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

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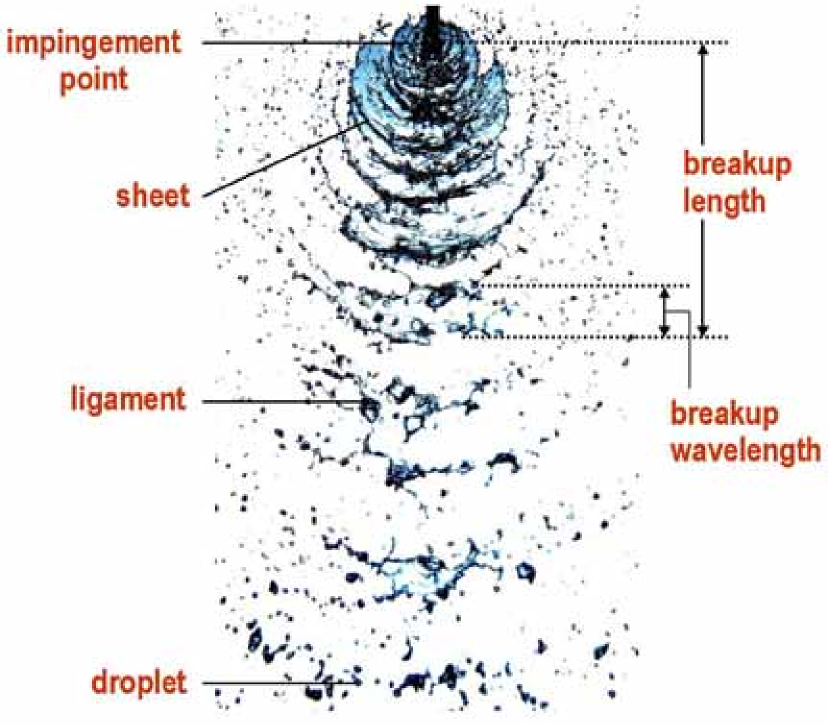
Korean Liquid Rockets

KSR-III

	KSR-III	KSLV-I
Period	1998 ~ 2002	2003 ~ 2007
Budge	$ 6,800,000	$ 300,000,000
Target	• Science Observation • 1st Liquid Rocket	• 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

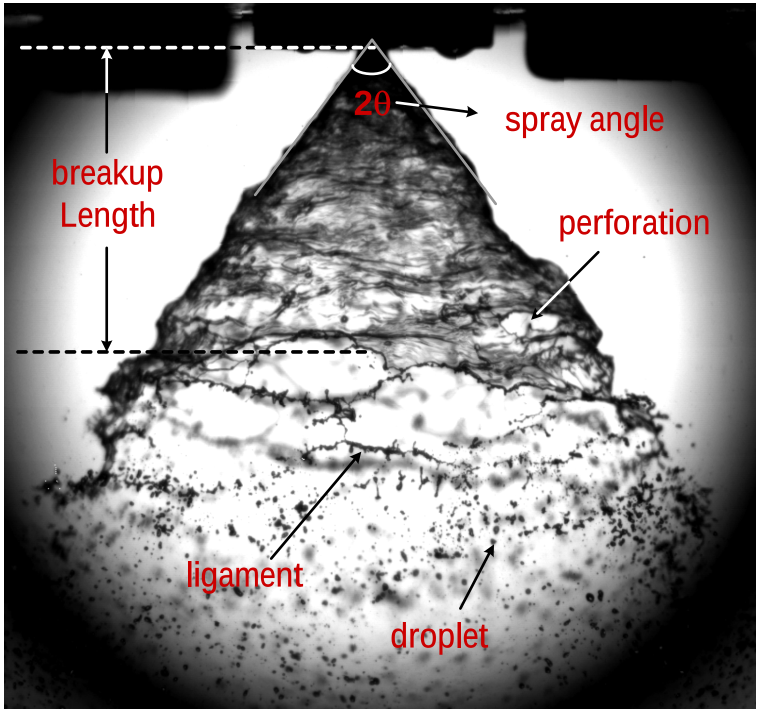
Breakup Mechanism

- **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)

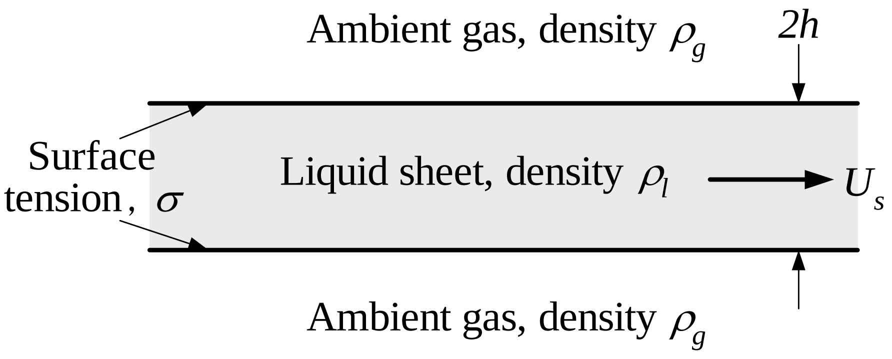
Linear Instability Theory

- Modeling sheet breakup length and droplet size

Huang [1970]

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

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



Ryan et al. [1995]

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

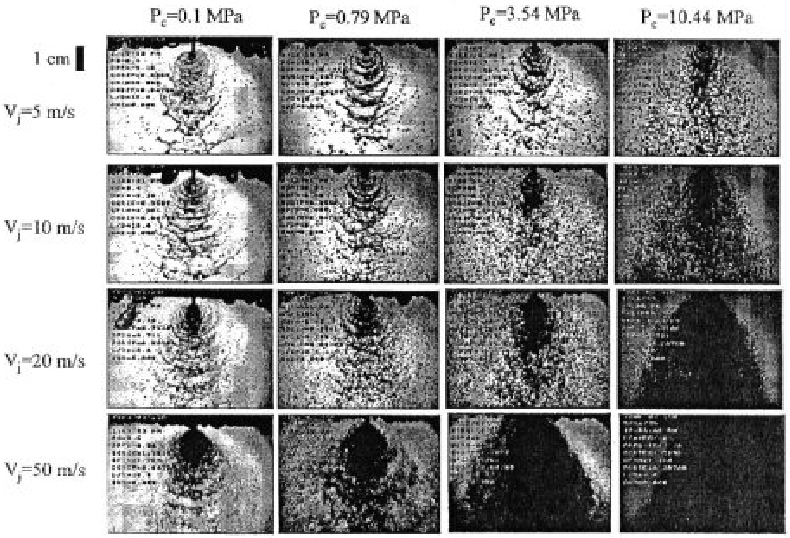
$$\frac{d_D}{d_o} = 1.25\rho^{-1/6} We_j^{-1/3}$$

$$\boxed{\begin{array}{c} x_b \propto \rho^{-2/3}\, We_j^{-1/3} \\ d_D \propto \rho^{-1/6}\, We_j^{-1/3} \end{array}}$$

Objectives

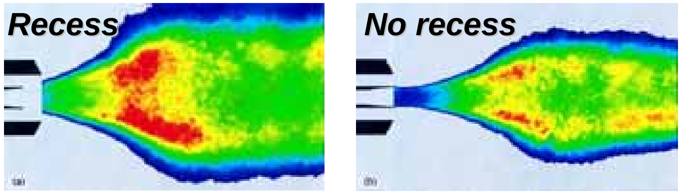
- **Impinging type injector (Like-Doublet)**

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


Strakey & Talley (2000)

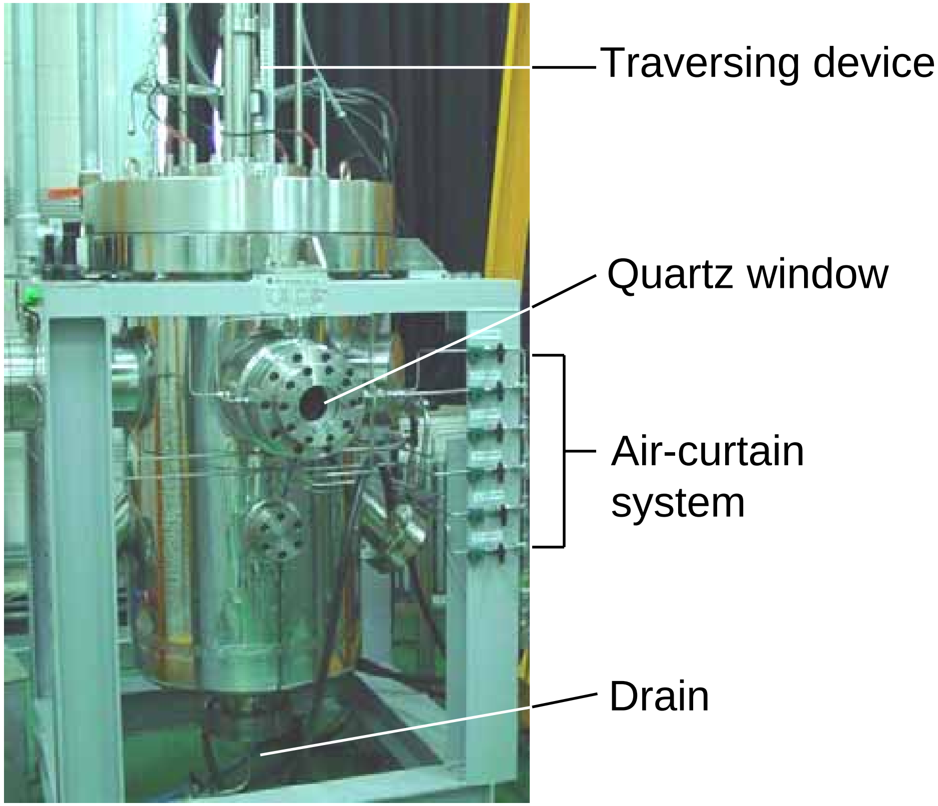
- **Coaxial type injector (Swirl-Coaxial)**

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



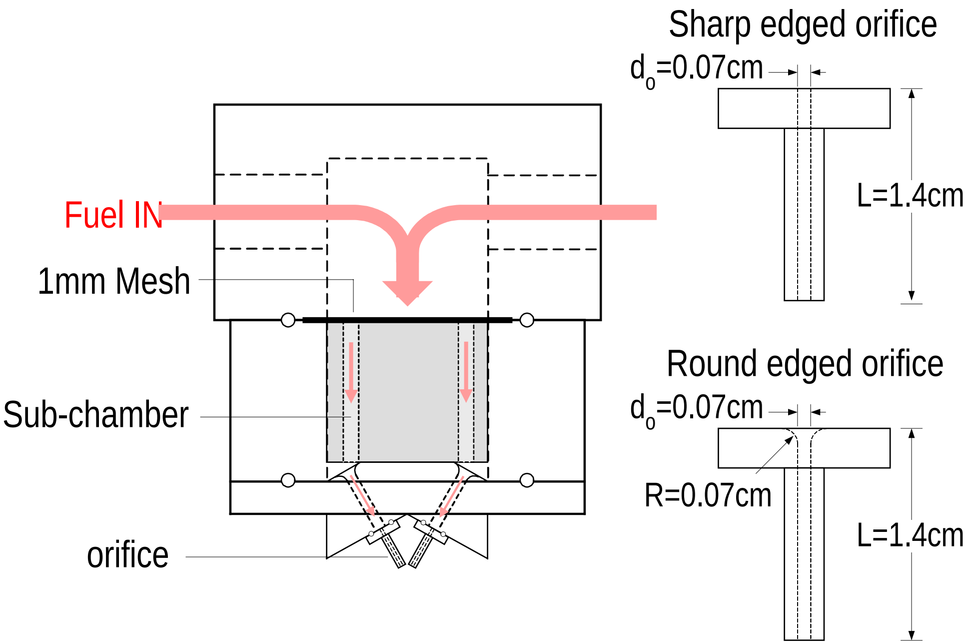
D. Kendrick et al.
(ONERA, FRANCE, 1999)

High Pressure Chamber

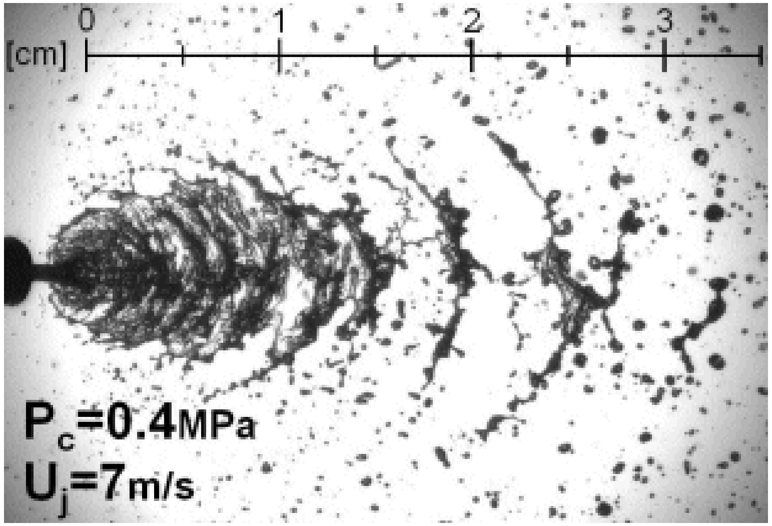


	Present	AFRL (USA)
Chamber Diameter	500mm	500mm
Window Size	80mm×4	50mm×3 120mm×1
Window Material	quartz	sapphire
Max. Pressure	6MPa	about 10MPa
Spray Simulant	water	water
Pressurizing Gas	nitrogen	nitrogen

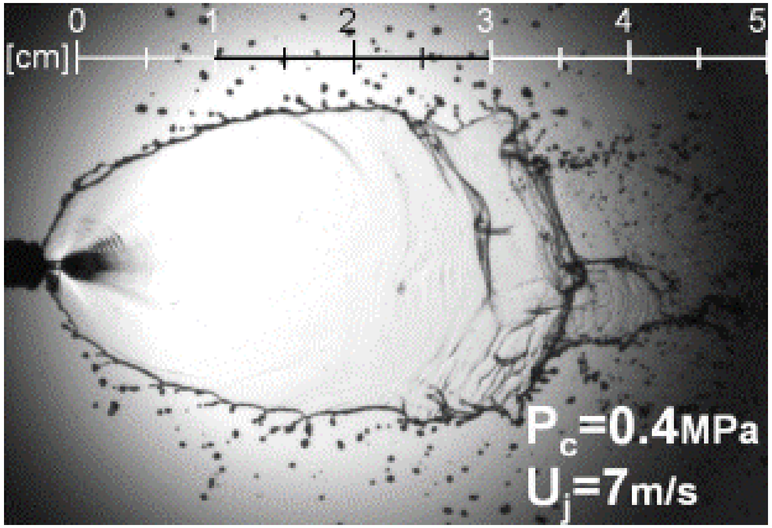
Like-Doublet Injector Design

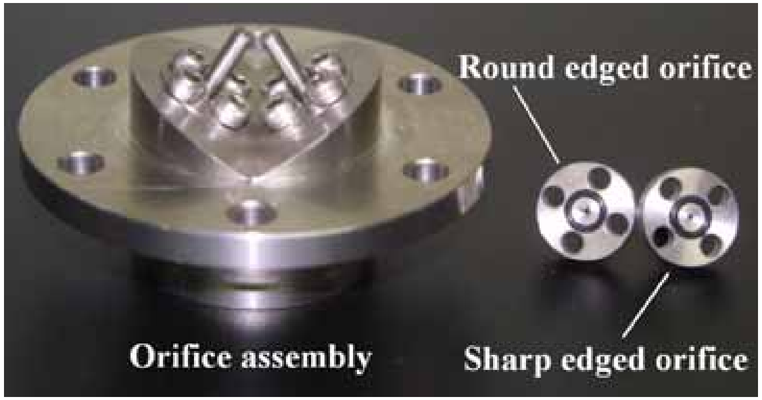


Turbulent Sheet



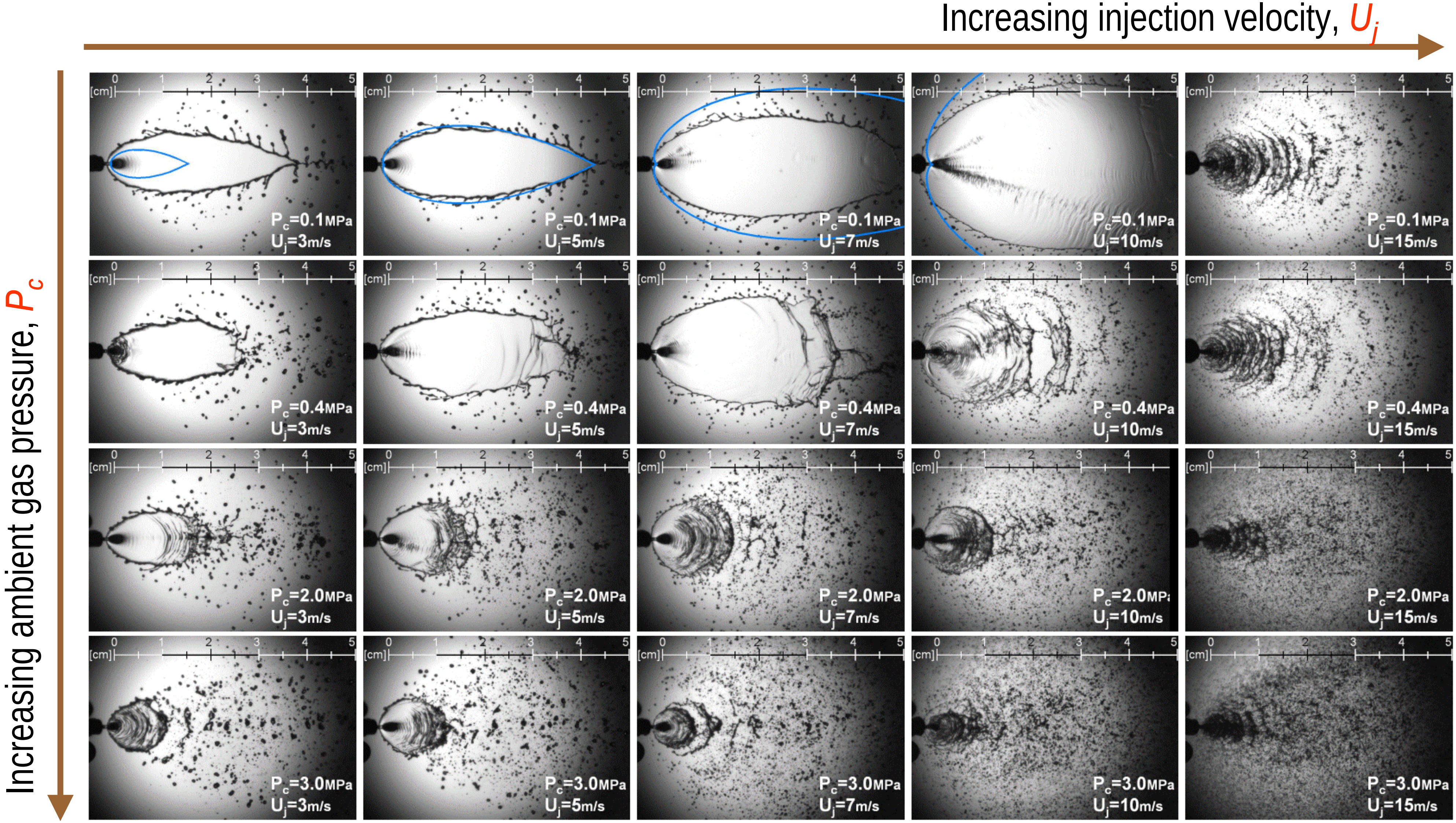
Laminar Sheet





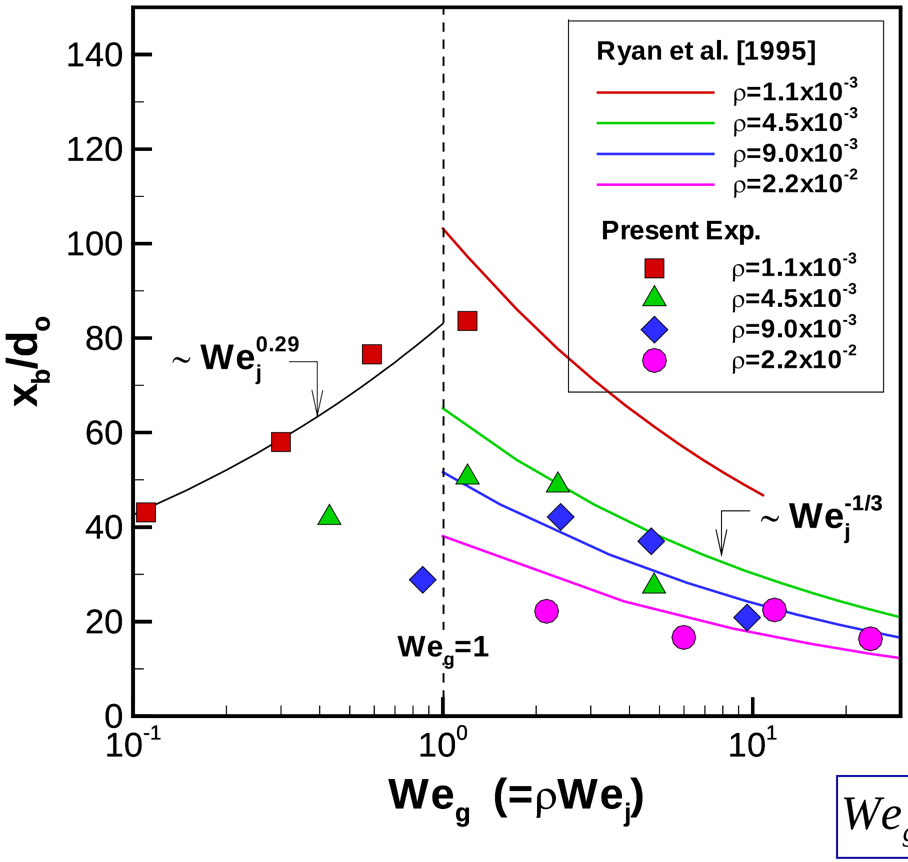
Laminar Sheet Breakup (1/3)

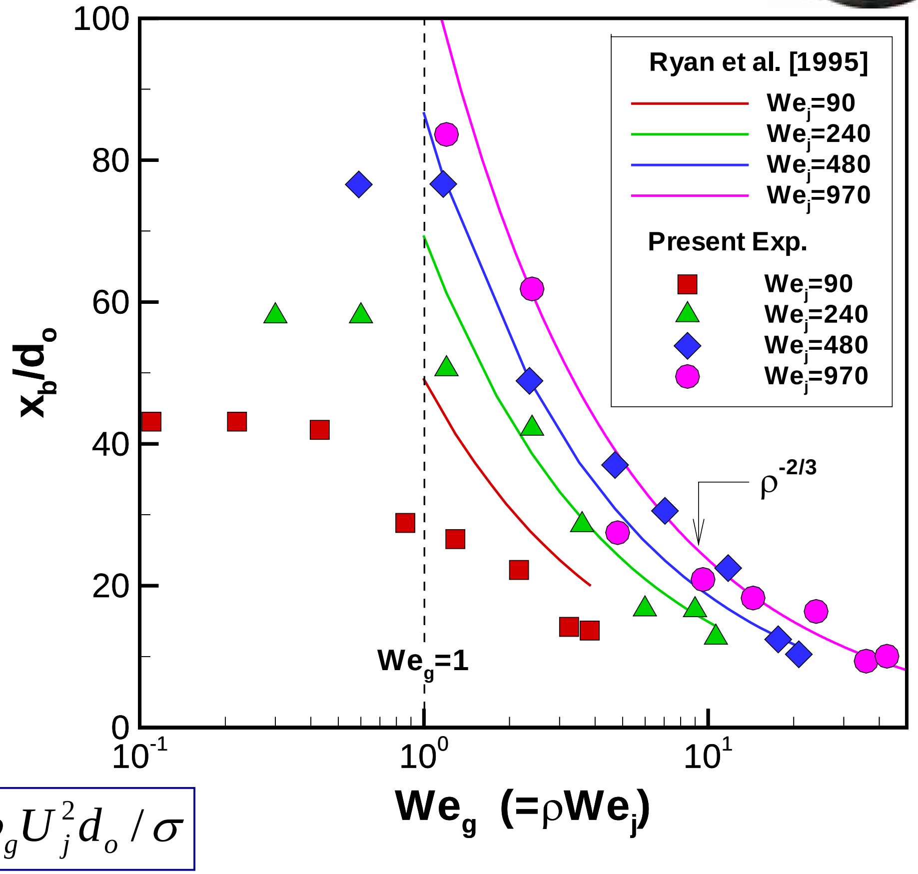
Changes of Sheet Shapes



Laminar Sheet Breakup (2/3)

Sheet Breakup Length



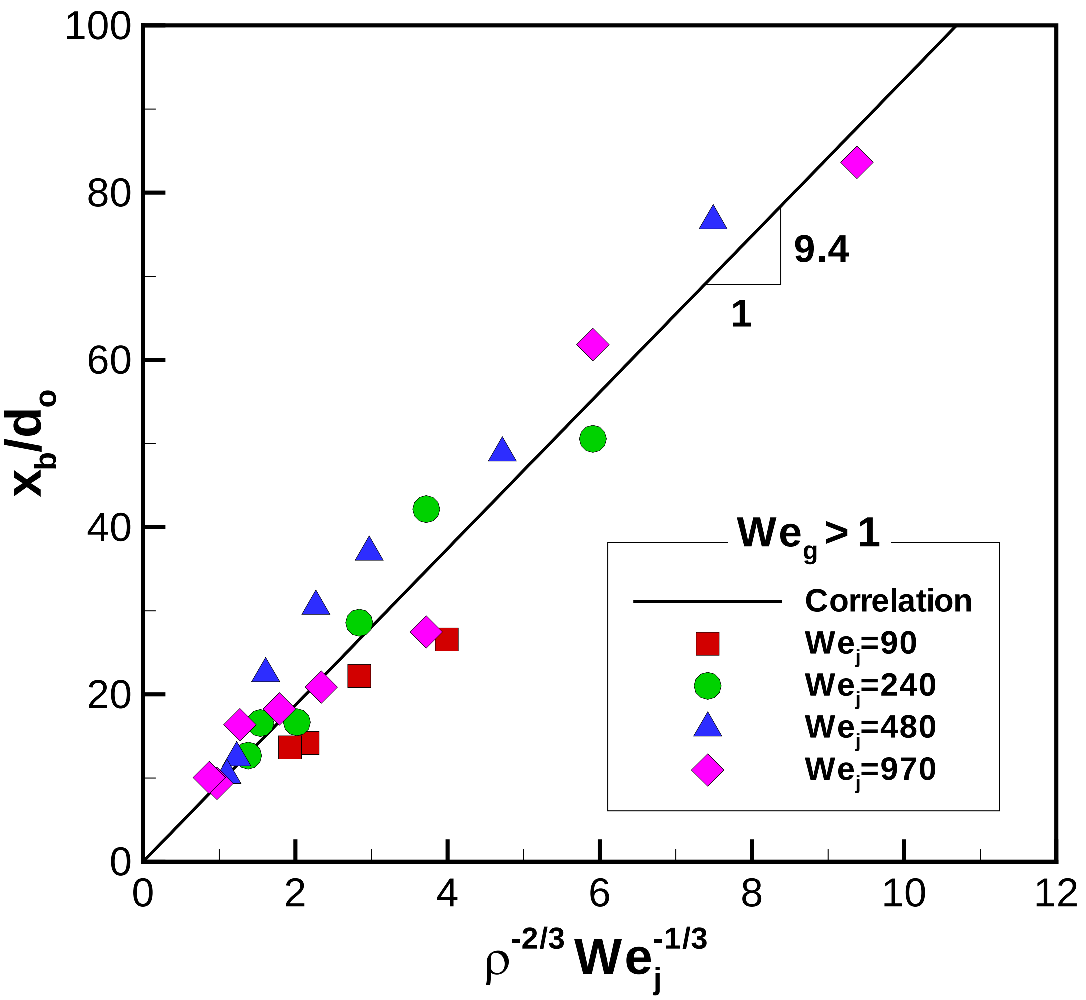


$$We_g = \rho_g U_j^2 d_o / \sigma$$

- 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.

Laminar Sheet Breakup (3/3)

Breakup Length Modeling



- Huang [1970] :

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

- Ryan et al. [1995] :

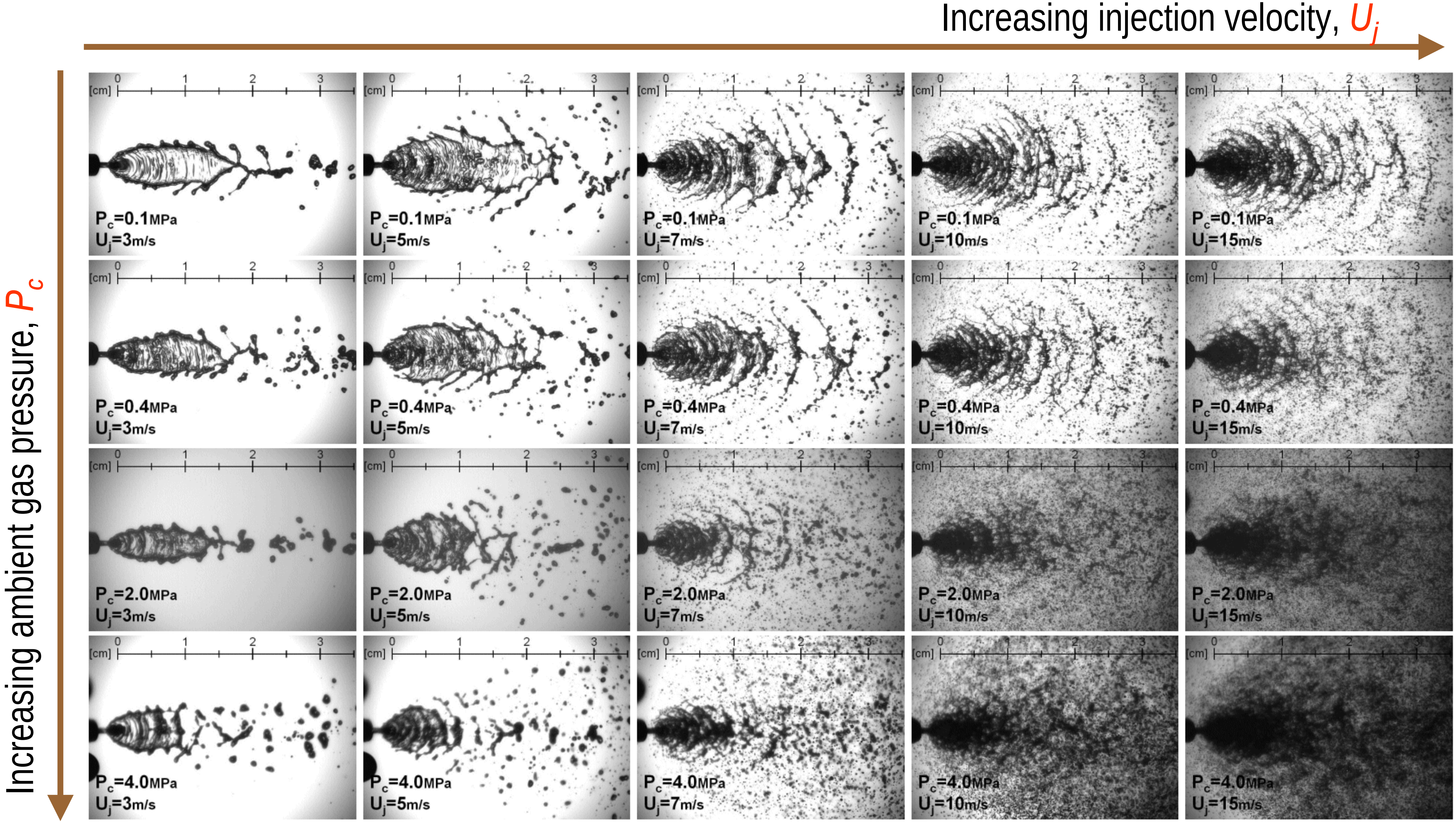
  $x_b/d_o = 10.4\rho^{-2/3}We_j^{-1/3}$

- Present :

  $x_b/d_o = 9.4\rho^{-2/3}We_j^{-1/3}$

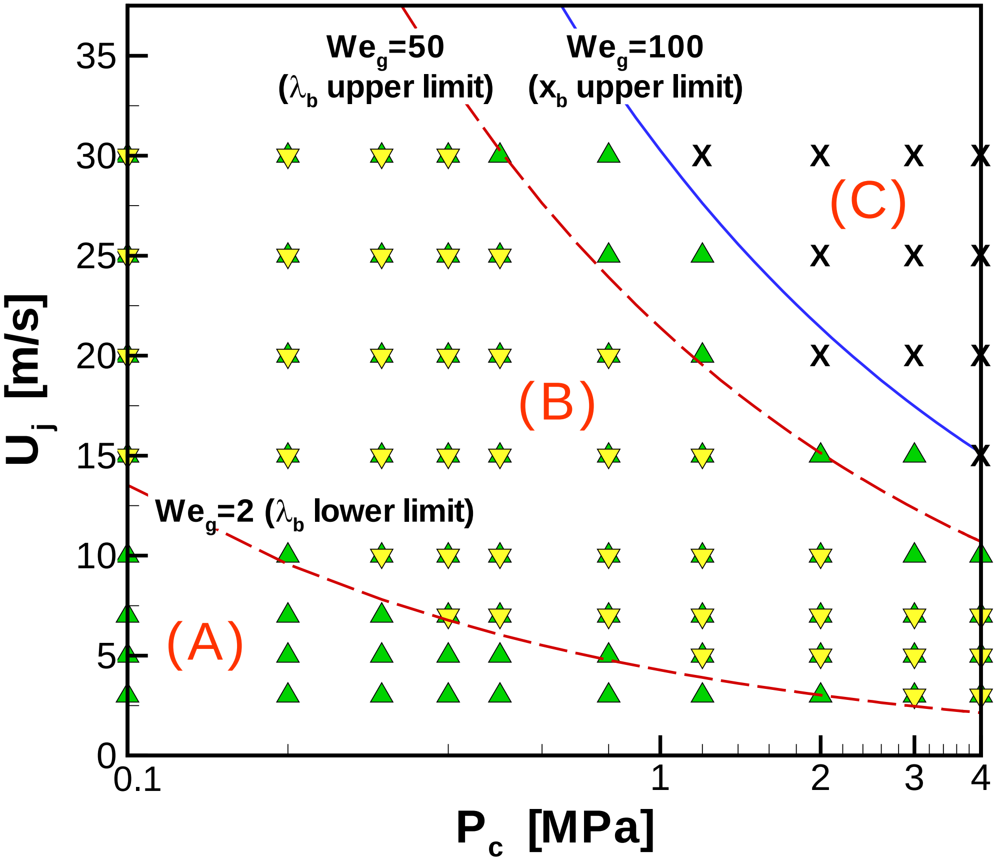
Turbulent Sheet Breakup (1/4)

Changes of Sheet Shapes



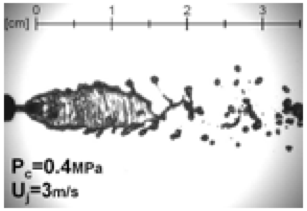
Turbulent Sheet Breakup (2/4)

Sheet Breakup Criteria



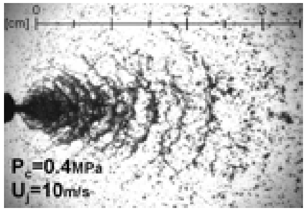
(A) Expansion Regime (We_g<2)

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



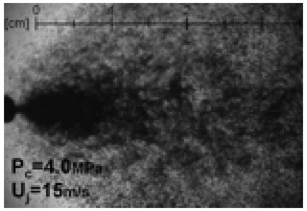
(B) Wave Breakup Regime (2< We_g<100)

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

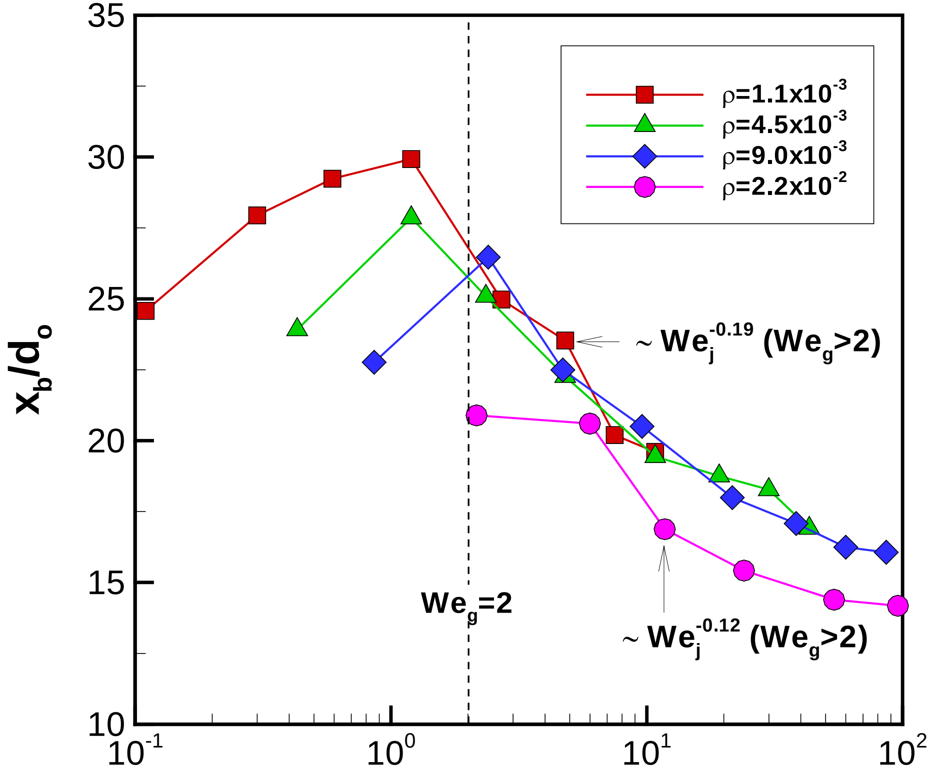


(C) Catastrophic Breakup Regime (We_g>100)

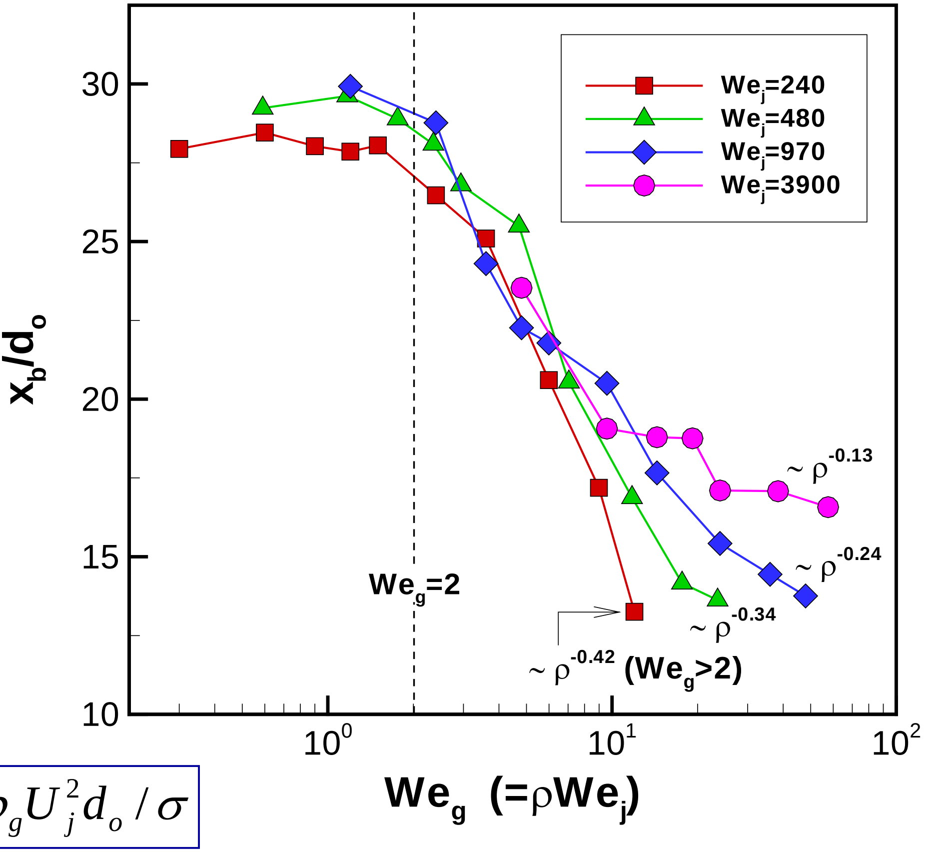
- Sheets are broken just after injection.
- x_b as well as λ_b can not be discriminated.



Sheet Breakup Length

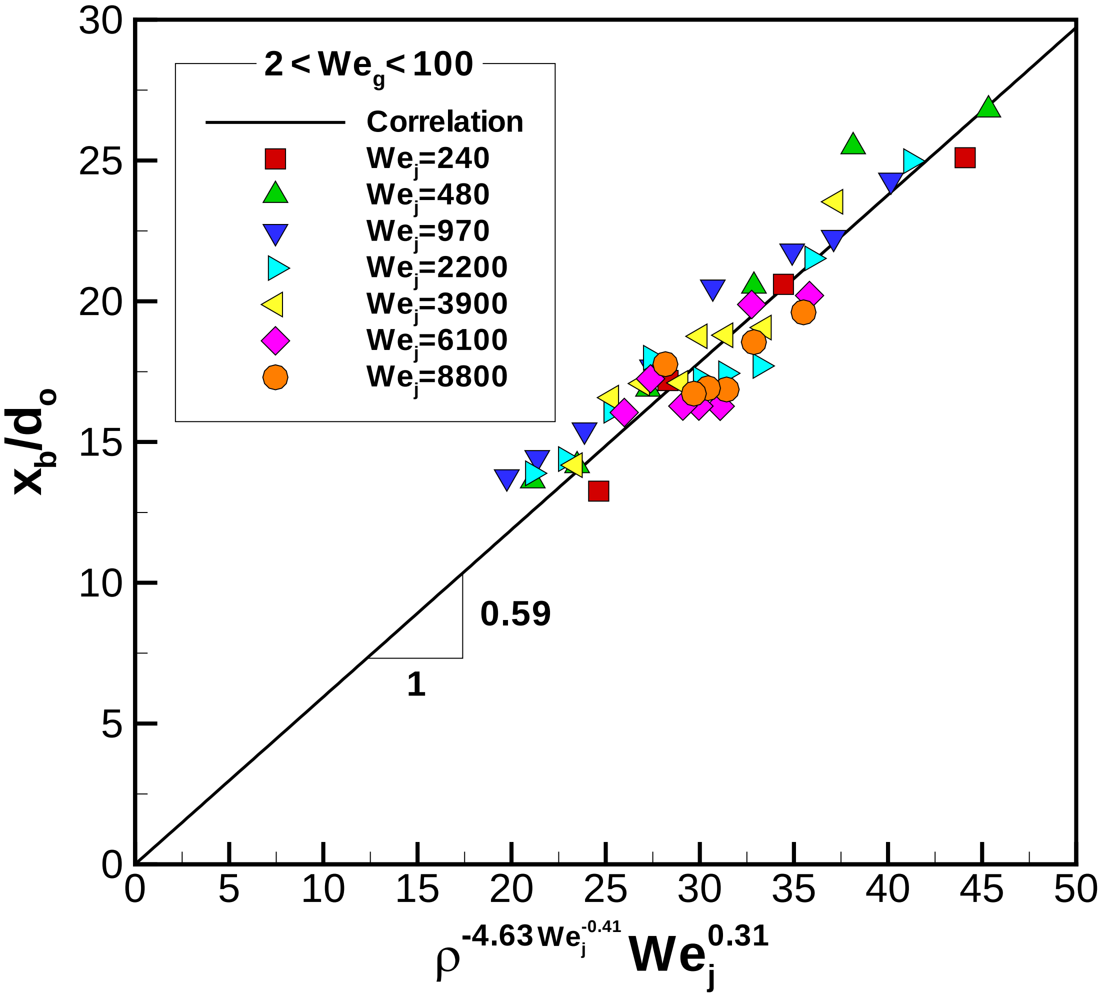


$$We_g = \rho_g U_j^2 d_o / \sigma$$



- 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



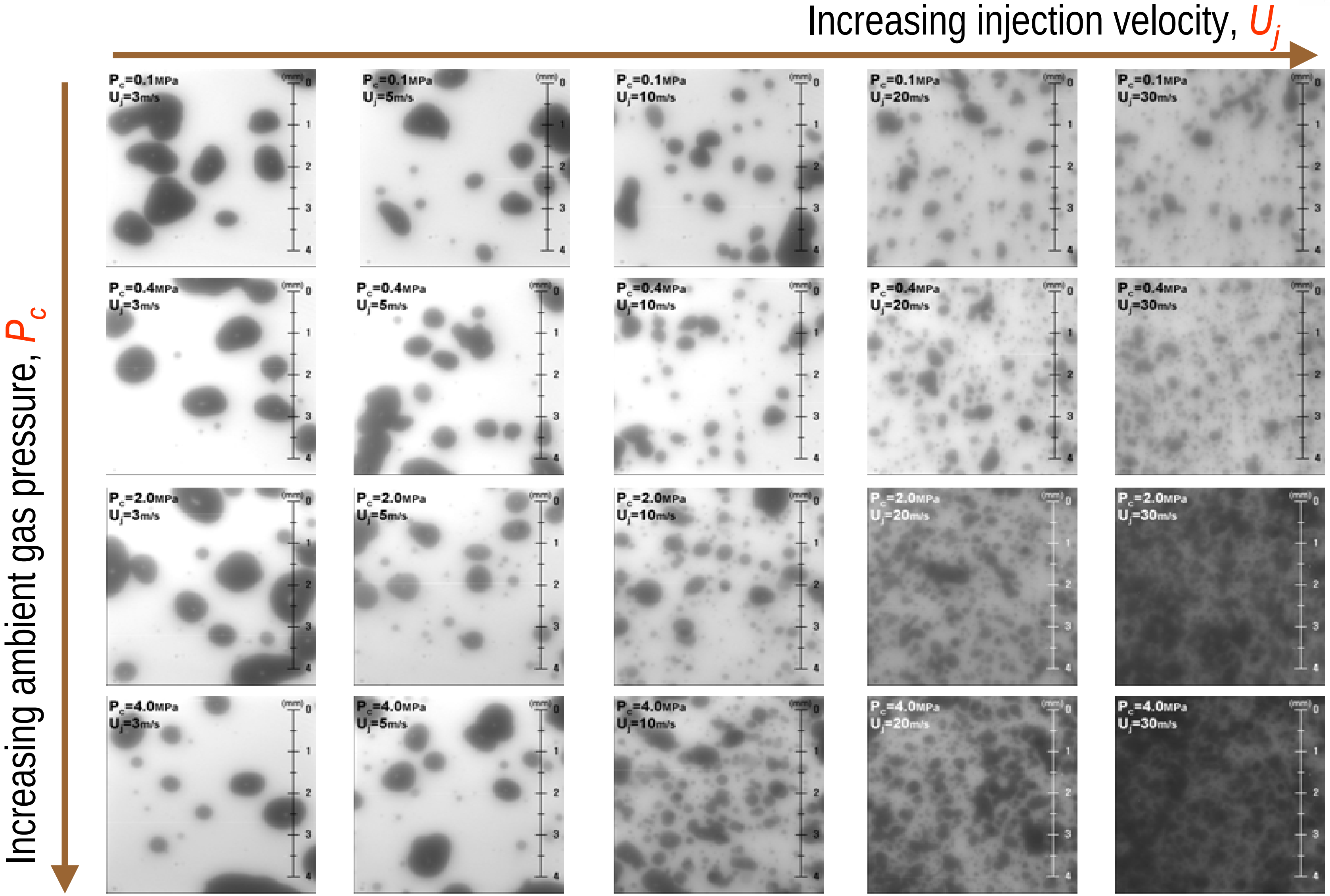
- When 2 < We_g < 100 ,

  $x_b/d_o = 0.59 \boxed{\rho^{-4.63 We_j^{-0.41}}} We_j^{0.31}$

- The effect of ambient density is mitigated as increasing jet Weber number (i.e., impact force).

Drop Size Measurements (1/3)

Changes of Drop Images


Increasing injection velocity, U_j

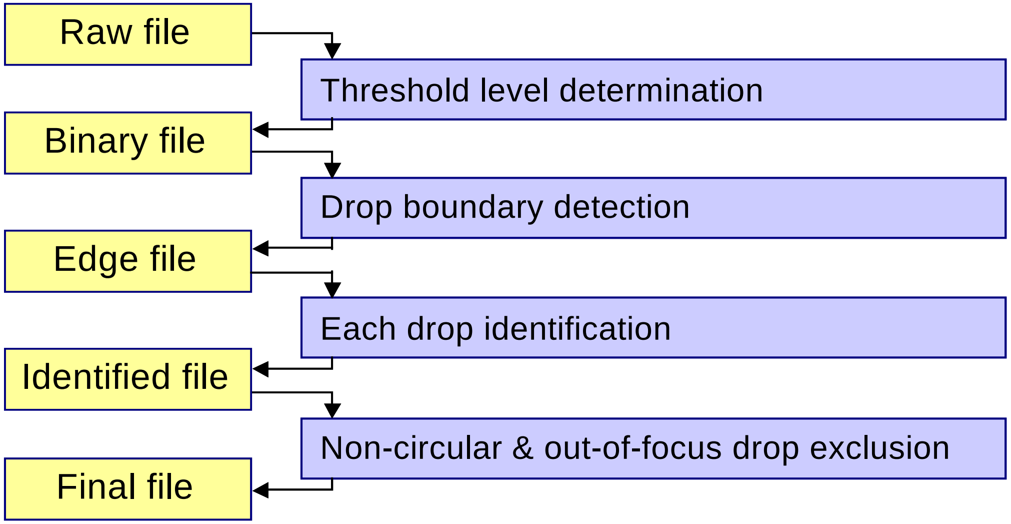
Increasing ambient gas pressure, P_c

Drop Size Measurements (2/3)

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



Raw file

Threshold level determination

Binary file

Drop boundary detection

Edge file

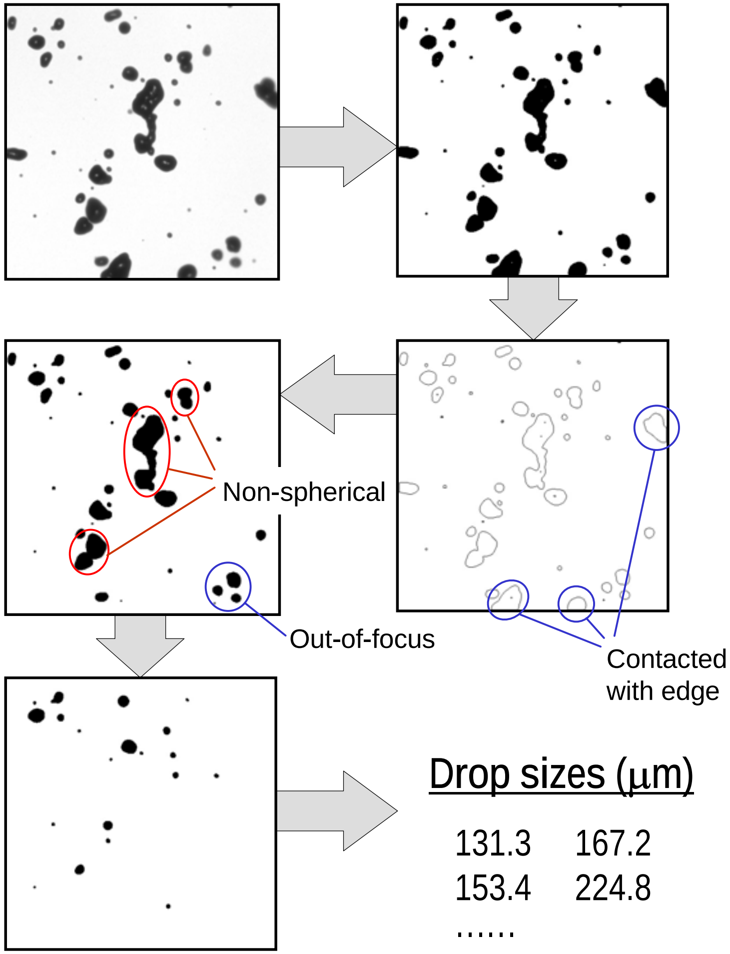
Each drop identification

Identified file

Non-circular & out-of-focus drop exclusion

Final file

Overall procedure of image processing method



Drop sizes (μm)

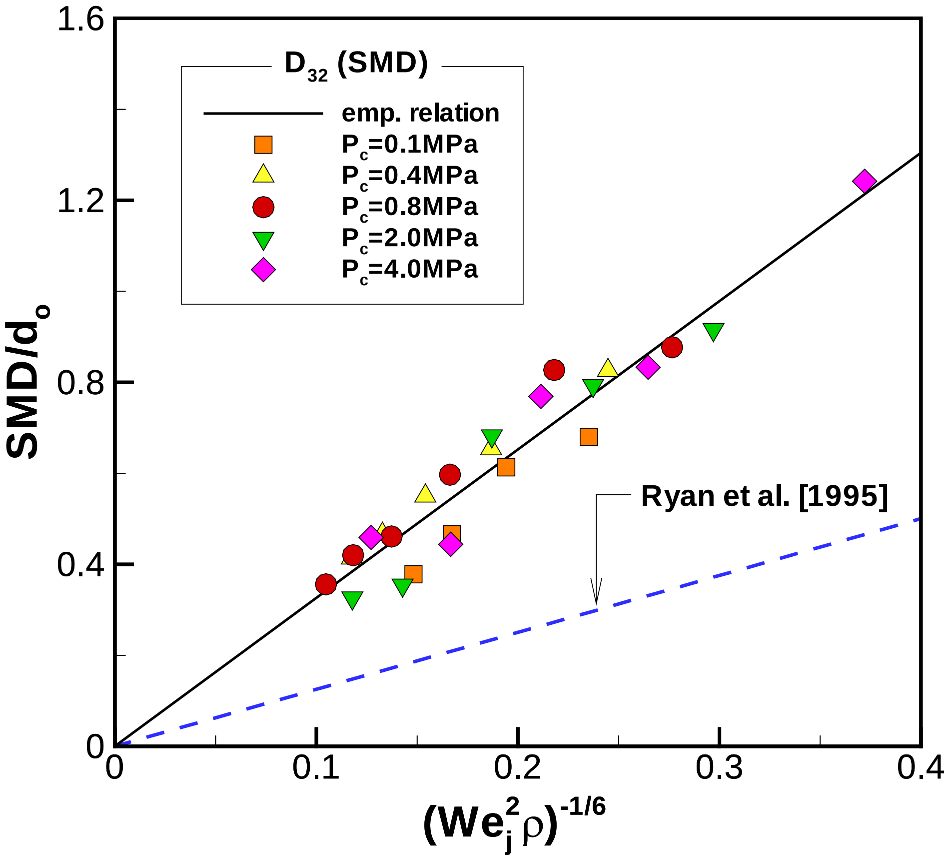
131.3	167.2
153.4	224.8

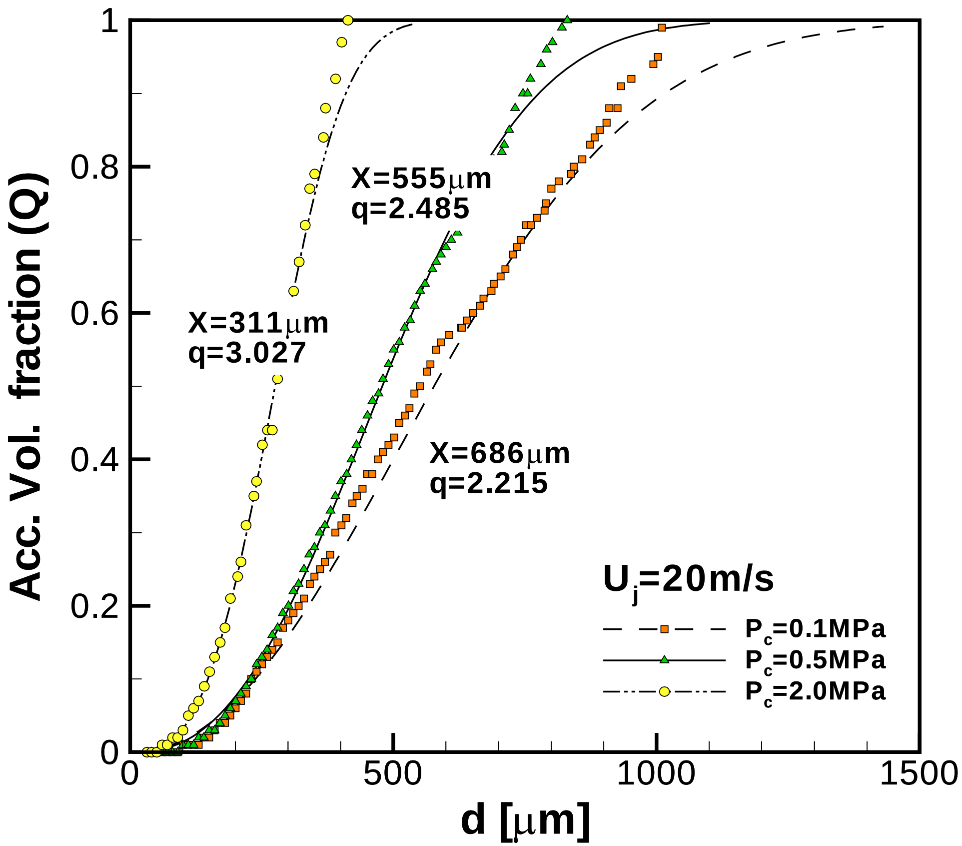
……

Intermediate images

Drop Size Measurements (3/3)

Drop Size & Distribution





Ryan et al. [1995]

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

Present

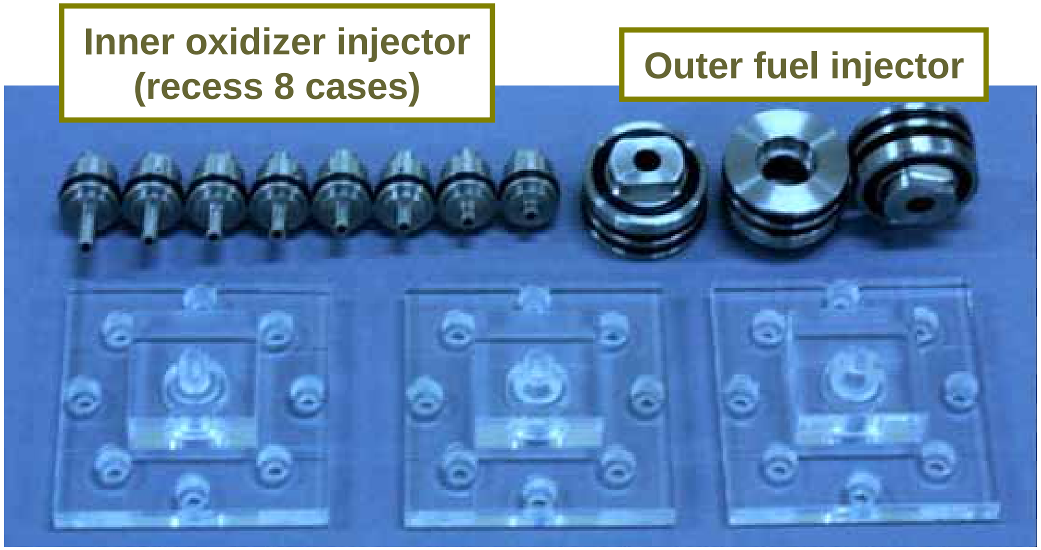
$$\frac{d_D}{d_o} = 1.64\rho^{-1/6} We_j^{-1/3}$$

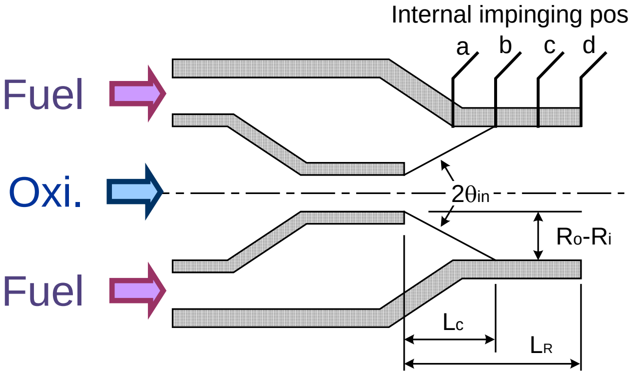
Rosin-Rammler distribution

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

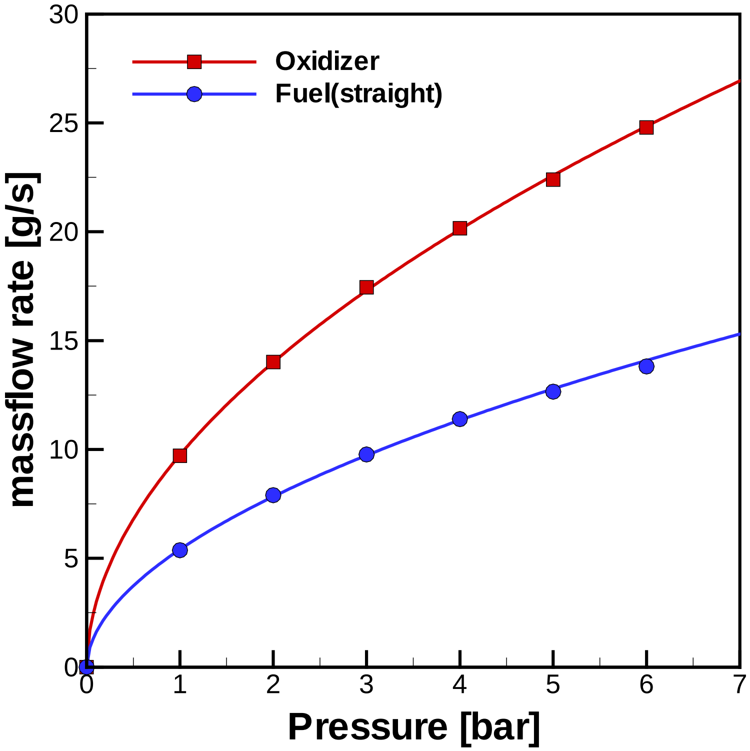
Swirl Coaxial Injector

- Injector Parts





- Operating Conditions

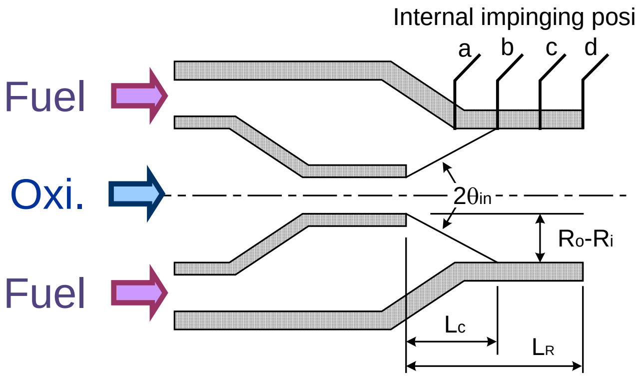


- Oxidizer flowrate : 25.6 g/s
- Fuel flowrate : 10.76 g/s
- O/F ratio : 2.38

Effect of Recess (1/5)

Spray Patterns

- Definition of Recess Number



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

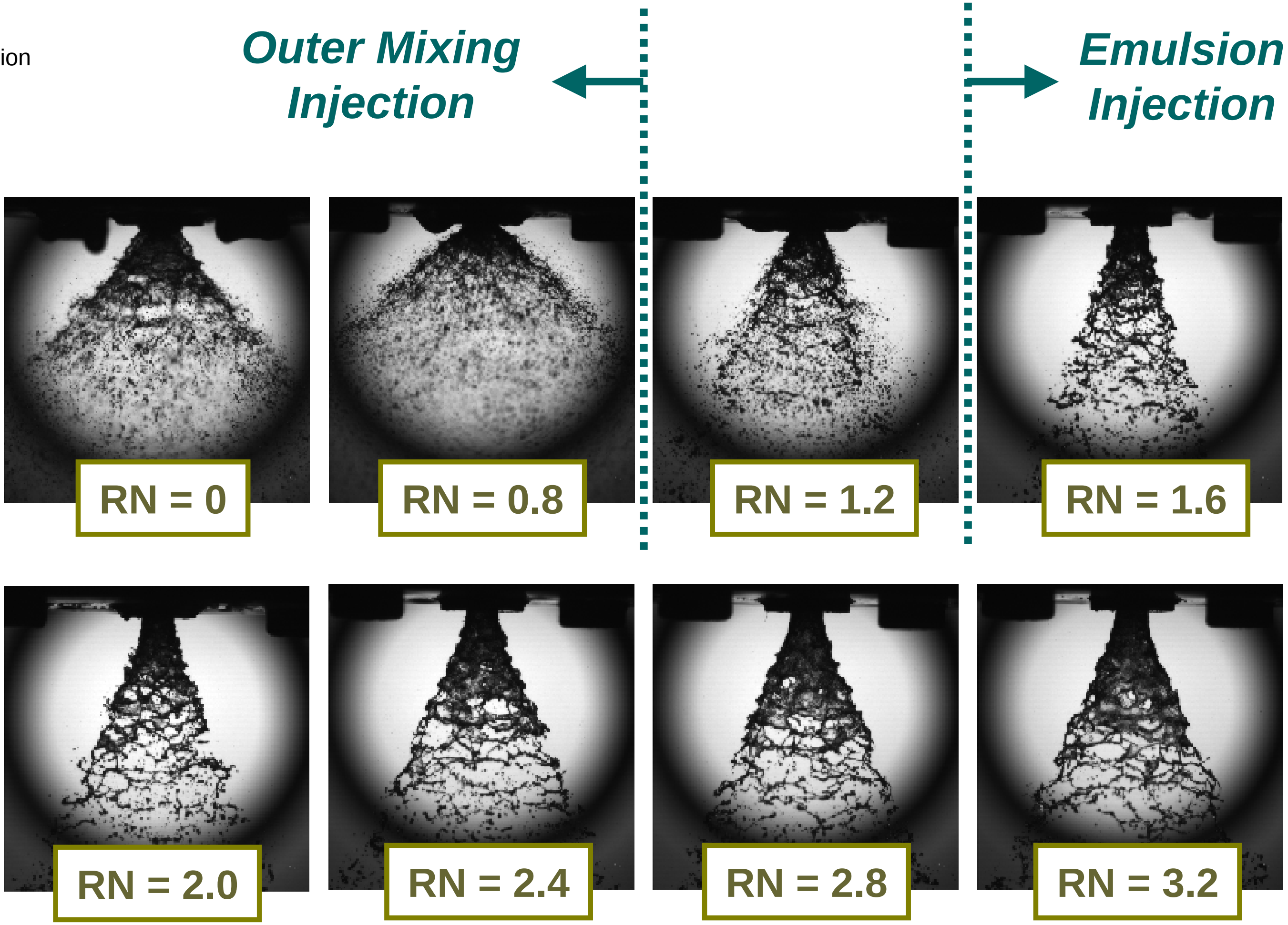
θ_{in} : inner spray angle

R_0 : outer injector radius

R_i : inner injector radius

L_R : recess length

- Spray patterns with recess number



Outer Mixing Injection

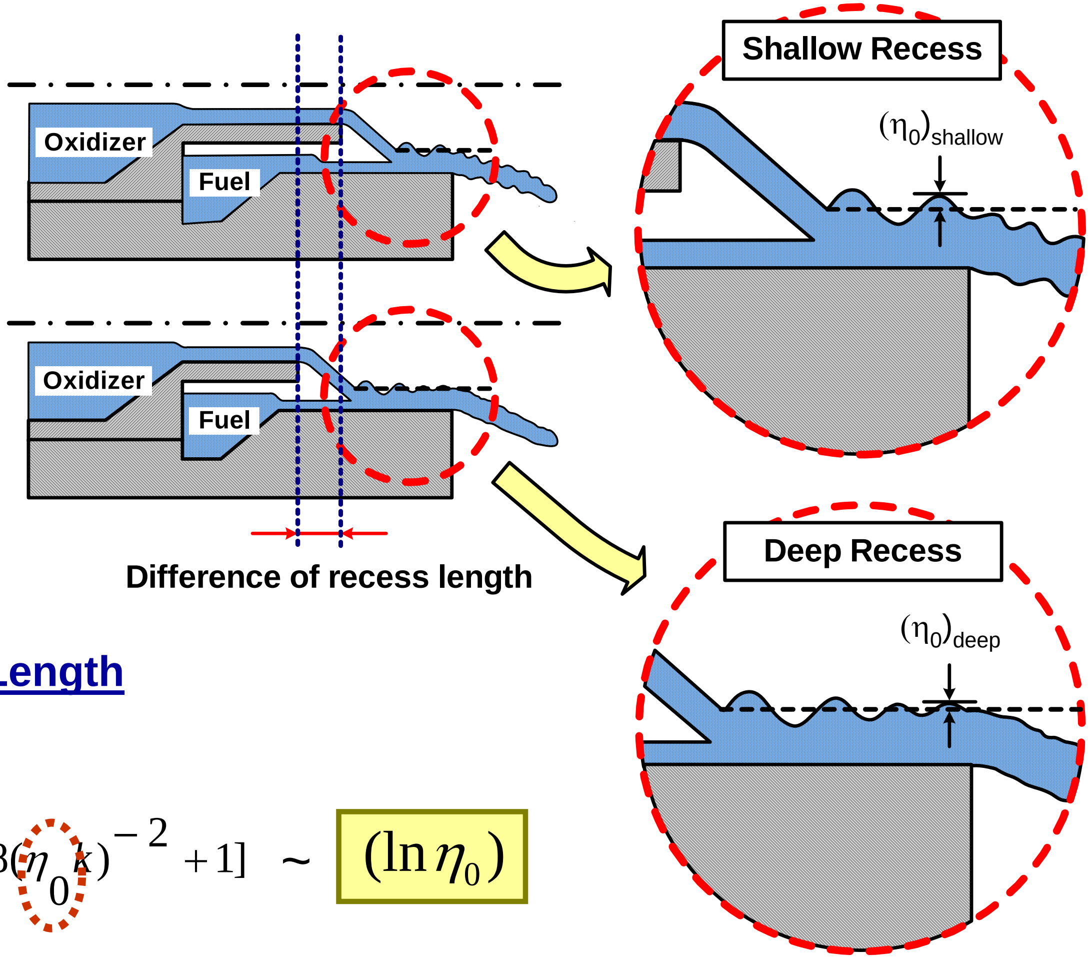
Emulsion Injection

Effect of Recess (2/5)

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.

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

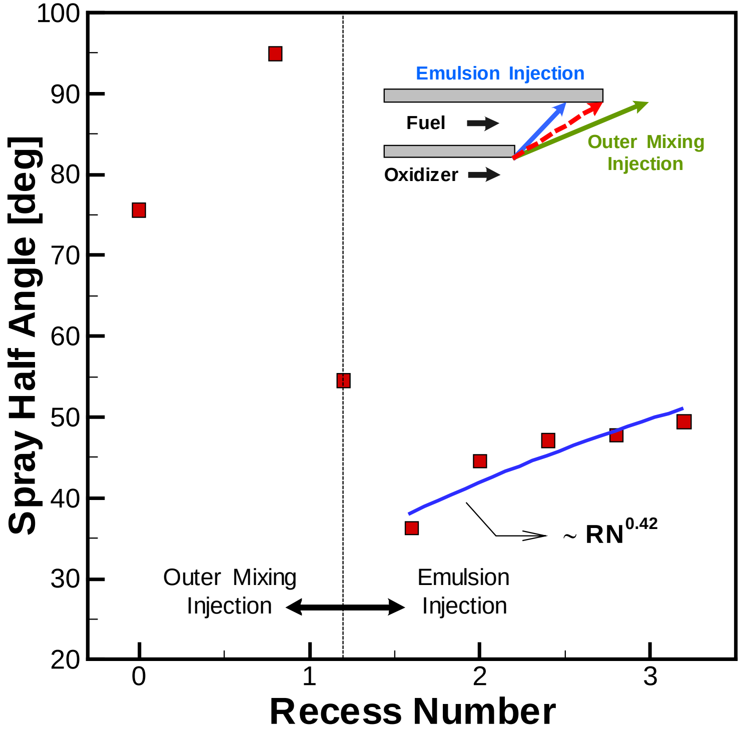


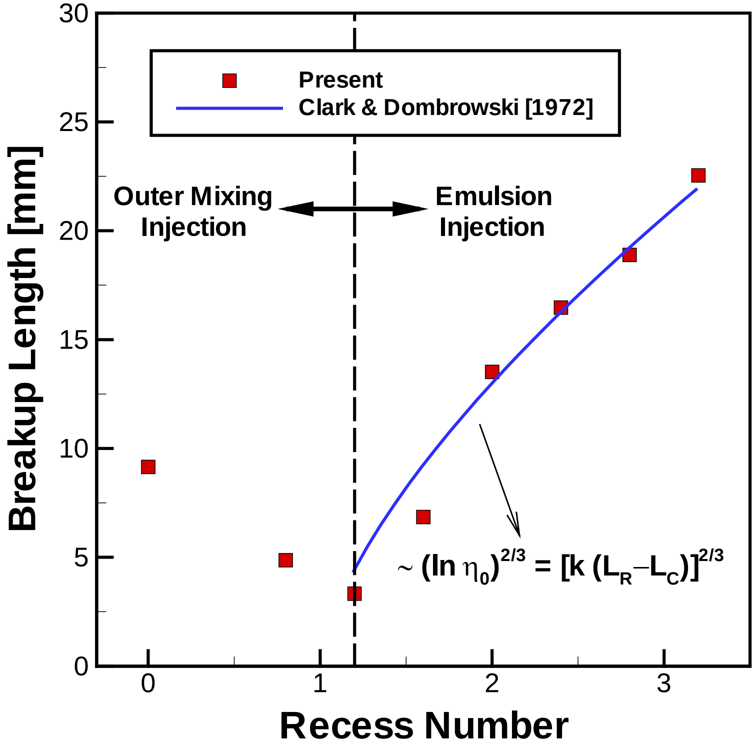
Clark and Dombrowski [1972] – Breakup Length

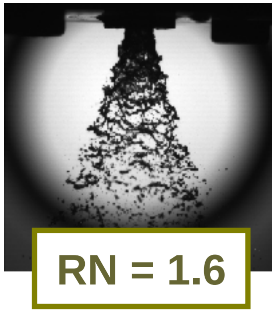
$$x_b^{2/3} = \left[\frac{9\rho_L K U^2}{32(\rho_a U^2 k - \sigma k^2)}\right]^{1/2} \cosh^{-1}[8(\eta_0 k)^{-2} + 1] \sim \boxed{(\ln \eta_0)}$$

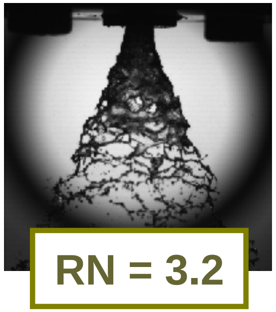
Effect of Recess (3/5)

Spray Angle & Breakup Length









- In large recess region (emulsion injection)

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

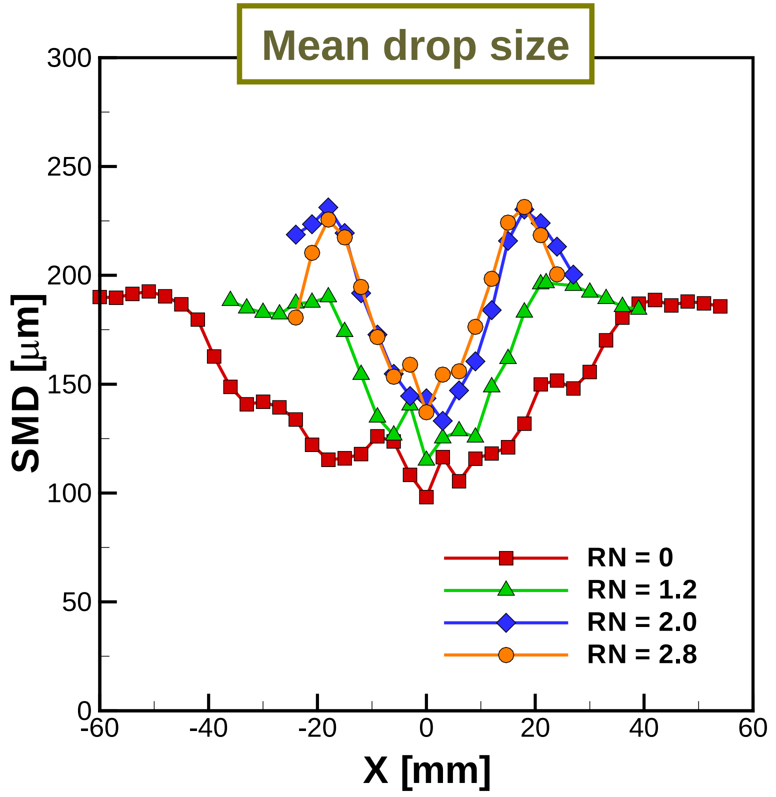
$$\ln(\eta_0 / \eta_i) = k(L_R - L_C)$$

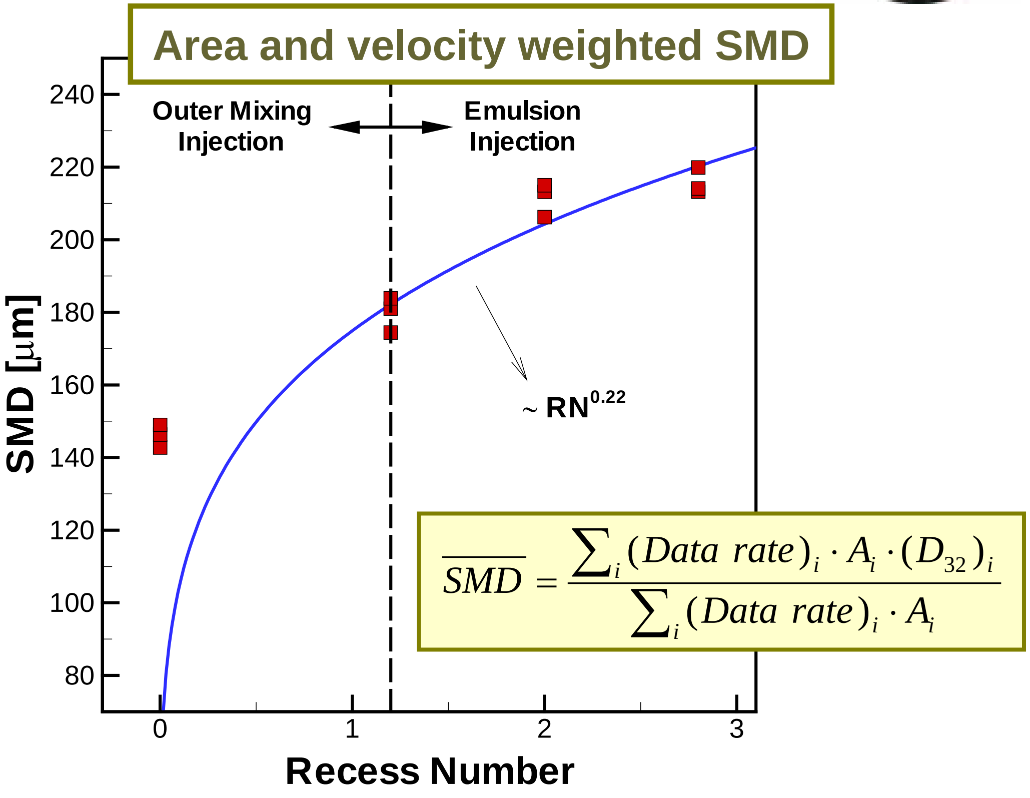
η_0 : wave amplitude at the injector tip

η_i : wave amplitude just after impinging

Effect of Recess (4/5)

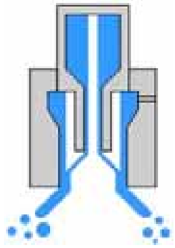
Atomization Characteristics





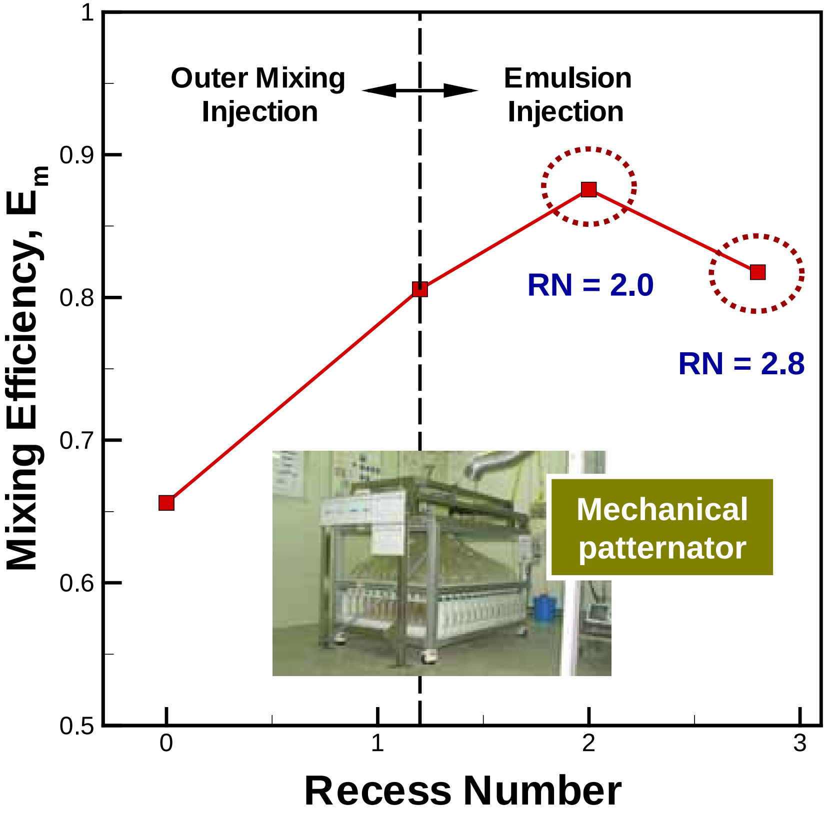
$$\overline{SMD} = \frac{\sum_i (Data\ rate)_i \cdot A_i \cdot (D_{32})_i}{\sum_i (Data\ rate)_i \cdot A_i}$$

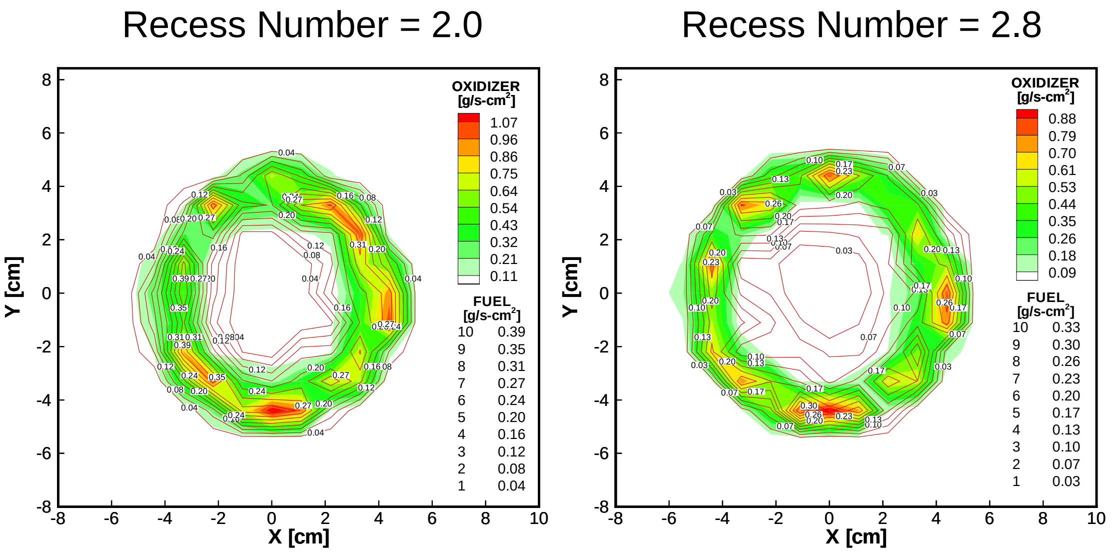
- The mean drop size increases with recess increased due to :
  - (i) the increase of effective film thickness and
  - (ii) the decrease of spray angle.

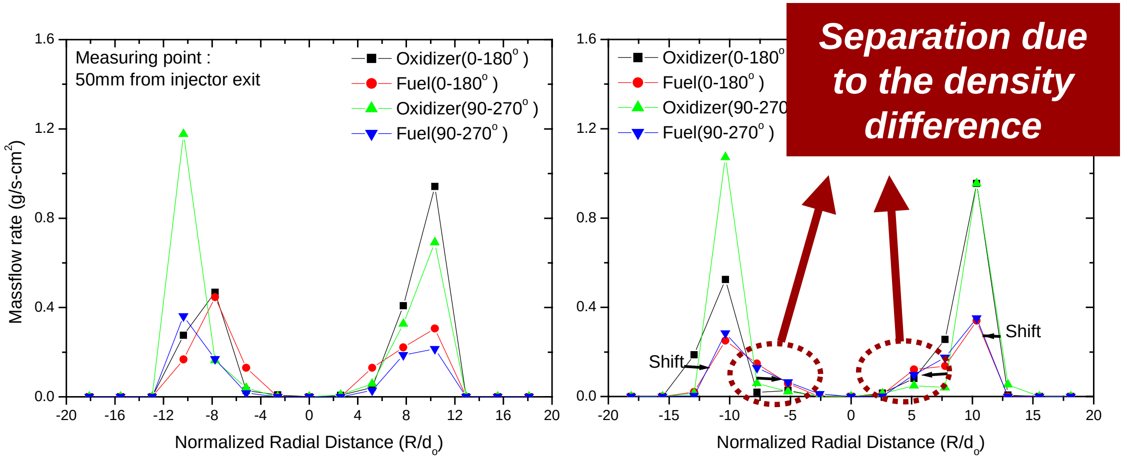


Effect of Recess (5/5)

Mixing Efficiency







Separation due to the density difference

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

Oxidizer Spray (1/3)

Inner Oxidizer Spray

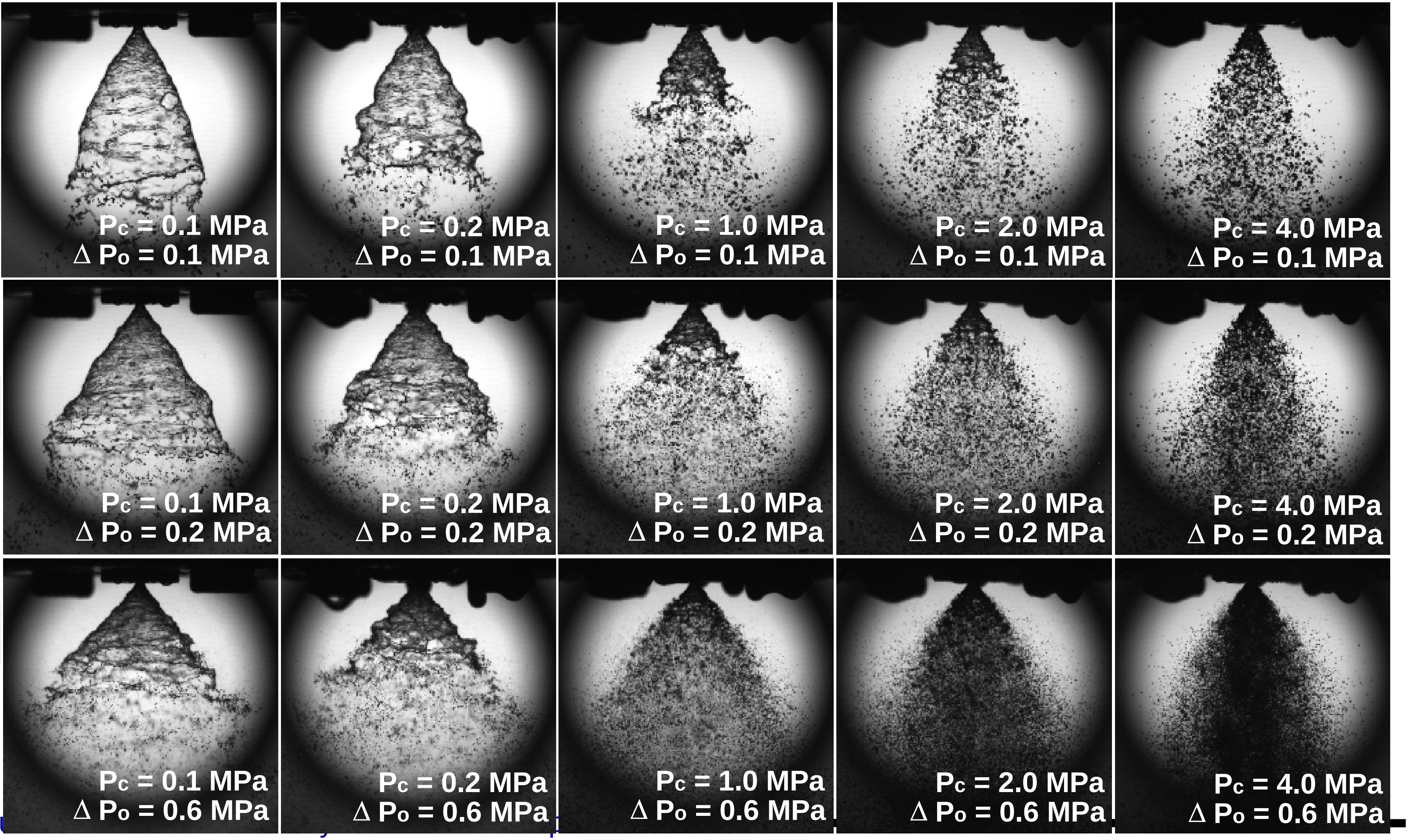
Increase of chamber pressure

Increase of oxidizer injection pressure

10.02 g/s

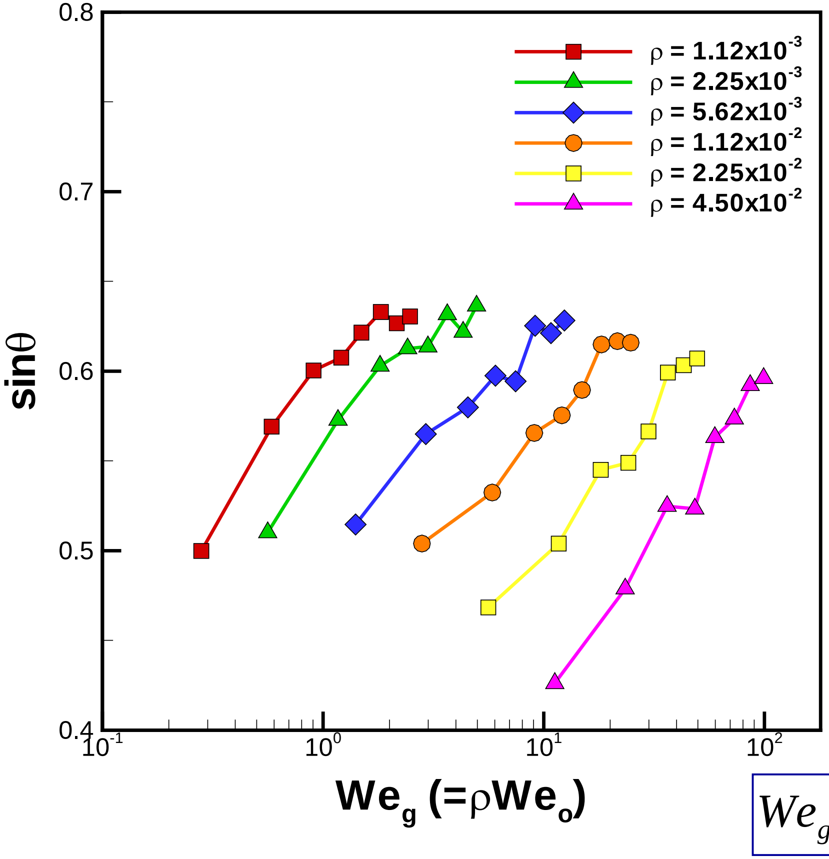
14.42 g/s

25.60 g/s

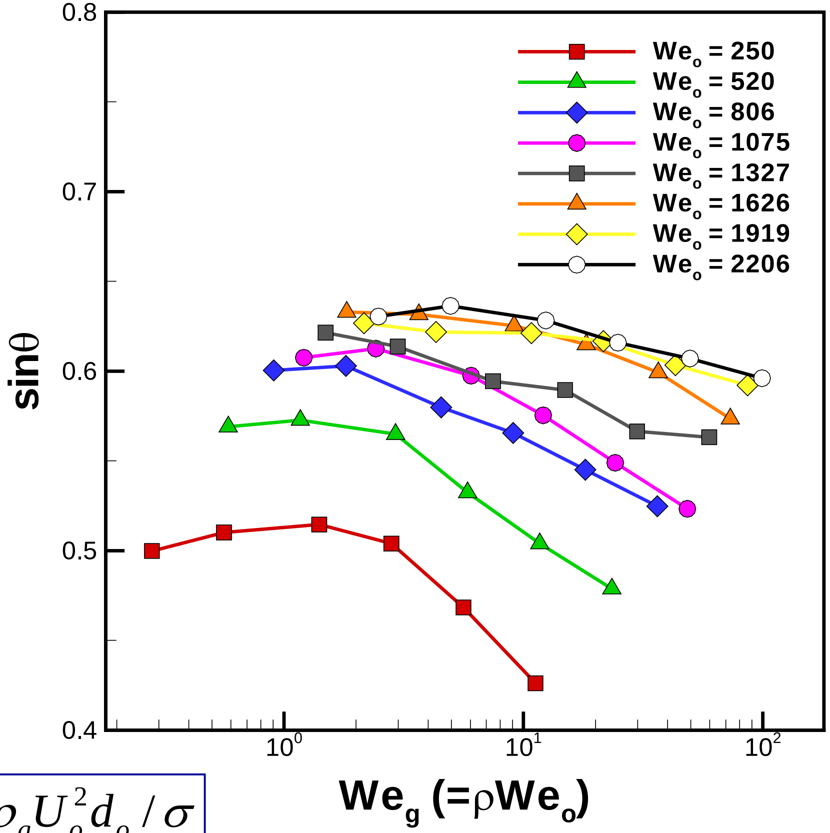


Oxidizer Spray (2/3)

Spray Angle (Single Oxidizer)



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

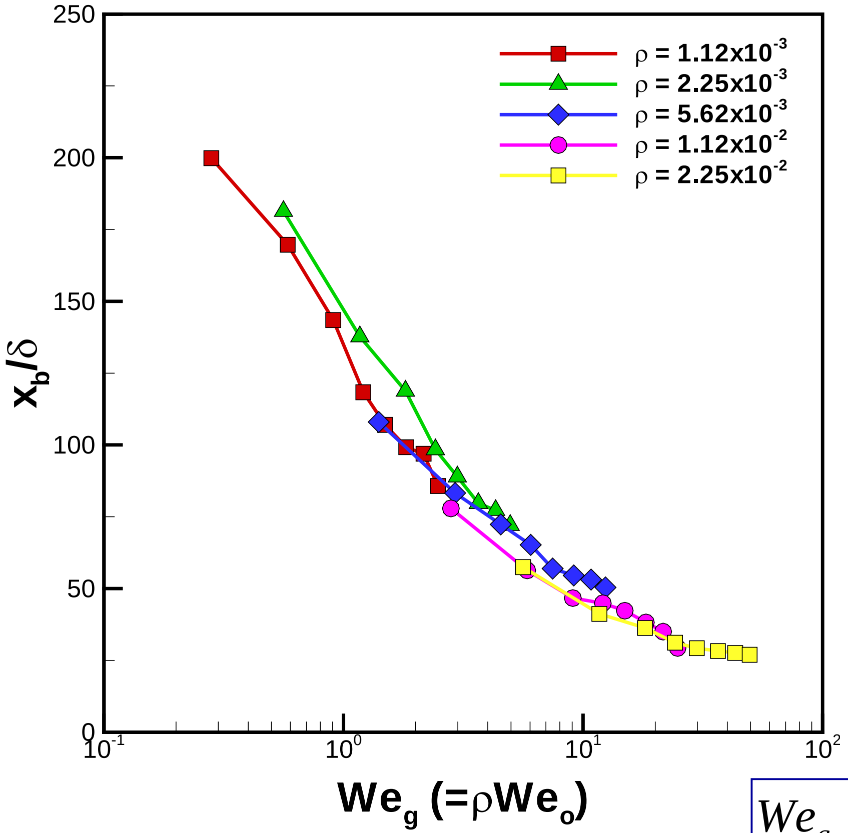


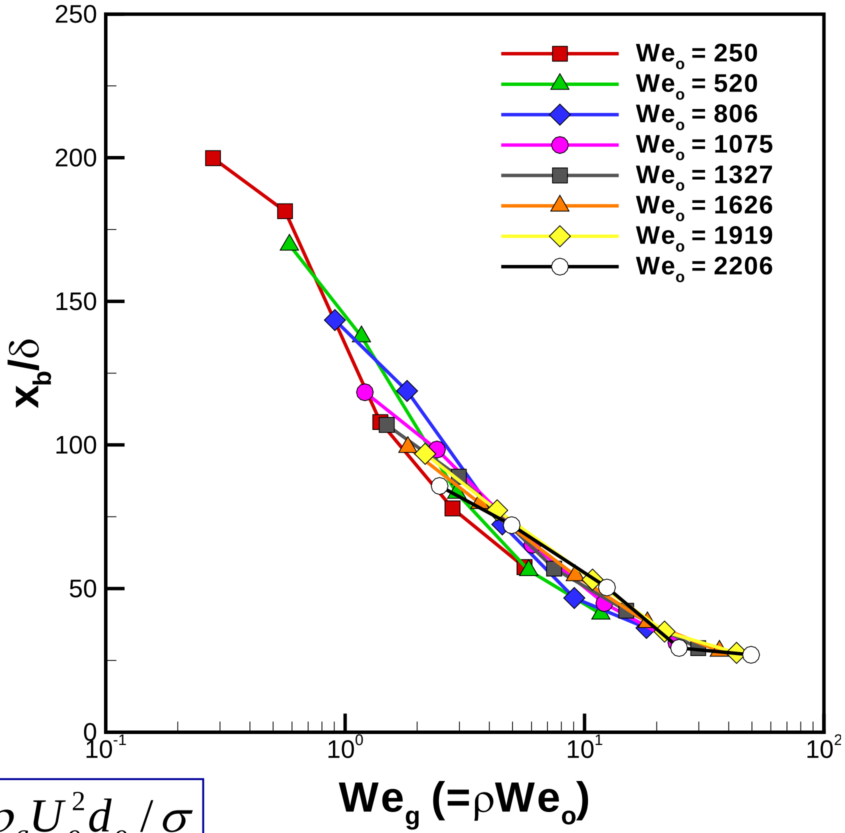
U_o : oxidizer axial velocity
d_o : oxidizer injector diameter
We_o : oxidizer Weber number

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

Oxidizer Spray (3/3)

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 the the increase of spray angle.

Coaxial Spray with Recess

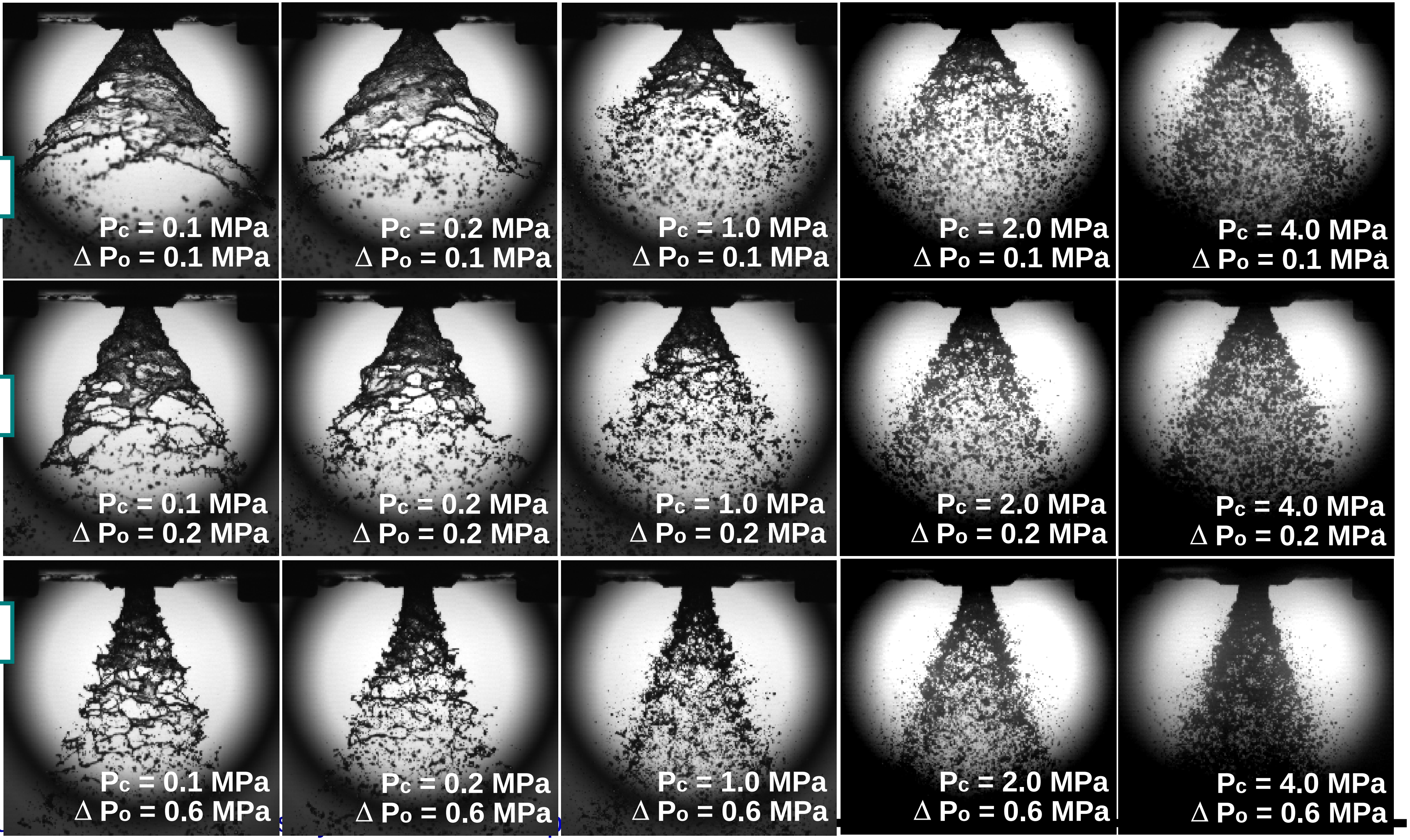
Increase of chamber pressure

Increase of oxidizer injection pressure

O/F = 0.94

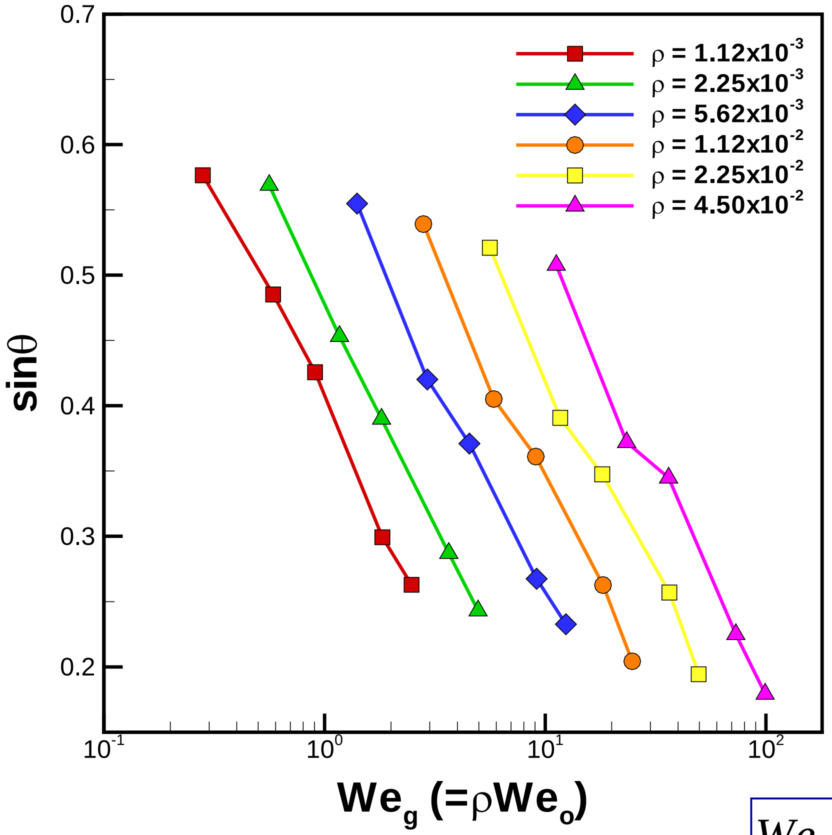
O/F = 1.33

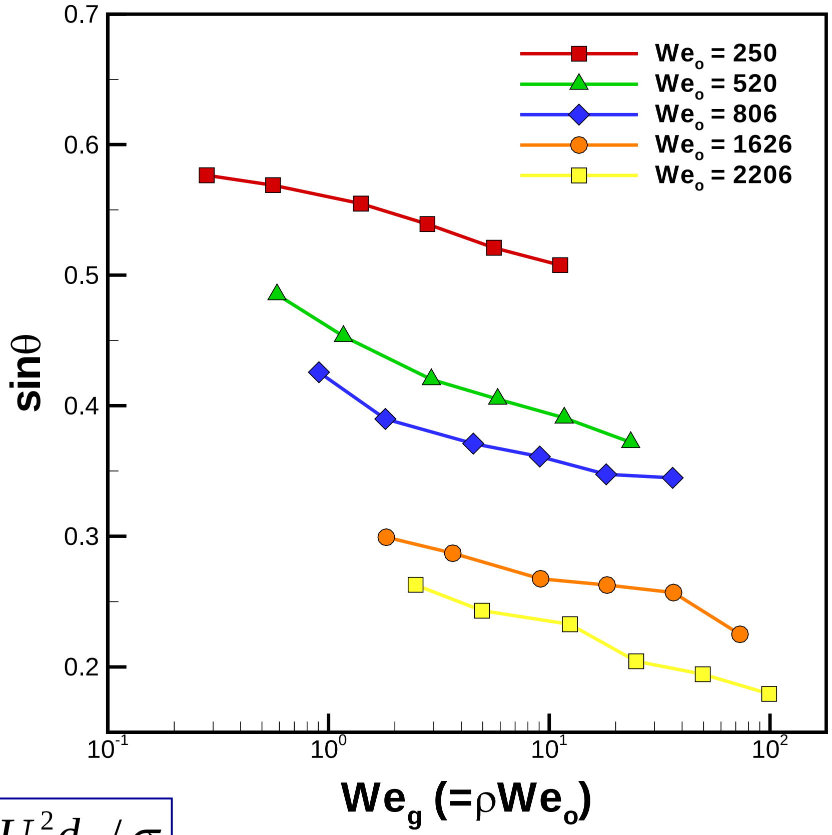
O/F = 2.38



Coaxial Spray (2/3)

Spray Angle (Coaxial Spray)



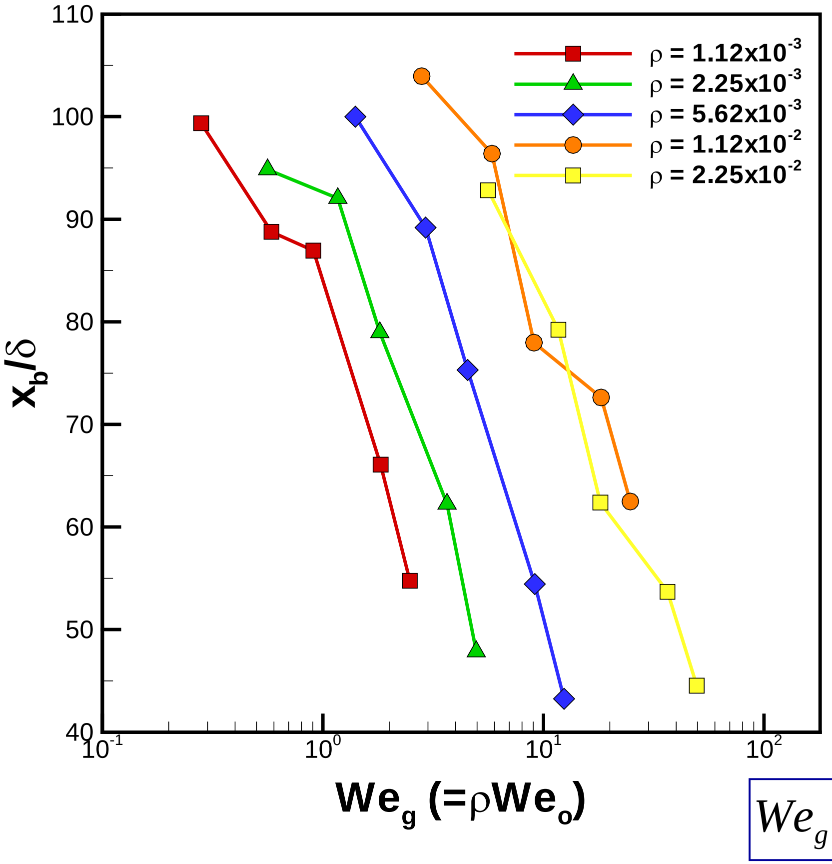


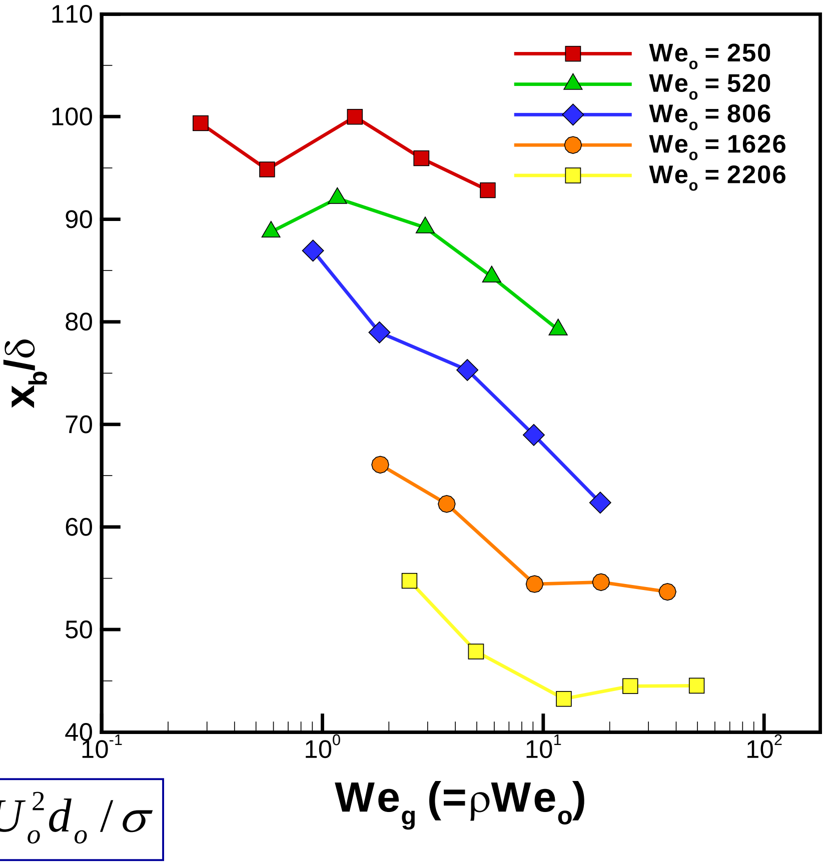
$$We_g = \rho_g U_o^2 d_o / \sigma$$

- 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.

Coaxial Spray (3/3)

Breakup Length (Coaxial Spray)

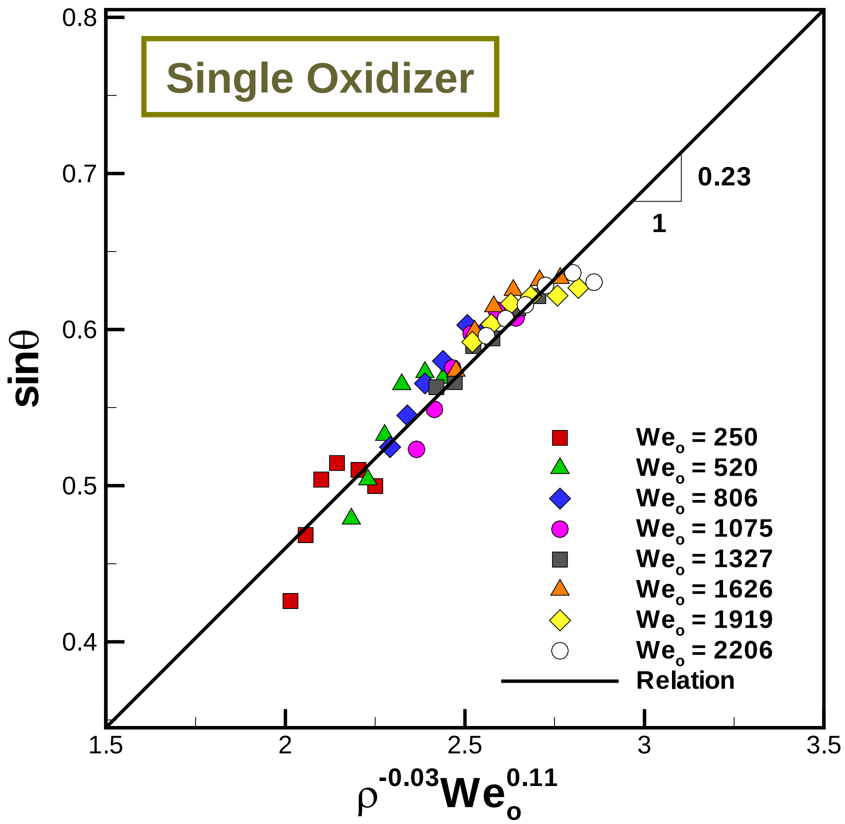


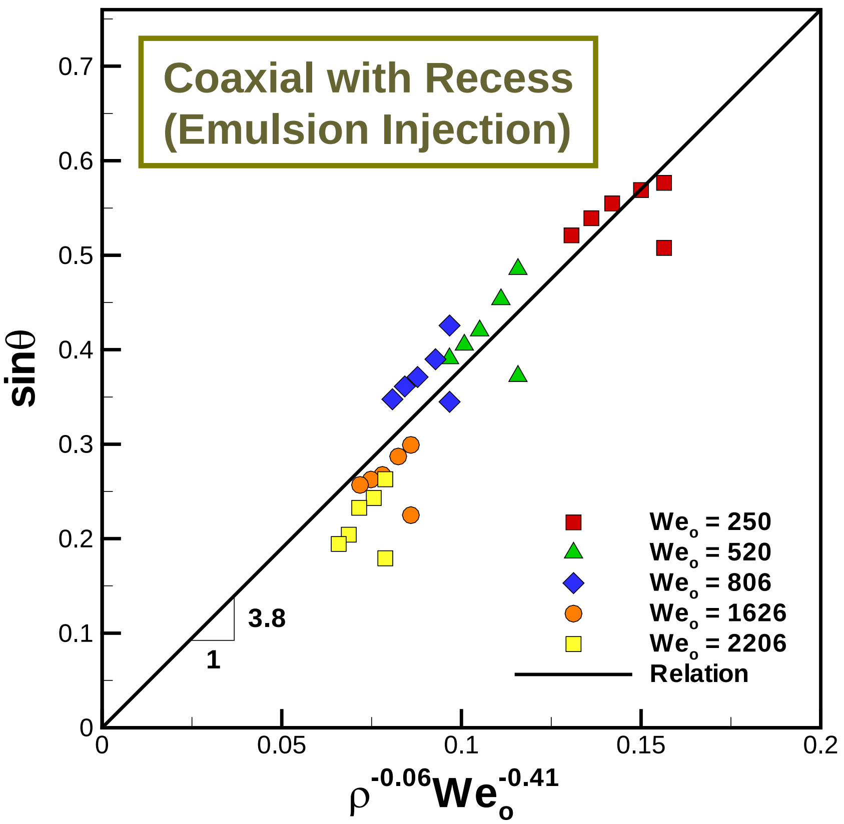


$$We_g = \rho_g U_o^2 d_o / \sigma$$

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

Modeling of Spray Angle





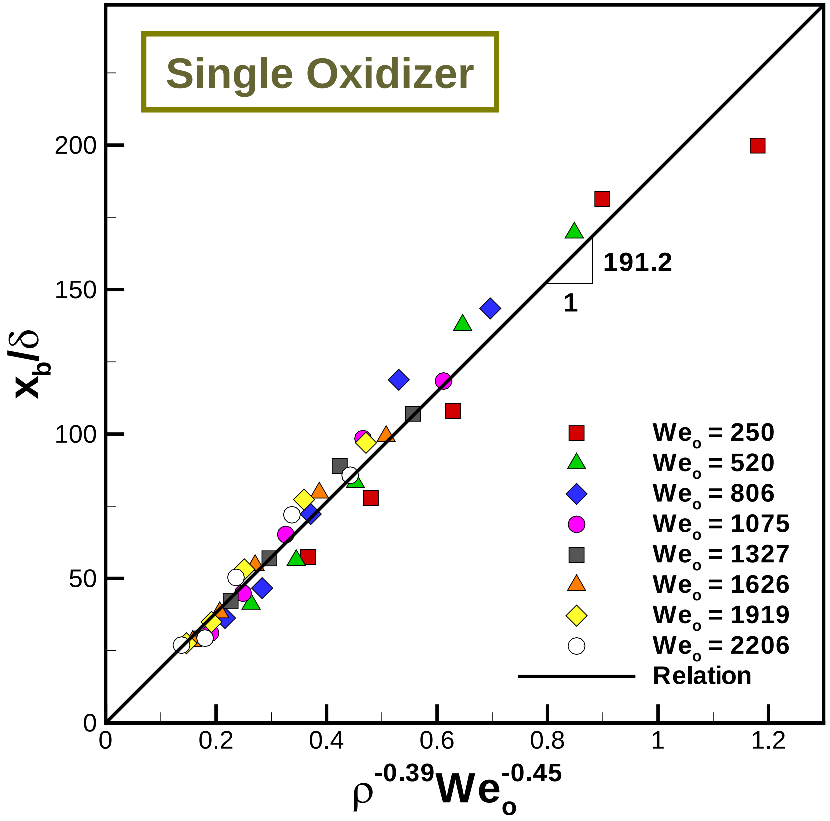
De Corso and Kemeny [1957]

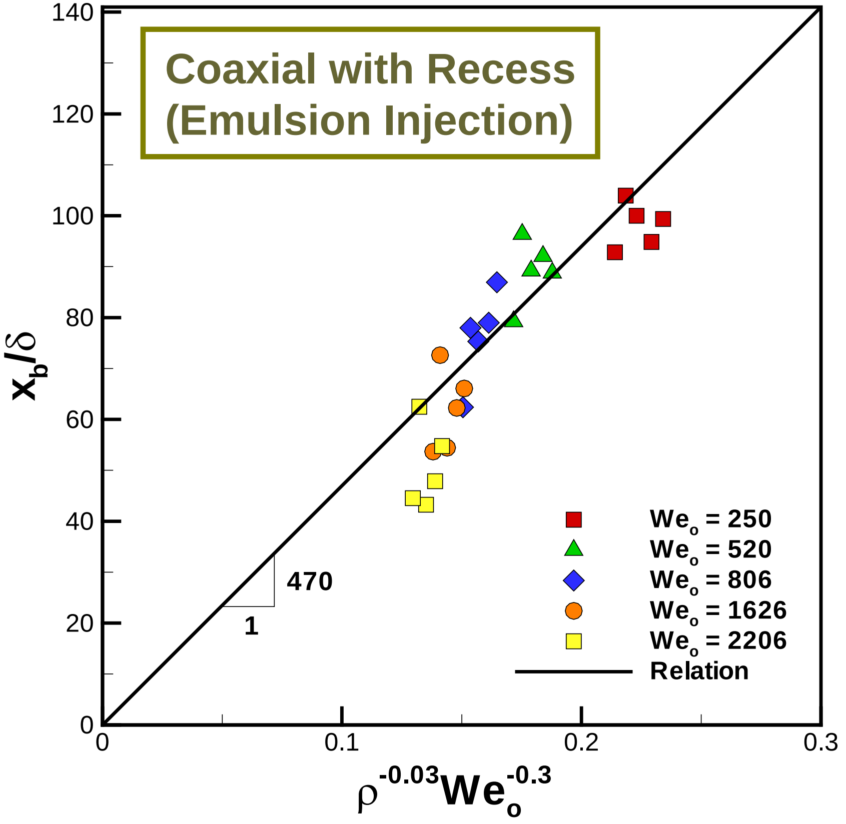
$$\theta \sim P_a^{-1.6}$$

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

Spray Modeling (2/2)

Modeling of Breakup Length



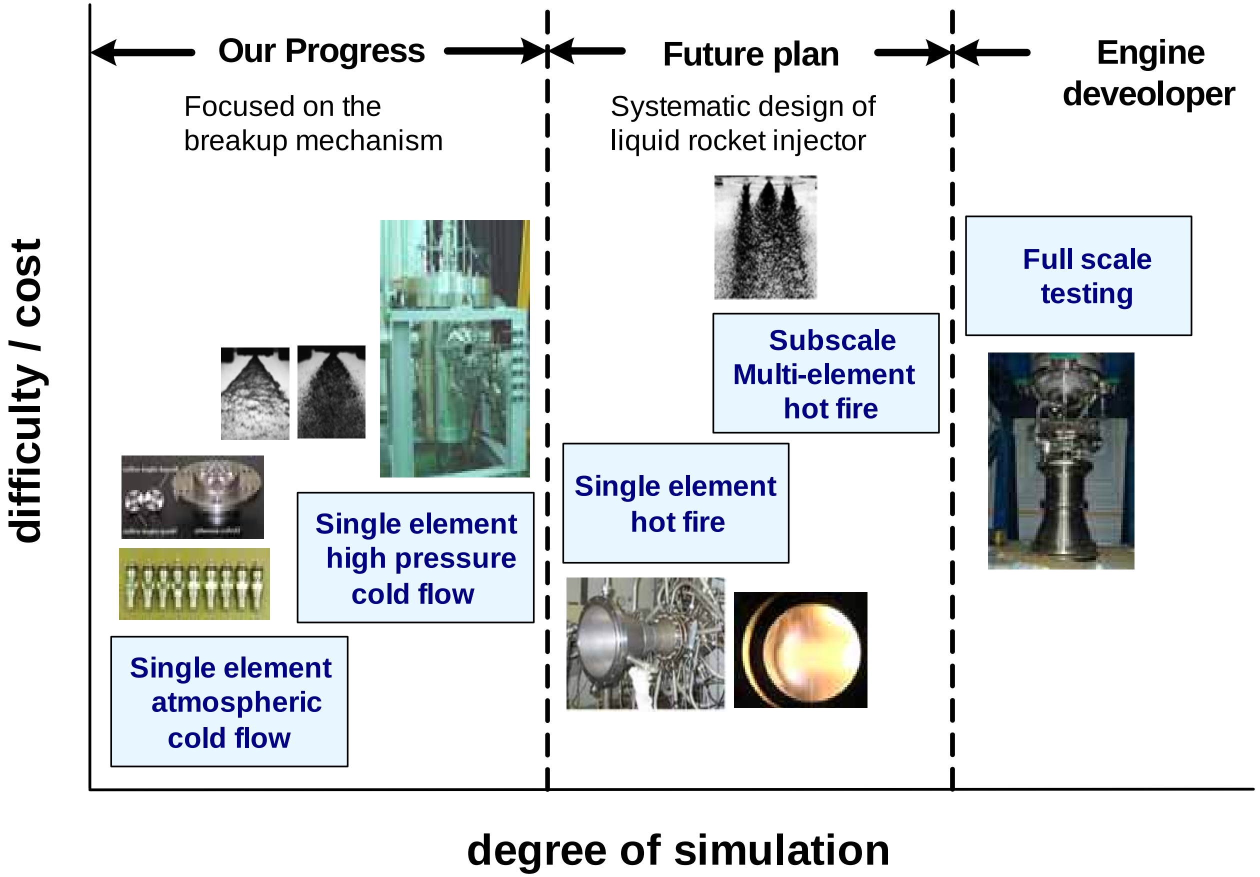


- The effect of ambient density on the breakup length of coaxial spray is very small.

  → 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



Our Progress

Focused on the breakup mechanism

Future plan

Systematic design of liquid rocket injector

Engine deveoloper

Single element atmospheric cold flow

Single element high pressure cold flow

Single element hot fire

Subscale Multi-element hot fire

Full scale testing

difficulty / cost

degree of simulation

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

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

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_o .