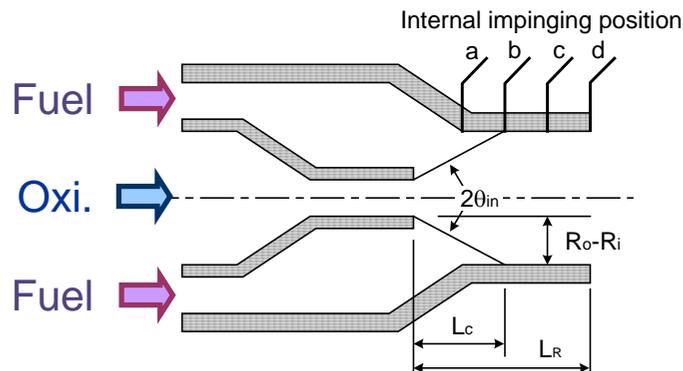
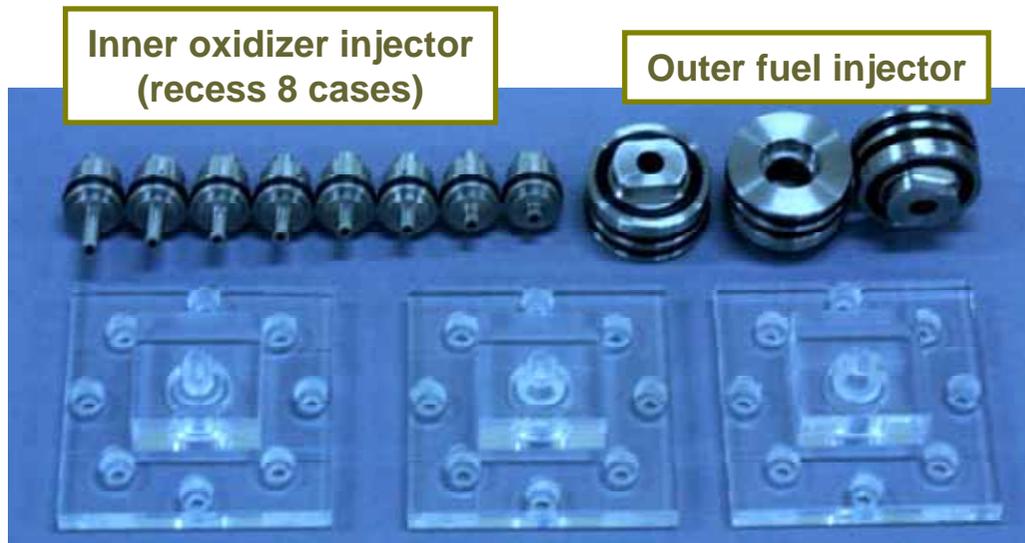
Rosin-Rammler distribution

$$1-Q = \exp[-(d/X)^q]$$

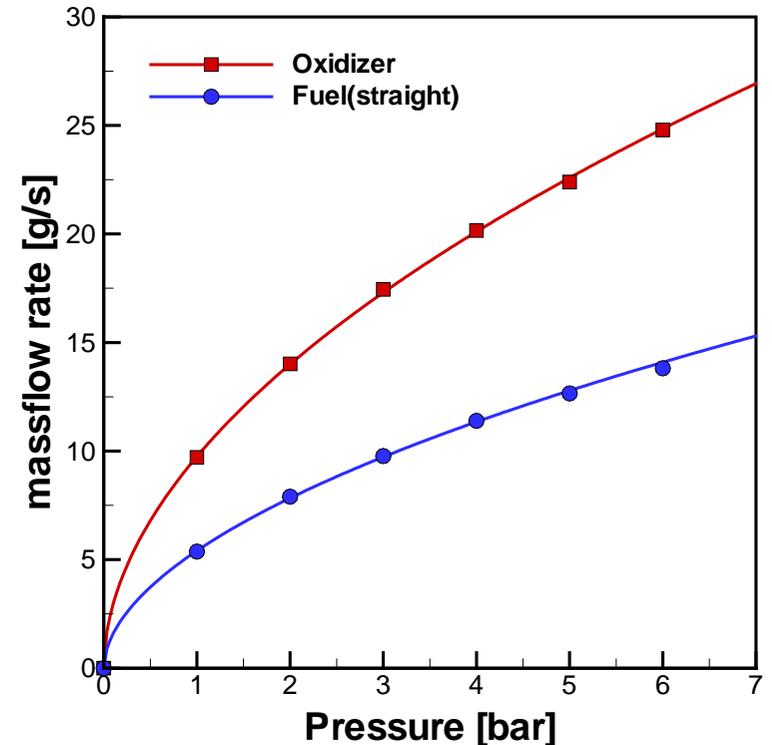
Swirl Coaxial Injector



➤ Injector Parts



➤ Operating Conditions

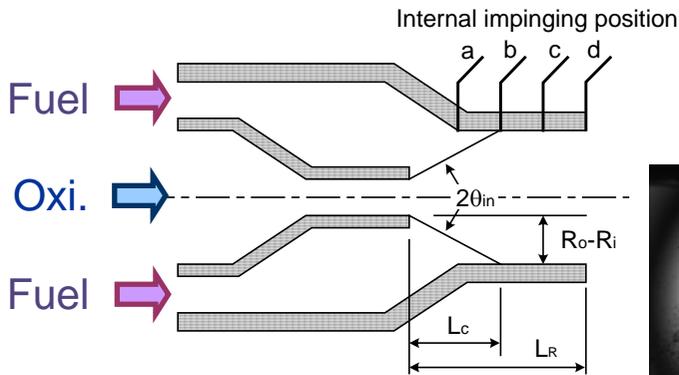


- Oxidizer flowrate : 25.6 g/s
- Fuel flowrate : 10.76 g/s
- O/F ratio : 2.38

Spray Patterns



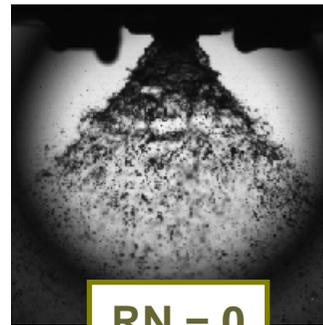
➤ Definition of Recess Number



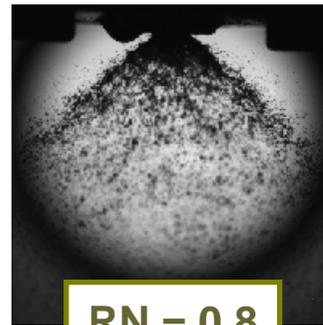
➤ Spray patterns with recess number

Outer Mixing Injection

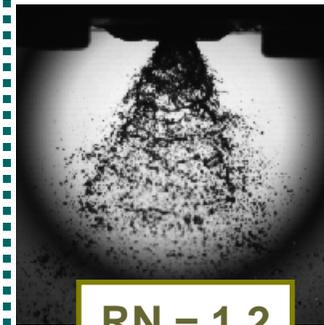
Emulsion Injection



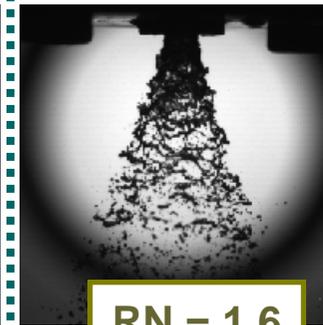
RN = 0



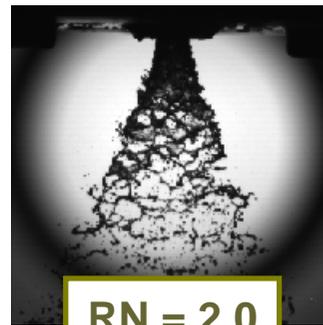
RN = 0.8



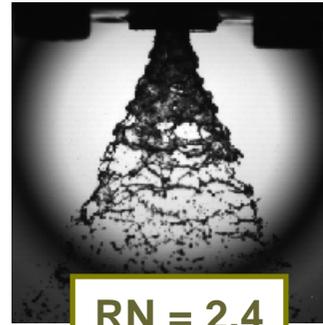
RN = 1.2



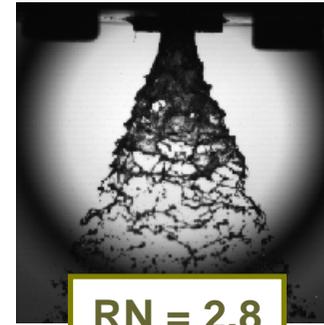
RN = 1.6



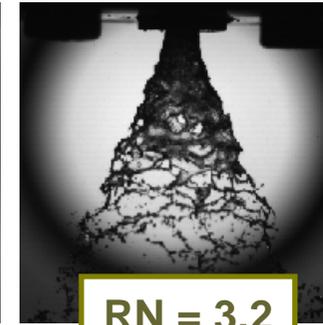
RN = 2.0



RN = 2.4



RN = 2.8



RN = 3.2

$$RN = \frac{L_R}{L_C}, \quad L_C = \frac{R_o - R_i}{\tan \theta_{in}}$$

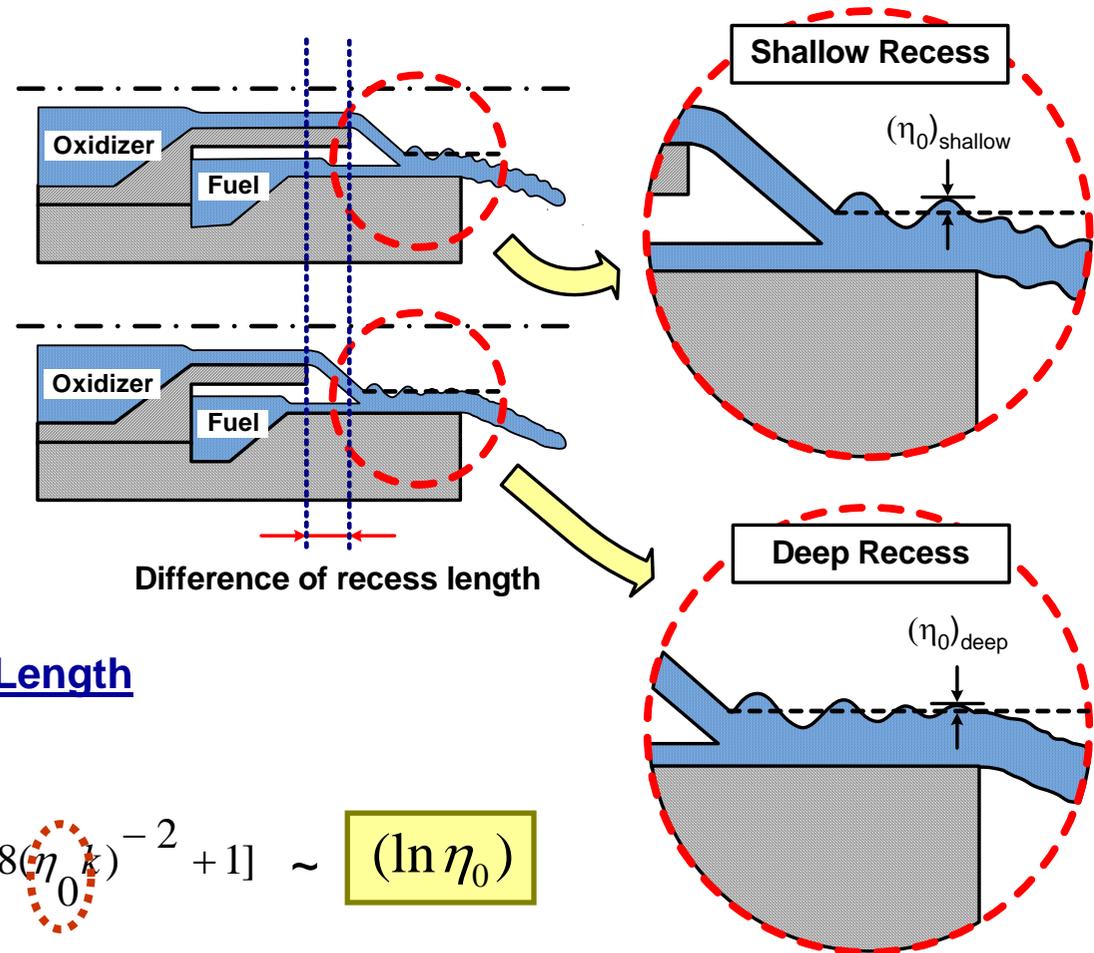
θ_{in} : inner spray angle
 R_o : outer injector radius
 R_i : inner injector radius
 L_R : recess length

Breakup Length



- The **ripple** is formed due to the internal interaction of propellants.
- The breakup length is affected by the initial wave amplitude, η_0 , of the ripple in the recess.

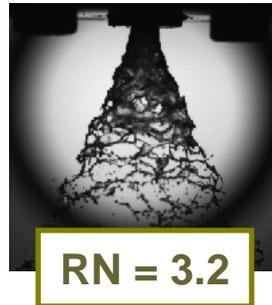
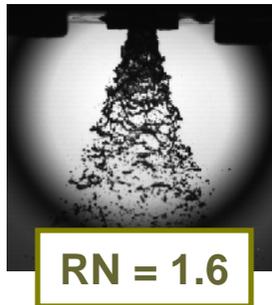
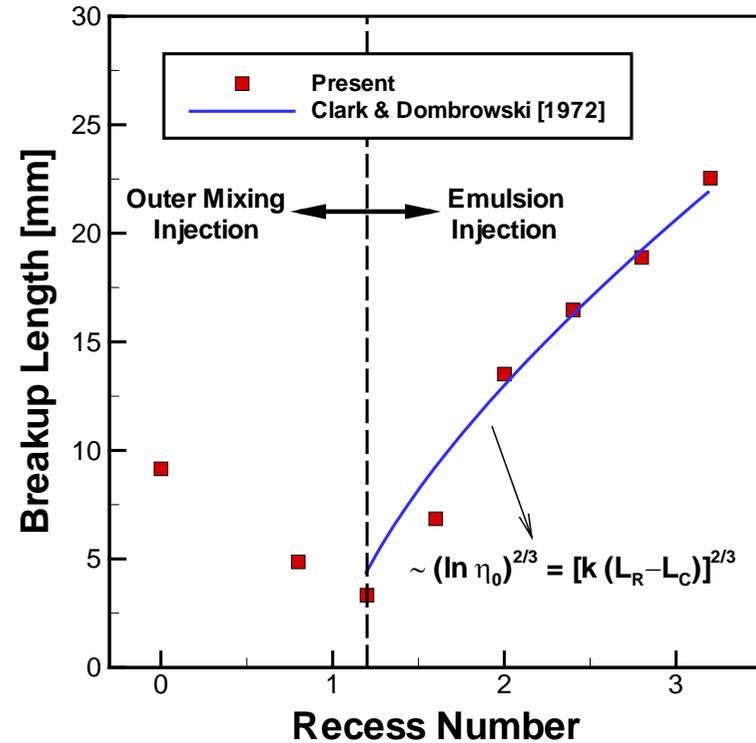
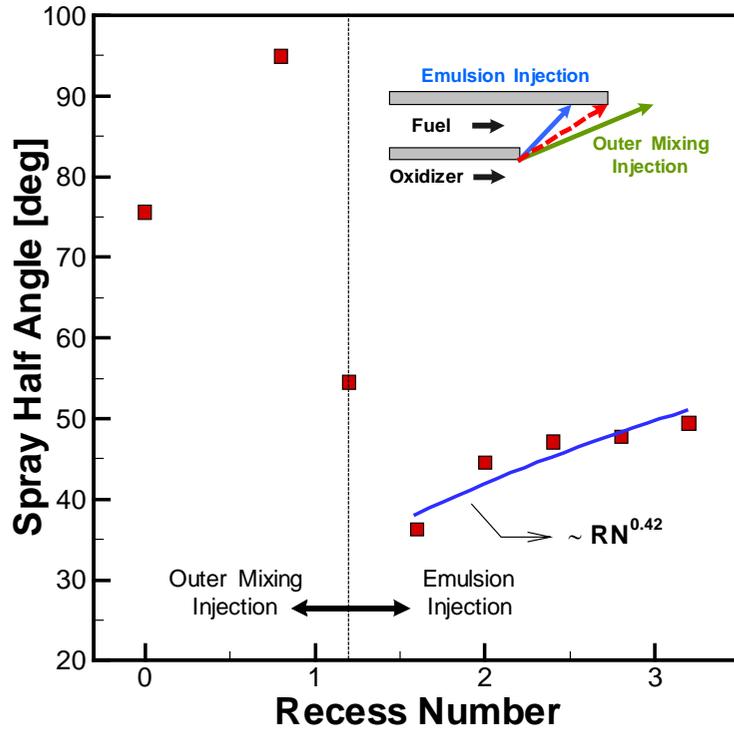
$$(\eta_0)_{\text{shallow}} > (\eta_0)_{\text{deep}}$$



Clark and Dombrowski [1972] – Breakup Length

$$x_b^{2/3} = \left[\frac{9\rho_L K U^2}{32(\rho_a U^2 k - \sigma k^2)} \right]^{1/2} \cosh^{-1} [8(\eta_0 k)^{-2} + 1] \sim (\ln \eta_0)$$

Spray Angle & Breakup Length



➤ In large recess region (emulsion injection)

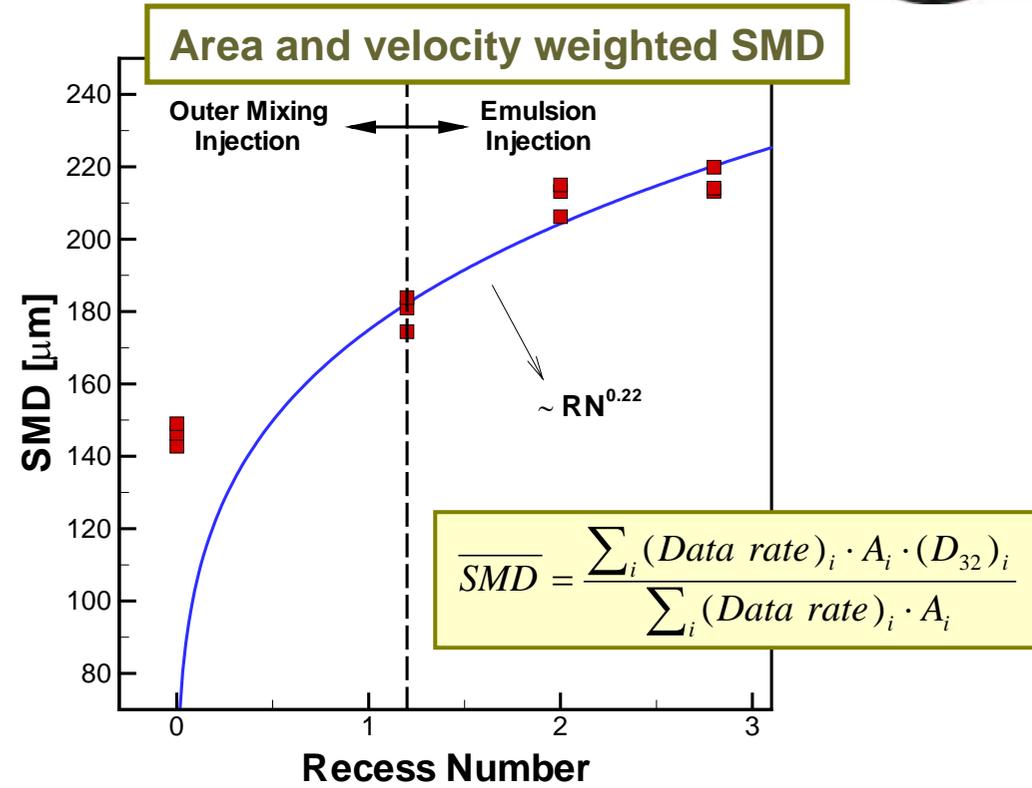
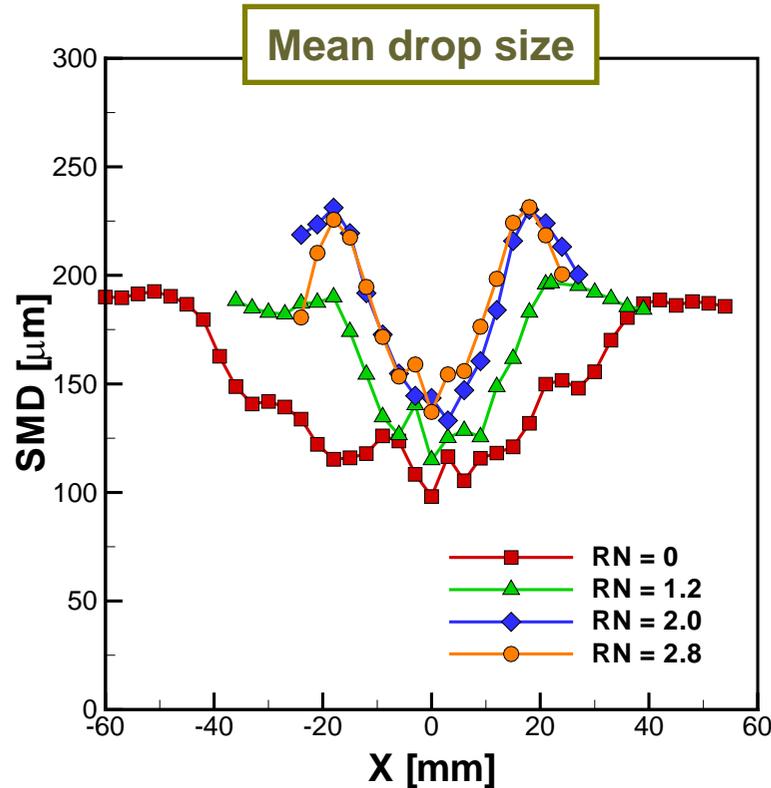
$$\eta_0 = \eta_i \exp(ikx) \quad k = k_r + ik_i$$

$$\ln(\eta_0 / \eta_i) = k(L_R - L_C)$$

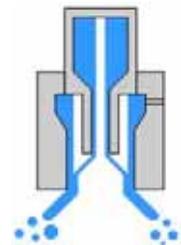
η_0 : wave amplitude at the injector tip

η_i : wave amplitude just after impinging

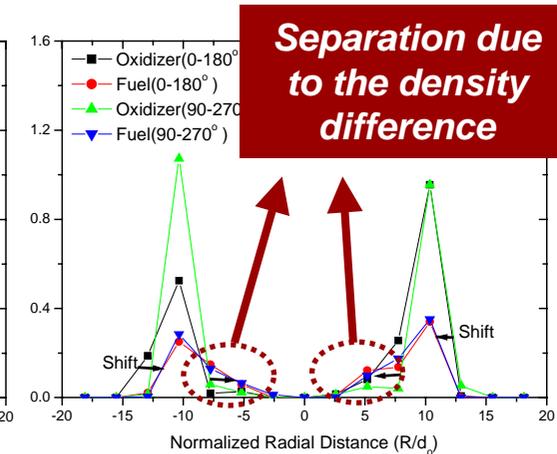
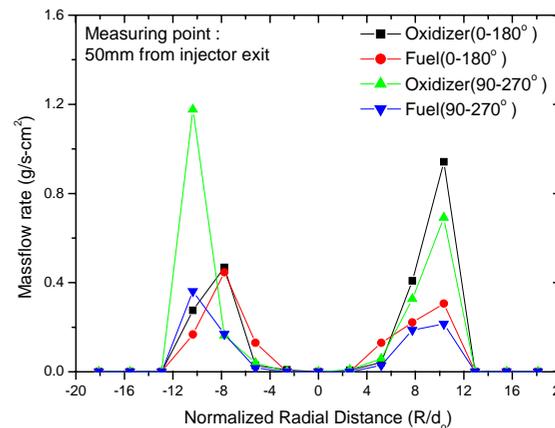
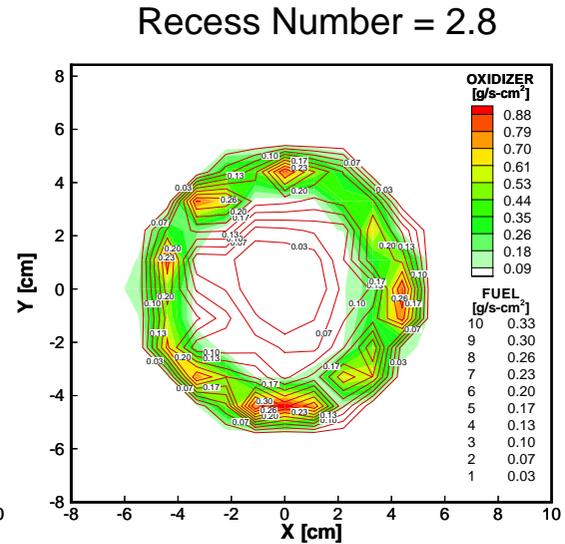
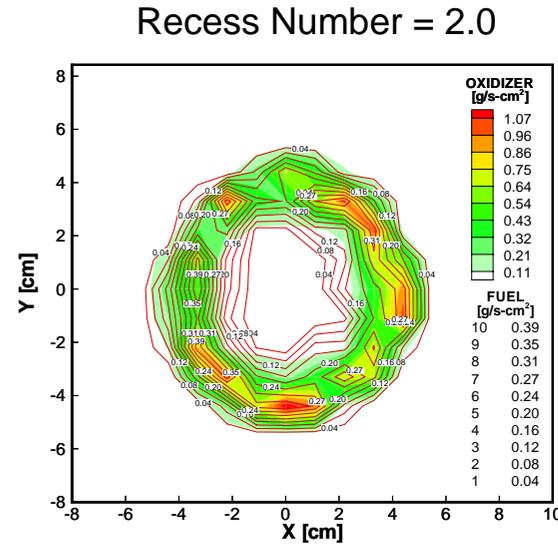
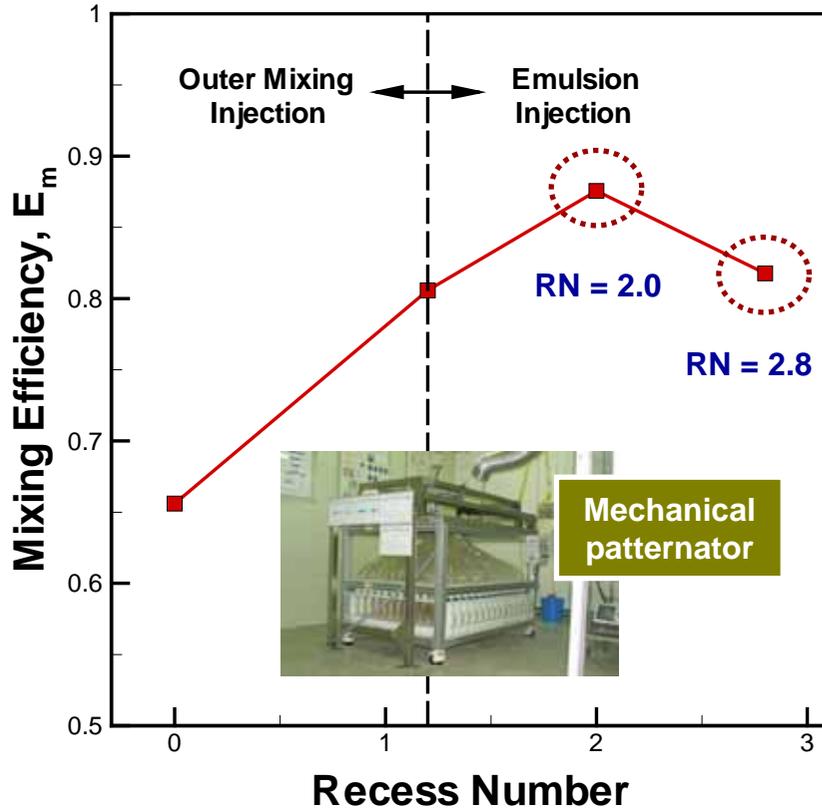
Atomization Characteristics



- The mean drop size increases with recess increased due to :
 - the increase of effective film thickness and
 - the decrease of spray angle.



Mixing Efficiency



➤ The decrease of mixing efficiency beyond the recess number of 2.0 is due to the propellant separation by the **density difference**.

Inner Oxidizer Spray



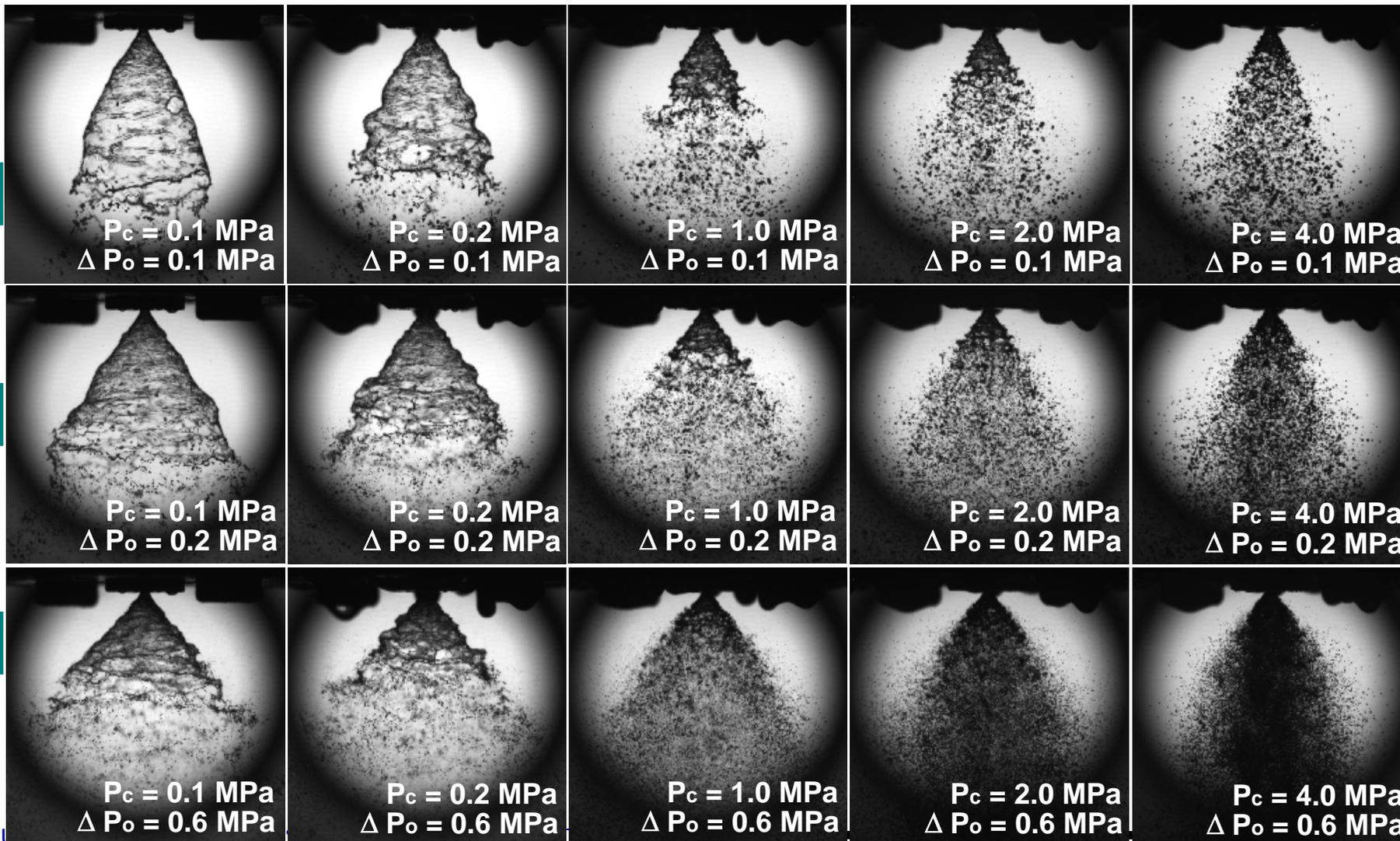
Increase of chamber pressure

Increase of oxidizer injection pressure

10.02 g/s

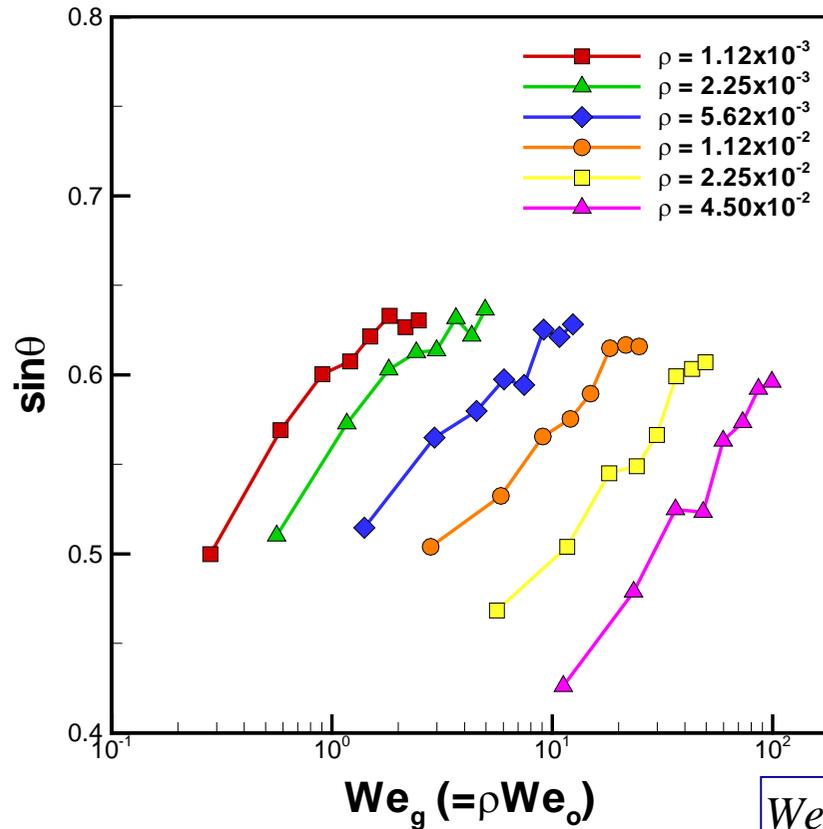
14.42 g/s

25.60 g/s

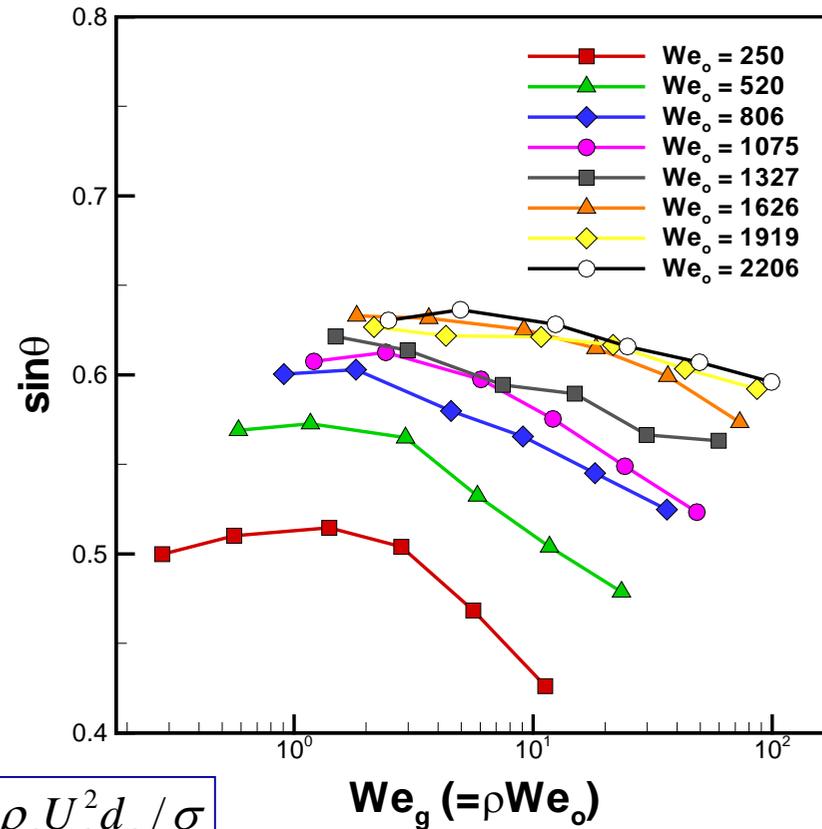




Spray Angle (Single Oxidizer)



$$We_g = \rho_g U_o^2 d_o / \sigma$$

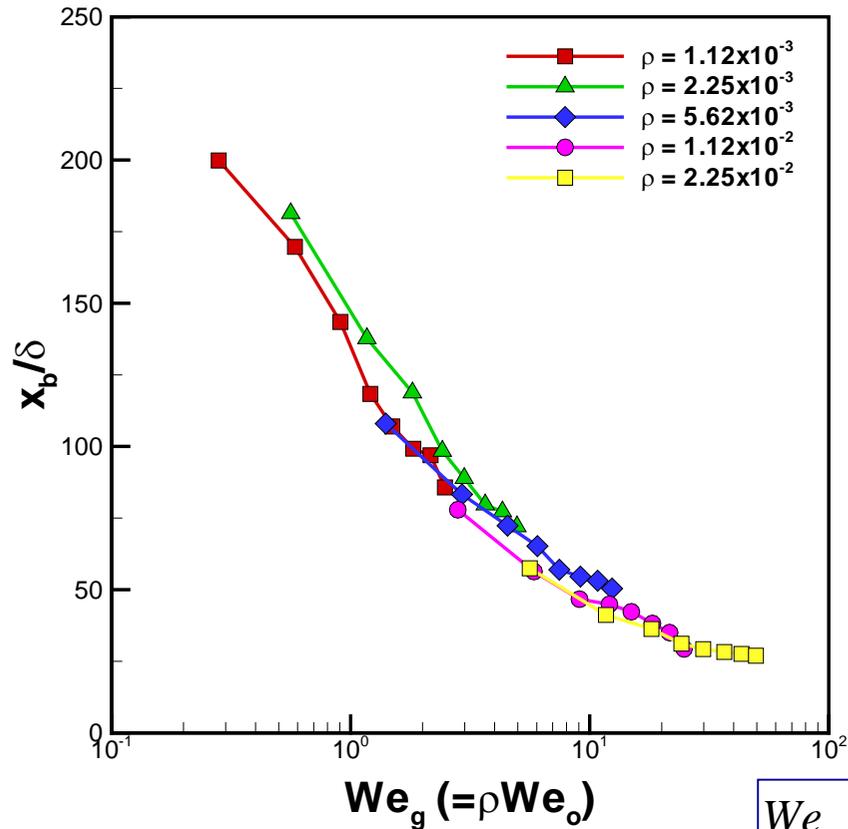


U_o : oxidizer axial velocity
 d_o : oxidizer injector diameter
 We_o : oxidizer Weber number

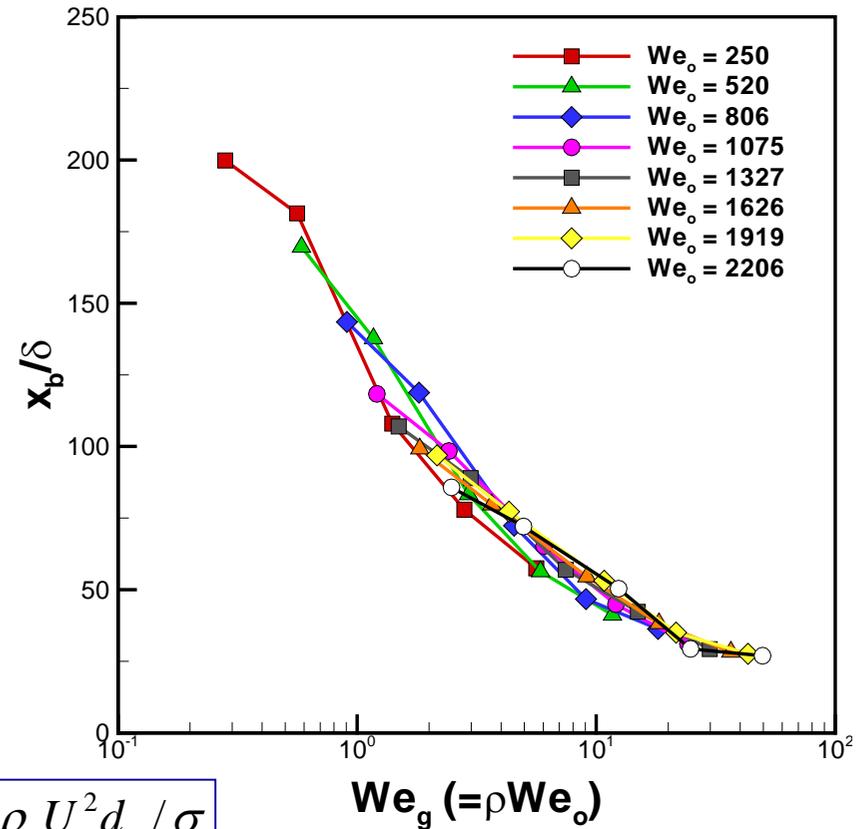
- The spray cone angle increases as We_o or mass flow rate increases.
- The spray cone angle decreases as ambient chamber pressure increases.



Breakup Length (Single Oxidizer)



$$We_g = \rho_g U_o^2 d_o / \sigma$$



- The breakup length decreases as ambient density or We_o increases.
- In spite of $We_g < 1$, the breakup length decreases as ambient density or We_o increases due to the increase of spray angle.

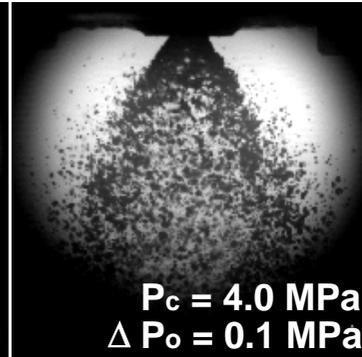
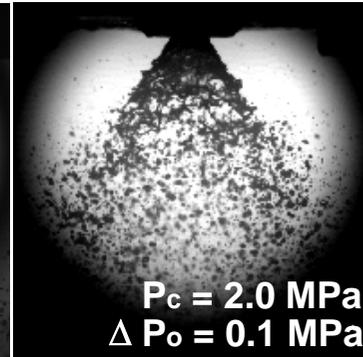
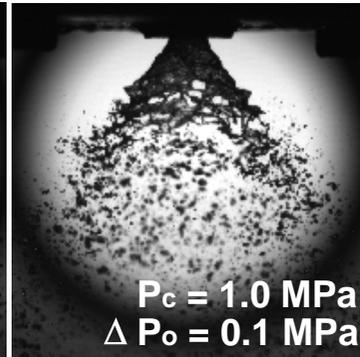
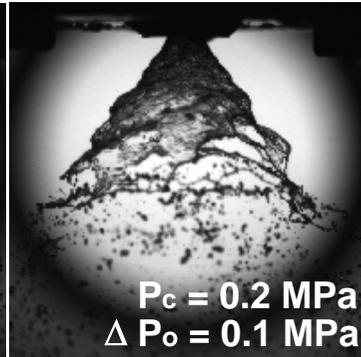
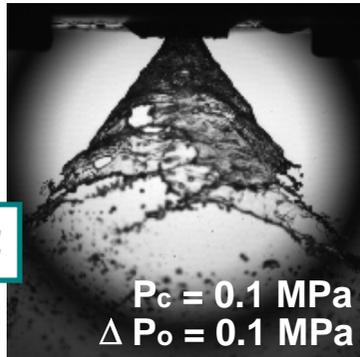
Coaxial Spray with Recess



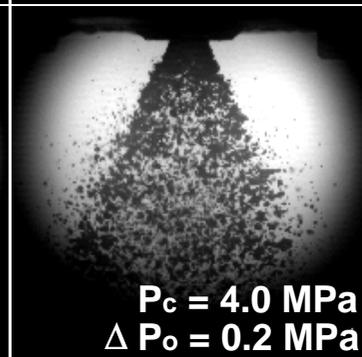
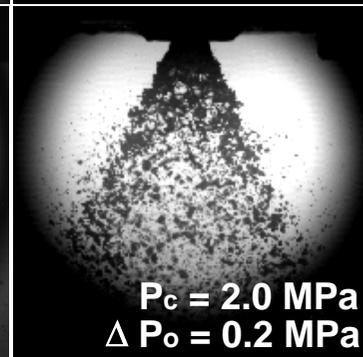
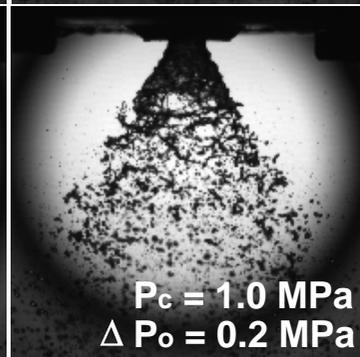
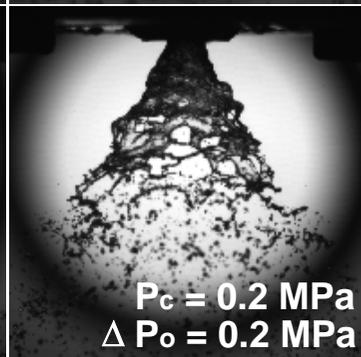
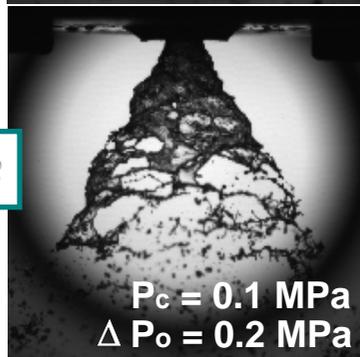
Increase of chamber pressure

Increase of oxidizer injection pressure

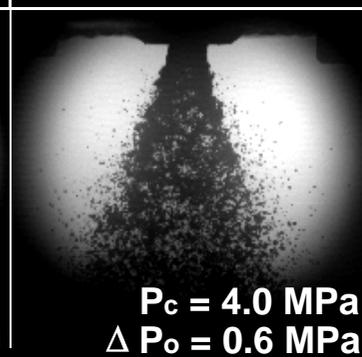
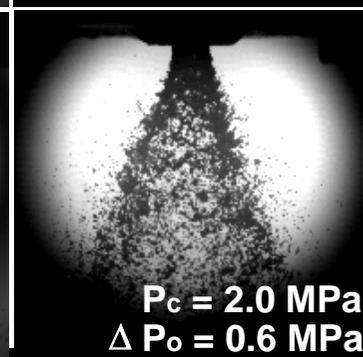
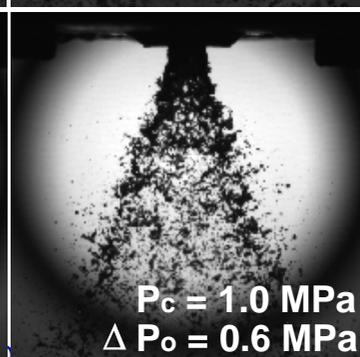
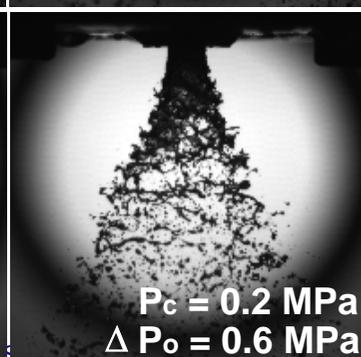
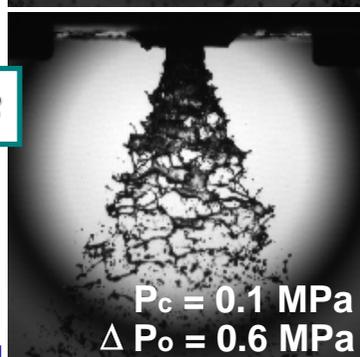
O/F = 0.94



O/F = 1.33

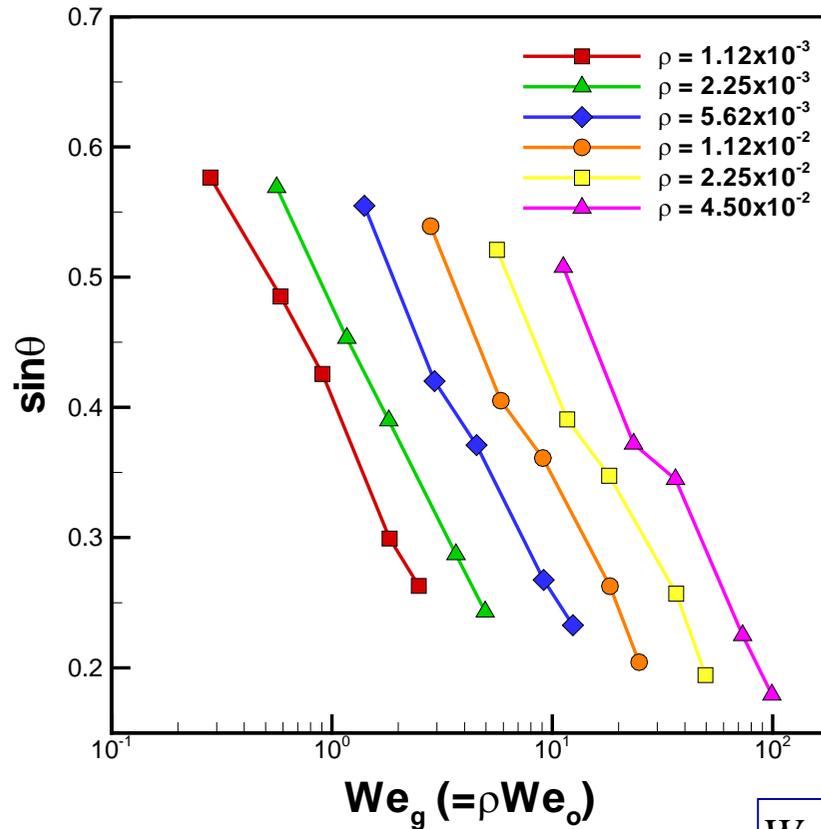


O/F = 2.38

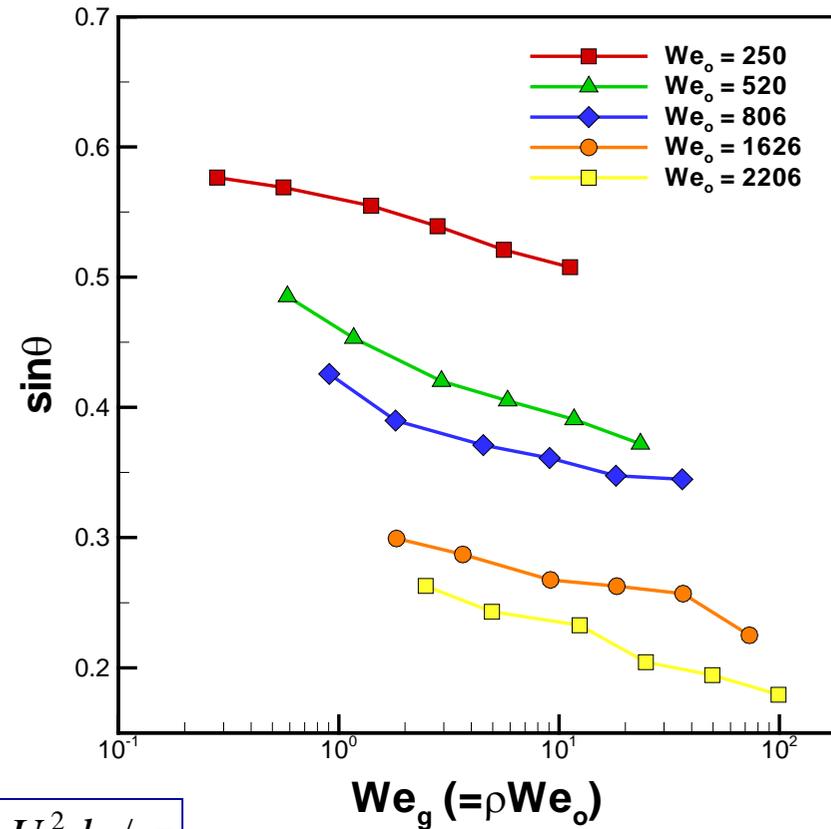




Spray Angle (Coaxial Spray)



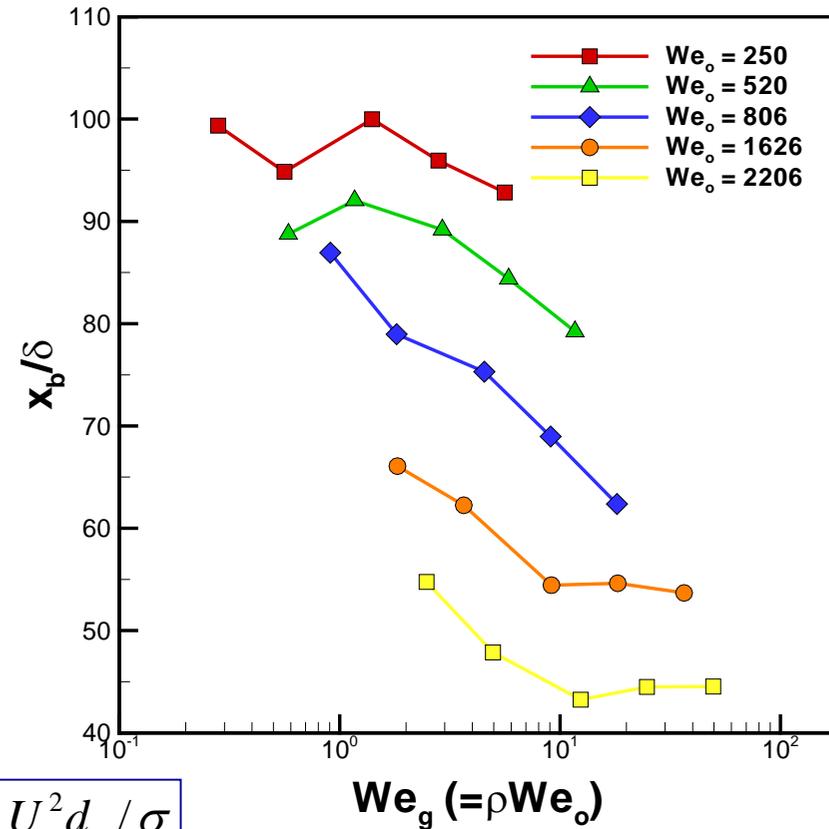
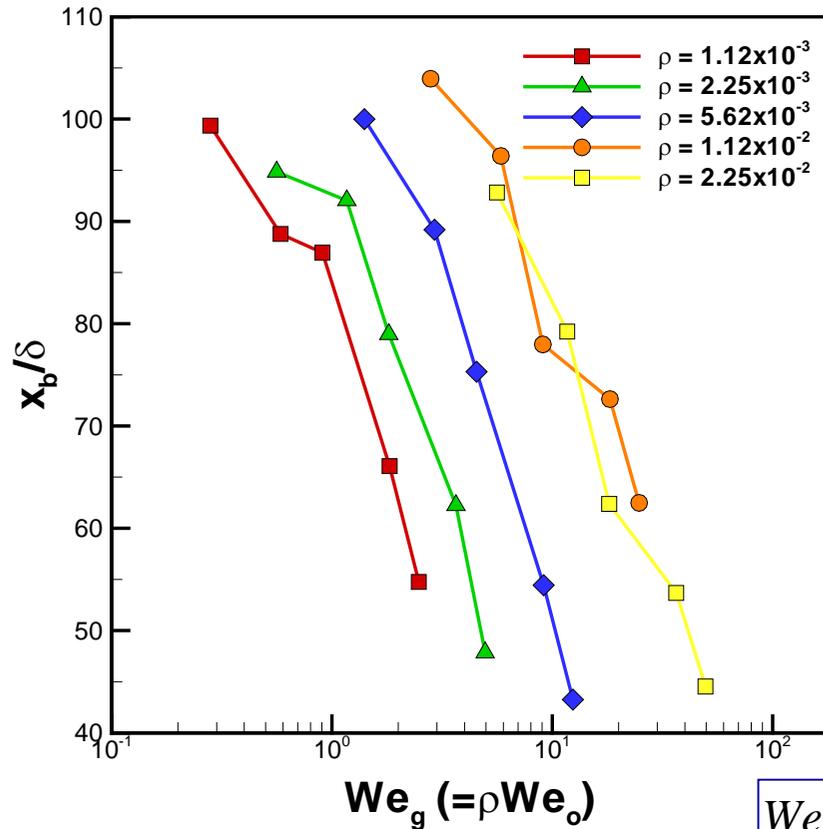
$$We_g = \rho_g U_o^2 d_o / \sigma$$



- The spray cone angle decreases by increasing oxidizer We_o .
- The effect of ambient density on the spray angle is not significant compared with that of oxidizer We_o .

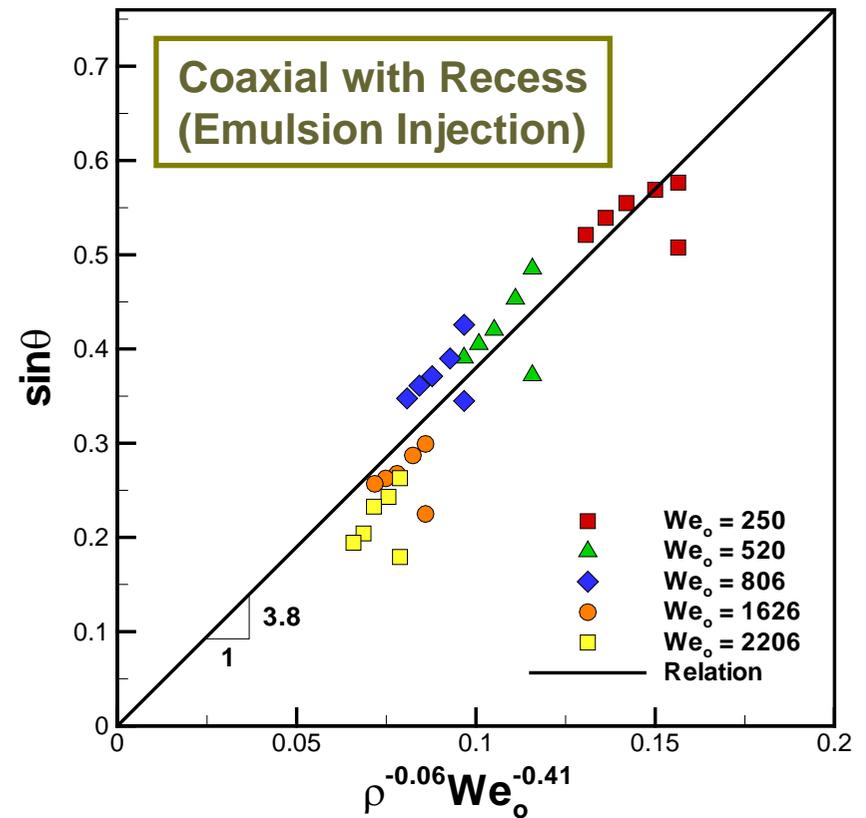
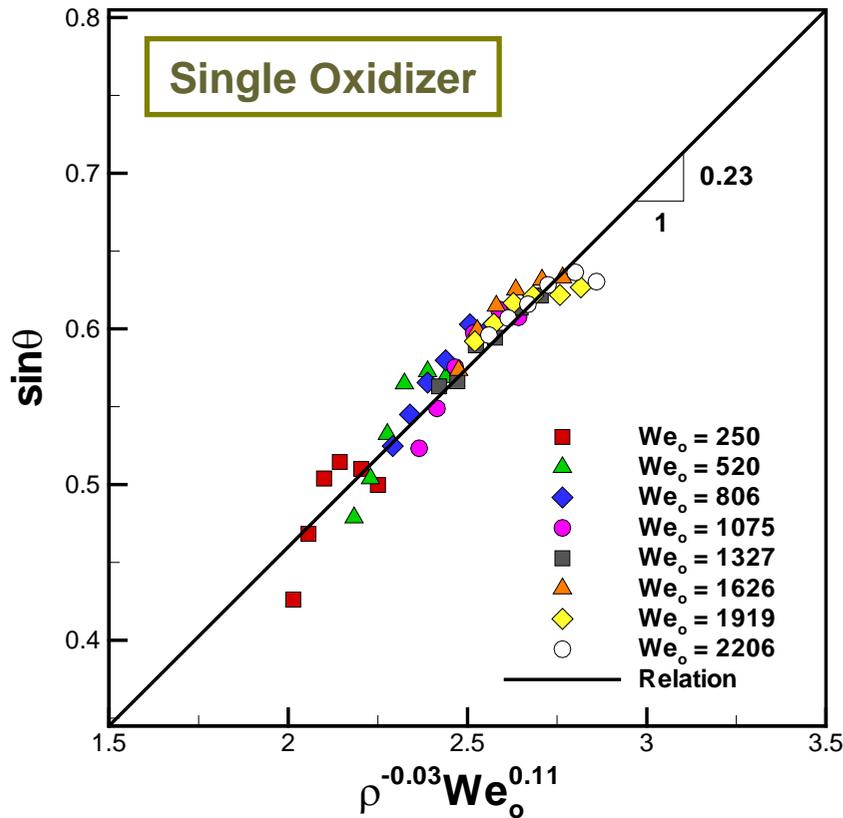


Breakup Length (Coaxial Spray)



- As the oxidizer We_o increases,
 - internal impact force increases. \rightarrow strong wave occurs. \rightarrow x_b decreases.

Modeling of Spray Angle

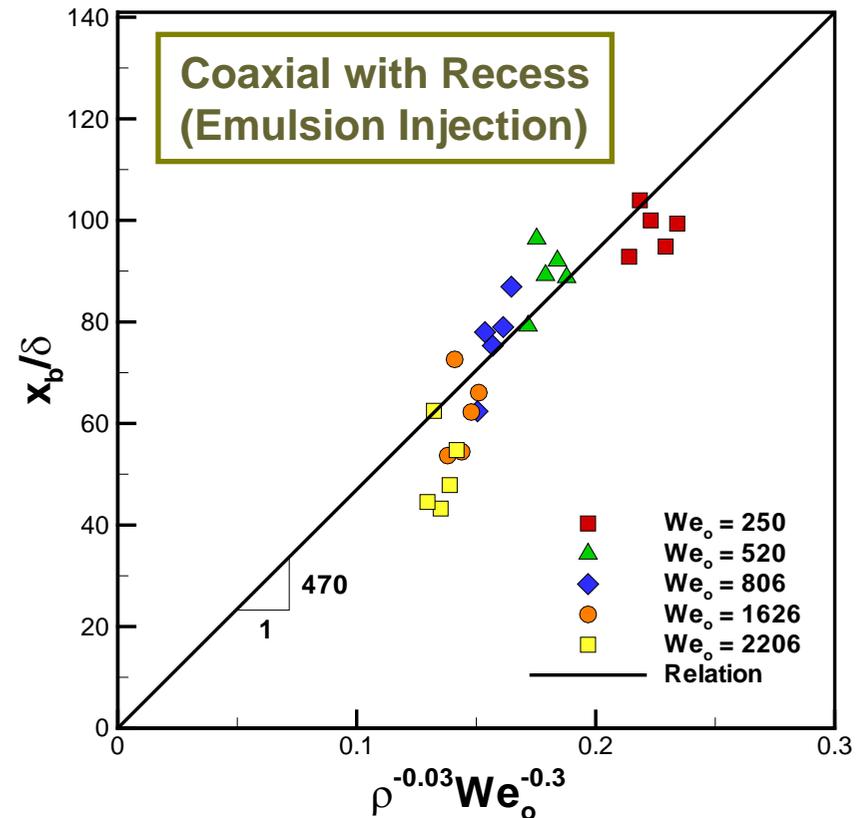
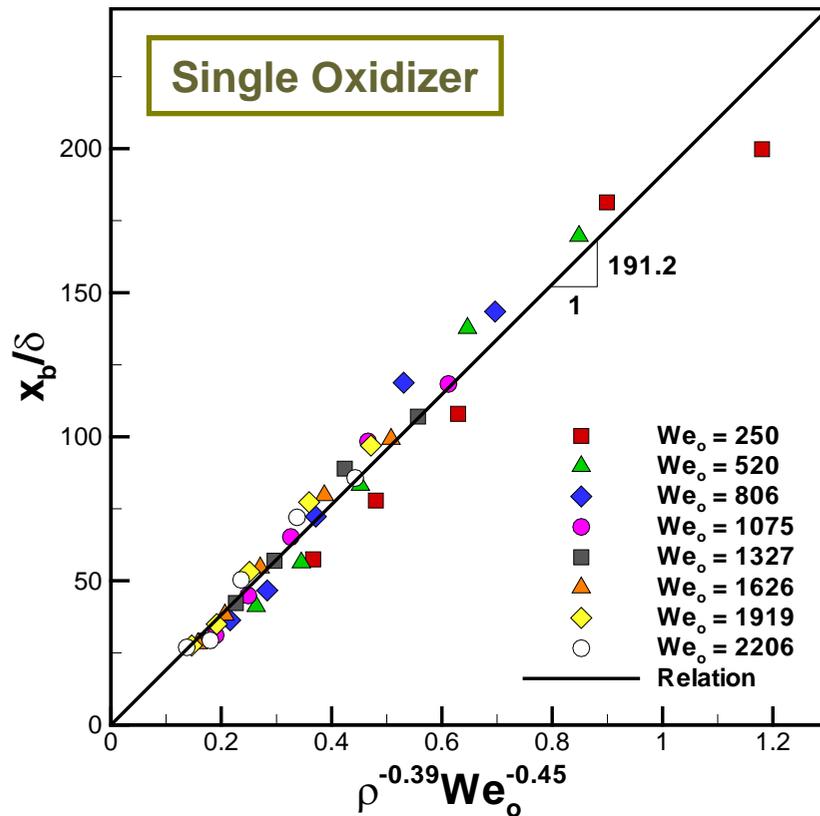


De Corso and Kemeny [1957]

$$\theta \sim P_a^{-1.6}$$

(a range of gas pressure : 0.01-0.8 MPa)

Modeling of Breakup Length

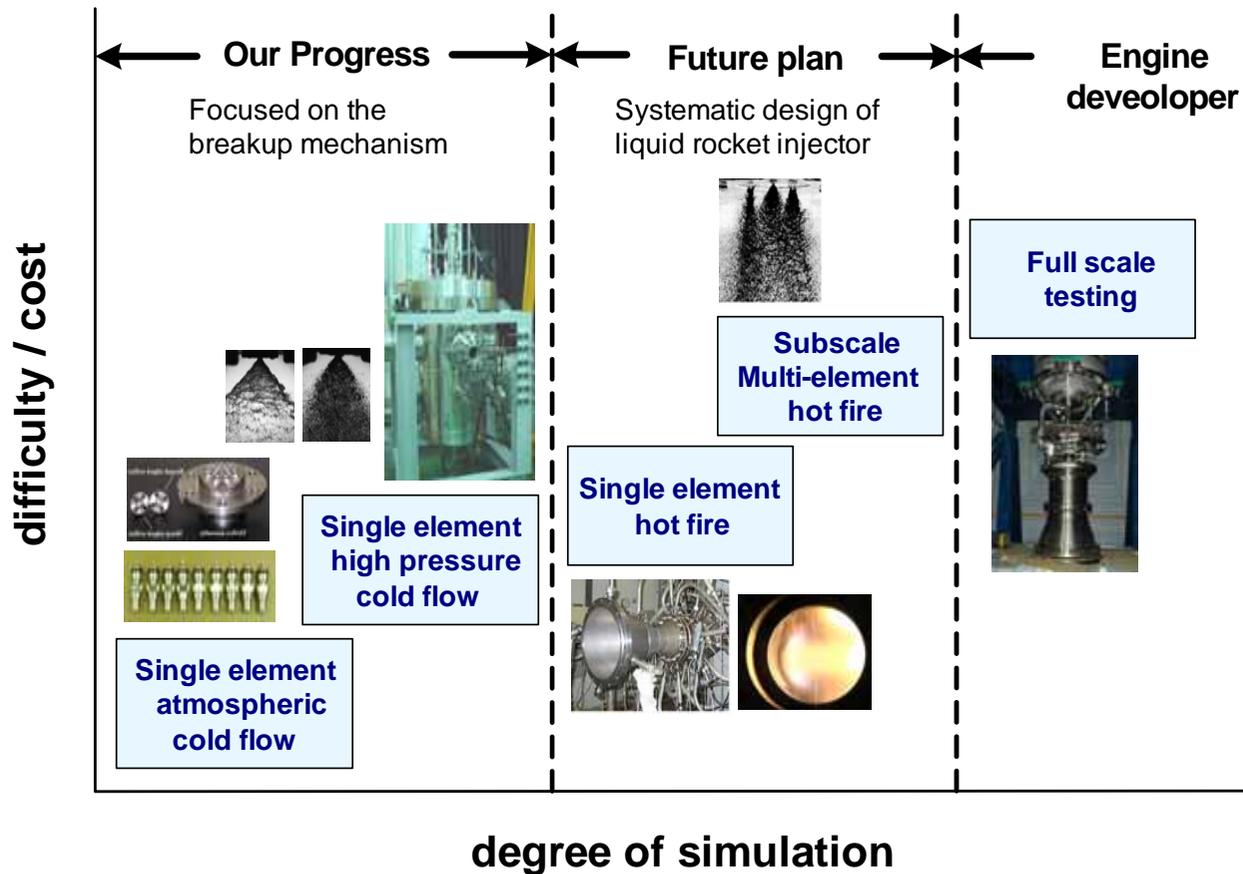


- The effect of **ambient density** on the breakup length of coaxial spray is very small.
 - The main breakup mechanism of coaxial spray spray is the **impingement** of both propellants and the formation of **unstable wave** on the conical liquid sheet.

Research Progress in SNU



Hierarchy of injector experiments



Progress of injector design

Single element **atmospheric** cold flow test



Single element **high pressure** cold flow test



Single element **cryogenic/supercritical** cold flow test



Multi-element cold flow test



Single element **hot fire** test



Subscale **hot fire** test



Modeling of high pressure spray and combustion field



Development of **numerical code** for liquid rocket engine

(Ref.: D.Talley, AFRL / USA)

Conclusions : impinging type injector



- ❖ The **aerodynamic force** significantly affects the breakup of **laminar sheet** when the aerodynamic force is higher than the surface tension force (i.e. $We_g > 1$).
 - When $We_g < 1$, the laminar sheet expands as increasing the injection velocity; the aerodynamic force does not affect the sheet breakup.
- ❖ The breakup characteristics of **turbulent sheets** had three regimes: i.e. expansion regime, wave breakup regime and catastrophic breakup regime based on We_g .
- ❖ **Droplet size** agrees well with that of linear instability theory.
 - Drop size distribution can be modeled with Rosin-Rammler distribution function.

Conclusions : swirl coaxial injector



- ❖ The spray characteristics of swirl coaxial injectors are much influenced by **the interaction position of propellants** in the recess.
 - Two regimes are found : outer mixing injection and emulsion injection.
- ❖ In the case of **single inner oxidizer spray**, the spray angle and breakup length decrease as the ambient chamber pressure increases.
- ❖ In the case of **coaxial spray with recess**, the effects of ambient density on the spray characteristics are not significant compared with those of inner oxidizer We_0 .