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

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Seoul National University, Korea

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<table>
<thead>
<tr>
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<thead>
<tr>
<th>6. AUTHOR(S)</th>
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<tr>
<th>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</th>
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<th>11. SPONSOR/MONITOR’S REPORT NUMBER(S)</th>
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<th>12. DISTRIBUTION/AVAILABILITY STATEMENT</th>
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<th>13. SUPPLEMENTARY NOTES</th>
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</thead>
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<tr>
<th>16. SECURITY CLASSIFICATION OF:</th>
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</tr>
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Standard Form 298 (Rev. 8-98) Prescribed by ANSI Std Z39-18
# Korean Liquid Rockets

<table>
<thead>
<tr>
<th></th>
<th>KSR-III</th>
<th>KSLV-I</th>
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<tbody>
<tr>
<td><strong>Budge</strong></td>
<td>$ 6,800,000</td>
<td>$ 300,000,000</td>
</tr>
<tr>
<td><strong>Target</strong></td>
<td>• Science Observation</td>
<td>• Launch of Small Satellite (100kgf)</td>
</tr>
<tr>
<td></td>
<td>• 1st Liquid Rocket</td>
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<tr>
<td><strong>Injector</strong></td>
<td>Impinging Type</td>
<td>Swirl Coaxial Type</td>
</tr>
<tr>
<td></td>
<td>(Kerosene/LOX)</td>
<td>(Kerosene/LOX)</td>
</tr>
<tr>
<td><strong>System</strong></td>
<td>Non-staged</td>
<td>2 stage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1st: liquid, 2nd: solid)</td>
</tr>
<tr>
<td><strong>Supply</strong></td>
<td>Pressure Type</td>
<td>Tubopump</td>
</tr>
<tr>
<td><strong>Cooling</strong></td>
<td>Ablative Cooling</td>
<td>Regenerative Cooling</td>
</tr>
<tr>
<td><strong>Engine Development</strong></td>
<td>Independent Development</td>
<td>Co-development with Russia</td>
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</table>

**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           |

KSR-III
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

\[
\rho = \frac{\rho_g}{\rho_l}, \quad We_j = \frac{\rho_l U_j^2 d_o}{\sigma}
\]

**Ryan et al. [1995]**

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

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

Ambient gas, density \( \rho_g \)

Liquid sheet, density \( \rho_l \)

Surface tension, \( \sigma \)

Ambient gas, density \( \rho_g \)

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

\[
d_D \propto \rho^{-1/6} We_j^{-1/3}
\]
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.

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Strakey & Talley (2000)

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D. Kendrick et al.
(ONERA, FRANCE, 1999)
### High Pressure Chamber

**Traversing device**

**Quartz window**

**Air-curtain system**

**Drain**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Present</th>
<th>AFRL (USA)</th>
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<tr>
<td>Chamber Diameter</td>
<td>500mm</td>
<td>500mm</td>
</tr>
<tr>
<td>Window Size</td>
<td>80mm×4</td>
<td>50mm×3</td>
</tr>
<tr>
<td>Window Material</td>
<td>quartz</td>
<td>sapphire</td>
</tr>
<tr>
<td>Max. Pressure</td>
<td>6MPa</td>
<td>about 10MPa</td>
</tr>
<tr>
<td>Spray Simulant</td>
<td>water</td>
<td>water</td>
</tr>
<tr>
<td>Pressurizing Gas</td>
<td>nitrogen</td>
<td>nitrogen</td>
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</tbody>
</table>
Like-Doublet Injector Design

- Fuel IN
- 1mm Mesh
- Sub-chamber
- Sharp edged orifice: \(d_o = 0.07\text{cm}\), \(L = 1.4\text{cm}\)
- Round edged orifice: \(d_o = 0.07\text{cm}\), \(R = 0.07\text{cm}\), \(L = 1.4\text{cm}\)

Turbulent Sheet

Laminar Sheet

- Orifice assembly
- Sharp edged orifice

Seoul National University Rocket Propulsion Lab.
Laminar Sheet Breakup (1/3)

Changes of Sheet Shapes

Increasing injection velocity, $U_j$

Increasing ambient gas pressure, $P_c$
Laminar Sheet Breakup (2/3)

Sheet Breakup Length

\[ \frac{x_b}{d_o} \sim \text{We}_j^{0.29} \]

\[ \text{We}_g = \rho g \frac{U_j^2 d_o}{\sigma} \]

- When \( \text{We}_g < 1 \), laminar sheets expand as increasing mass flow rate and aerodynamic force does not affect the sheet breakup.

- When \( \text{We}_g > 1 \), laminar sheets are broken by aerodynamic force.
Laminar Sheet Breakup (3/3)

Breakup Length Modeling

- Huang [1970]:
  \[ \frac{x_b}{d_o} = 7.1 \rho^{-2/3} We_j^{-1/3} \]

- Ryan et al. [1995]:
  \[ \frac{x_b}{d_o} = 10.4 \rho^{-2/3} We_j^{-1/3} \]

- Present:
  \[ \frac{x_b}{d_o} = 9.4 \rho^{-2/3} We_j^{-1/3} \]
Turbulent Sheet Breakup (1/4)

Changes of Sheet Shapes

Increasing injection velocity, $U_j$

Increasing ambient gas pressure, $P_c$
(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 $\lambda_b$ cannot be discriminated.
Turbulent Sheet Breakup (3/4)

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 $2 < \text{We}_g < 100$, 
  \[ x_b/d_o = 0.59 \rho^{-4.63} \text{We}_j^{-0.41} \text{We}_j^{0.31} \]

- 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, $P_c$

Seoul National University Rocket Propulsion Lab.
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

Overall procedure of image processing method

Intermediate images

<table>
<thead>
<tr>
<th>Drop sizes (µm)</th>
<th>131.3</th>
<th>167.2</th>
<th>153.4</th>
<th>224.8</th>
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</table>
Drop Size & Distribution

**Ryan et al. [1995]**

\[
\frac{d_D}{d_o} = 1.25 \rho^{-1/6} We^{-1/3}
\]

**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

- Inner oxidizer injector (recess 8 cases)
- Outer fuel injector

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**
- **Spray patterns with recess number**

![Diagram showing spray patterns with recess number](image)

**Equation:**

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

- \(\theta_{in}\): inner spray angle
- \(R_o\): outer injector radius
- \(R_i\): inner injector radius
- \(L_R\): recess length

---

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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, $\eta_0$, of the ripple in the recess.

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

Clark and Dombrowski [1972] – Breakup Length

$$x_b^{2/3} = \left[ \frac{9 \rho L K U^2}{32 (\rho_a U^2 k - \sigma k^2)} \right]^{1/2} \cosh^{-1} \left[ 8 (\eta_0 k)^{-2} + 1 \right] \sim (\ln \eta_0)$$
Effect of Recess (3/5)

Spray Angle & Breakup Length

![Diagram with graphs]

- In large recess region (emulsion injection)
  \[
  \eta_0 = \eta_i \exp(ikx)
  \]
  \[
  k = k_r + ik_i
  \]
  \[
  \ln(\frac{\eta_0}{\eta_i}) = k(L_R - L_C)
  \]

- \( \eta_0 \): wave amplitude at the injector tip
- \( \eta_i \): wave amplitude just after impinging
Effect of Recess (4/5)

Atomization Characteristics

![Graph showing mean drop size and SMD vs. Recess Number](graph.png)

The mean drop size increases with recess increased due to:

(i) the increase of effective film thickness and
(ii) the decrease of spray angle.

Area and velocity weighted SMD

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

ODIM Injection

Emulsion Injection

\[\sim RN^{0.22}\]
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)

- The spray cone angle increases as $W_{eo}$ or mass flow rate increases.
- The spray cone angle decreases as ambient chamber pressure increases.

\[ W_{eg} = \rho_g U_o^2 d_o / \sigma \]

$U_o$ : oxidizer axial velocity
$d_o$ : oxidizer injector diameter
$W_{eo}$ : oxidizer Weber number
The breakup length decreases as ambient density or Weo increases.
In spite of $We_g<1$, the breakup length decreases as ambient density or Weo 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**
Coaxial Spray (2/3)

Spray Angle (Coaxial Spray)

\[
\sigma = \frac{\rho}{2} \sin^2 \theta
\]

\[
W_{e_g} = \rho \left( \frac{U_o^2 d_o}{\sigma} \right)
\]

- The spray cone angle decreases by increasing oxidizer \( W_{e_o} \).
- The effect of ambient density on the spray angle is not significant compared with that of oxidizer \( W_{e_o} \).
Coaxial Spray (3/3)

Breakup Length (Coaxial Spray)

- As the oxidizer $\text{We}_o$ increases,
  - internal impact force increases. $\rightarrow$ strong wave occurs. $\rightarrow x_b$ decreases.

$$\text{We}_g = \rho g \frac{U_o^2 d_o}{\sigma}$$
Spray Modeling (1/2)

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)
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 developer

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)

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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 $\text{We}_o$. 