High-Pressure Combustion Chamber Dynamics

Vigor Yang
The Pennsylvania State University
University Park, Pennsylvania 16802, U.S.A.
*Email: vigor@psu.edu

Presented at
International Symposium on Energy Conversion Fundamentals
Istanbul, Turkey, June 21-25, 2004
1. REPORT DATE  
22 JUN 2004  

2. REPORT TYPE  
N/A  

3. DATES COVERED  
-  

4. TITLE AND SUBTITLE  
High-Pressure Combustion Chamber Dynamics  

5a. CONTRACT NUMBER  

5b. GRANT NUMBER  

5c. PROGRAM ELEMENT NUMBER  

5d. PROJECT NUMBER  

5e. TASK NUMBER  

5f. WORK UNIT NUMBER  

6. AUTHOR(S)  

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)  
The Pennsylvania State University  
University Park, Pennsylvania 16802, U.S.A.  

8. PERFORMING ORGANIZATION REPORT NUMBER  

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)  

10. SPONSOR/MONITOR’S ACRONYM(S)  

11. SPONSOR/MONITOR’S REPORT NUMBER(S)  

12. DISTRIBUTION/AVAILABILITY STATEMENT  
Approved for public release, distribution unlimited  

13. SUPPLEMENTARY NOTES  

14. ABSTRACT  

15. SUBJECT TERMS  

16. SECURITY CLASSIFICATION OF:  

a. REPORT  

classified  

b. ABSTRACT  

classified  

c. THIS PAGE  

classified  

17. LIMITATION OF ABSTRACT  
UU  

18. NUMBER OF PAGES  
51  

19. NAME OF RESPONSIBLE PERSON  

Standard Form 298 (Rev. 8-98)  
Prescribed by ANSI Z39-18
Why Supercritical Combustion Research?

- most booster engines operate at supercritical conditions
- current understanding not sufficient to support design optimization
Liquid Rocket Chamber Conditions

Critical Properties of Propellants

<table>
<thead>
<tr>
<th>Propellant</th>
<th>( P_{cr} ) (MPa)</th>
<th>( T_{cr} ) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{H}_2 )</td>
<td>1.3</td>
<td>33.3</td>
</tr>
<tr>
<td>Oxygen</td>
<td>5.04</td>
<td>154.4</td>
</tr>
<tr>
<td>RP-1</td>
<td>2.344</td>
<td>685.95</td>
</tr>
</tbody>
</table>

F-1 Engine (Saturn V)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( T ) (K)</td>
<td>294.3</td>
<td>89.5</td>
<td>3546</td>
</tr>
<tr>
<td>( P ) (MPa)</td>
<td>7.9</td>
<td>8.8</td>
<td>7.8</td>
</tr>
</tbody>
</table>

Space Shuttle Main Engine

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( T ) (K)</td>
<td>879.0</td>
<td>126.0</td>
<td>3700</td>
</tr>
<tr>
<td>( P ) (MPa)</td>
<td>24.8</td>
<td>33.0</td>
<td>22.58</td>
</tr>
</tbody>
</table>
Flow Diagram of RD-170 Engine

- Energia booster and Zenit first stage, up to 10 flights.
- LOX/kerosene, one main two boost turbopumps
- 806 ton thrust (vacuum), 337 seconds of $I_{sp}$, O/F ratio of 2.63
- Chamber pressure 250 bar, turbine inlet pressure 519 bar and temperature 772 K
Worldwide Efforts on Supercritical Combustion Research (1/2)

- Tamura et al. / NAL (Japan)
- Mayer, Oschwald, Haidn, etc. / DLR (Germany)
- Habiballah, Vingert, Grisch, etc. / ONERA (France)
  Candel et al. / Ecole Central Paris (France)
- Woodward, Pal, Santoro, etc. / Penn State (USA)
  Talley, Chehroudi, etc. / AFRL (USA)
  Blevins, Morris, etc. / NASA Marshall (USA)

\[ T_{\text{LOX}} \sim 100 \text{ K} \]
\[ d_{\text{LOX}} \sim 1 \text{ mm} \]
Worldwide Efforts on Supercritical Combustion Research (2/2)

- Oefelein / DoE Sandia Lab. (USA)
- Bellan / NASA JPL (USA)
- Farmer / U. of Nevada (USA)
- Habiballah, et al. / ONERA (France)
- Yang / Penn State (USA)
Shadowgraph Results – LN2 into GN2
Chehroudi et. al., AIAA 99-0206, AIAA 99-2489

\[ p_{cr} = 3.39 \text{ MPa}, \quad T_{cr} = 126 \text{ K}, \quad T_{\infty} = 300 \text{ K}, \quad T_{in} = 99 \sim 120 \text{ K} \]
\[ u_{in} = 10 \sim 15 \text{ m/s}, \quad D_{in} = 0.254 \text{ mm}, \quad Re = 25,000 \sim 75,000 \]
Characteristics of Supercritical Fluid Jet

- Thermodynamic non-idealities and transport anomalies in transcritical regime
  - rapid property variations
  - large density gradient
- Diminishment of surface tension and enthalpy of vaporization
- Pressure-dependent solubility
- High Reynolds number

Mayer et al.
AIAA 1996-2620
TLN2 = 105 K
TGN2 = 300 K
uLN2 = 10 m/s
D_in = 1.9 mm
**Effect of Pressure on Turbulence Scales**

- Pressure increases from 1 to $10^2$ atm, $Re_t$ increases by $10^2$
- Kolmogorov microscale $\eta_t/l_t \sim Re_t^{-3/4}$ (decrease by 1.5 order)
- Taylor microscale $\lambda_t/l_t \sim Re_t^{-1/2}$ (decrease by 1.0 order)
LES Formulation of Supercritical Fluid Dynamics

\[ \frac{\partial \bar{\rho}}{\partial t} + \frac{\partial (\bar{\rho} \bar{u}_j)}{\partial x_j} = 0 \]

\[ \frac{\partial (\bar{\rho} \bar{u}_j)}{\partial t} + \frac{\partial (\bar{\rho} \bar{u}_i \bar{u}_j + \bar{p} \delta_{ij} - \bar{T}_{ij})}{\partial x_j} = - \frac{\partial (R_{ij} + L_{ij} + C_{ij})}{\partial x_j} \]

\[ \frac{\partial (\bar{\rho} \bar{E} + q)}{\partial t} + \frac{\partial [(\bar{\rho} \bar{E} + \bar{P}) \bar{u}_j - \bar{u}_i \bar{T}_{ij}]}{\partial x_j} = - \frac{\partial (K_j + Q_j + q_j)}{\partial x_j} \]

- Favorable-filtered conservation equations
- Thermodynamic and transport properties \( Z, C_p, \mu, \lambda, D_{im} \)
- Subgrid-scale turbulence interaction \( R, L, C \)
- Chemical kinetics \( \bar{\omega}_i \)
- Closure requirements
Equations of State

- Soave-Redlich-Kwong (SRK)
  \[ p = \frac{RT}{v-b} - \frac{a}{v(v+b)} \]

- Peng-Rubinson (PR)
  \[ p = \frac{RT}{v-b} - \frac{a}{v(v+b)+b(v-b)} \]

- Benedict-Webb-Rubin (BWR)
  \[ p = \sum_{n=1}^{9} a_n \rho^n + \sum_{n=10}^{15} a_n \rho^{2n-17} e^{-\gamma \rho^2} \]
Evaluation of Thermodynamic Properties

- Sensible enthalpy: \[ h(\rho, T) = h^0(T) + \Delta h_{\text{exc}}(\rho, T) \]
- Internal energy: \[ u(\rho, T) = u^0(T) + \Delta u_{\text{exc}}(\rho, T) \]
- Specific heat \[ C_p(\rho, T) = C_p^0(T) + \Delta C_{p,\text{exc}}(\rho, T) \]

\[ \Delta h_{\text{exc}}, \Delta u_{\text{exc}}, \Delta C_{p,\text{exc}} = \text{dense fluid corrections} \]
\[ h^0(T), u^0(T), C_p^0(T), = \text{values in dilute-gas limit} \]

Pressure-explicit type of EOS:

\[ \Delta h_{\text{exc}} = \int_0^\rho \left[ \frac{p}{\rho^2} - \frac{T}{\rho^2} \left( \frac{\partial p}{\partial T} \right)_\rho \right] d\rho + RT(Z - 1) \]

\[ \Delta u_{\text{exc}} = \int_0^\rho \left[ \frac{p}{\rho^2} - \frac{T}{\rho^2} \left( \frac{\partial p}{\partial T} \right)_\rho \right] d\rho \]

\[ \Delta C_{p,\text{exc}} = -T \int_0^\rho \left[ \frac{1}{\rho^2} \left( \frac{\partial^2 p}{\partial T^2} \right)_\rho d\rho + \frac{T(\partial p / \partial T)^2}{\rho^2(\partial p / \partial \rho)_T} \right] - R \]
Thermophysical Properties of Nitrogen

- compressibility factor
- specific heat
- dynamic viscosity
- thermal conductivity

Graphs showing variations of compressibility factor, specific heat, dynamic viscosity, and thermal conductivity with temperature for different pressures.
### Droplet Vaporization and Combustion in Quiescent and Convective Environments

- **Liquid oxygen (LOX) droplet vaporization & combustion in hydrogen and water**
  - $5 < p_\infty < 300$ atm
  - $500 < T_\infty < 2500$ K
  - $50 < D_0 < 300$ µm

- **Hydrocarbon droplet vaporization & combustion in air and oxygen**
  - $5 < p_\infty < 200$ atm
  - $300 < T_\infty < 2500$ K
  - $100 < D_0 < 1000$ µm

- **Unsymmetrical dimethylhydrazine (UDMH) droplet vaporization and decomposition combustion**
  - $1 < p_\infty < 180$ atm
Spherical Mode (100 atm, 0.2 m/s; t=610 µs)
Breakup Mode (100 atm, 15 m/s; t=170 µs)
$P_\infty = 100$ atm, $T_\infty = 1000$ K, $u_\infty = 20$ m/s, $T_0 = 100$ K, $d_0 = 50$ µm, $H/R = 8$

**Flow and Temperature Fields**

### t=8 µs

![Graph showing flow and temperature fields at t=8 µs.](image)

### t=40 µs

![Graph showing flow and temperature fields at t=40 µs.](image)

### t=90 µs

![Graph showing flow and temperature fields at t=90 µs.](image)

### t=110 µs

![Graph showing flow and temperature fields at t=110 µs.](image)
Effect of Pressure and Velocity on Droplet Lifetime

- **atmospherical condition**
  - Ranz and Marshall’s correlation
    \[
    \frac{\tau_f}{\tau_{f, Re=0}} \propto \frac{h_{Re=0}}{h} = \frac{1}{1 + 0.3 \text{Re}^{1/2} \text{Pr}^{1/3}}
    \]
- **supercritical condition**
  - LOX/hydrogen system
    \[
    \frac{\tau_f}{\tau_{f, Re=0}} \propto \frac{h_{Re=0}}{h} = \frac{1}{1 + 0.15634 \text{Re}^{1.1} \text{Pr}_{O_2}^{-0.88}}
    \]

- **effect of ambient pressure on**
  - thermophysical properties
  - critical mixing state
  - convective heat transfer

- **effect of ambient velocity on**
  - convective heat transfer
Supercritical Fluid Injection

\[ p_{\infty} = 3.4 - 10.0 \text{ MPa}, \ T_{\infty} = 300 \text{ K}, \ T_{\text{in}} = 120 \text{ K}, \ D_{\text{in}} = 0.254 \text{ mm}, \ u_{\text{in}} = 15 \text{ m/s}, \ Re = 20000 - 40000 \]

\[ p_{\text{ch}} = 4.0 \text{ MPa}, \ T_{\text{LN2}} = 105 \text{ K}, \ T_{\text{GN2}} = 300 \text{ K}, \ u_{\text{LN2}} = 10 \text{ m/s}, \ D_{\text{in}} = 1.9 \text{ mm} \]
(p_∞ = 6.0 MPa, T_∞ = 300 K, u_in = 4.9 m/s, T_in = 132 K, D_in = 2.2 mm)
Computational Domain and Grids

- Kolmogorov microscale $\eta_t/l_t \sim Re_t^{-3/4}$
- Taylor microscale $\lambda_t/l_t \sim Re_t^{-1/2}$
- $3.4 \leq p_{ch} \leq 10.0 \text{ MPa}$ and $D_{in} = 0.254 \text{ mm}$
- $3 < \lambda_t < 5 \mu\text{m}$

Total grids $225 \times 75 \times 72 = 1,215,000$
Mean grid spacing in near injector region
$\Delta = 5 \mu\text{m}$
Density Gradient Field

\( p_\infty = 9.3 \text{ MPa}, T_\infty = 300 \text{ K}, u_\text{in} = 15 \text{ m/s}, T_\text{in} = 120 \text{ K}, D_\text{in} = 254 \mu\text{m} \)
Time Evolution of Density Gradient Field

\( (p_\infty = 6.9 \text{ MPa, } T_\infty = 300 \text{ K, } u_\text{in} = 15 \text{ m/s, } T_\text{in} = 120 \text{ K, } D_\text{in} = 254 \text{ µm}) \)

\( t = 0.000 \text{ ms} \)
Snapshots of Density and Temperature Gradient Fields

\( p_\infty = 9.3 \text{MPa}, \quad T_\infty = 300 \text{K}, \quad u_\text{in} = 15 \text{m/s}, \quad T_\text{in} = 120 \text{K}, \quad t = 1.550 \text{ms}, \quad D_\text{in} = 254 \mu\text{m} \)
(p_\infty^\infty = 9.3 \text{ MPa}, T_\infty^\infty = 300 \text{ K}, u_{\text{in}}^\infty = 15 \text{ m/s}, T_{\text{in}}^\infty = 120 \text{ K}, D_{\text{in}}^\infty = 254 \text{ \(\mu\text{m}\)})
Iso-Surfaces of Pressure and Density Gradients

\((p_\infty = 9.3 \text{ MPa}, T_\infty = 300 \text{ K}, u_{in} = 15 \text{ m/s}, T_{in} = 120 \text{ K}, D_{in} = 254 \mu m)\)
Effect of Pressure on Density and Temperature Fields

\( T_\infty = 300\text{K}, \ u_\text{in} = 15\text{m/s}, \ T_\text{in} = 120\text{K}, \ D_\text{in} = 254\mu\text{m} \)
Power Spectral Densities of Velocity Fluctuations

\[ (p_\infty = 9.3\text{MPa}, T_\infty = 300\text{K}, u_{in} = 15\text{m/s}, T_{in} = 120\text{K}, D_{in} = 254\mu m) \]

Large density-gradient regions act like a solid wall that amplifies the axial turbulent fluctuation but damps the radial one.
Vortex Shedding Frequency

$$(p_\infty = 9.3\text{MPa}, T_\infty = 300\text{K}, u_\text{in} = 15\text{m/s}, T_\text{in} = 120\text{K}, D_\text{in} = 254\mu\text{m})$$

Jet flow instability analysis

$$St_j = f_j\theta_0 / \bar{U}$$

where $0.044 \leq St_j \leq 0.048$

$$\bar{U} = 15\text{ m/s}$$

Momentum thickness

$$\theta_0 = 0.02\text{ mm}$$

$$\theta_0 = \int_0^\infty \frac{u}{U_{\text{max}}}(1 - \frac{u}{U_{\text{max}}})dy$$

choose

$$St_j = 0.046$$

then

$$f_1 = 34500$$

$$f_2 = 17250$$
Linear Stability Analysis of Real Fluid Jet

**Approach**

- Two-dimensional fluid jet instability at supercritical conditions.
- Unified treatment of real-fluid thermodynamics and transport phenomena.
- Disperse equation solved by Newton-Ralphson method.

**Conclusions**

- As the density ratio increases, the spatial growth rate of the interfacial instability wave decreases. Density stratification tends to stabilize the mixing layer.
- Density stratification has little effect on the frequency of the most unstable mode.
# Bi-Propellant Swirl Co-Axial Injector

<table>
<thead>
<tr>
<th>Component</th>
<th>Geometrical Characteristics</th>
<th>Spray cone angle</th>
<th>Pressure drop</th>
<th>Flow rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxidizer</td>
<td>2</td>
<td>80</td>
<td>0.426</td>
<td>172.9</td>
</tr>
<tr>
<td>Fuel</td>
<td>24.5</td>
<td>135</td>
<td>0.696</td>
<td>64.8</td>
</tr>
<tr>
<td>Oxidizer</td>
<td>-</td>
<td>-</td>
<td>0.426</td>
<td>172.3</td>
</tr>
<tr>
<td>Fuel</td>
<td>-</td>
<td>-</td>
<td>0.696</td>
<td>64.8</td>
</tr>
</tbody>
</table>
Large Eddy Simulation of Swirling Oxygen Jet

**Issues**

- Swirling jet dynamics at supercritical conditions.
- Flame stabilization mechanisms of swirl co-axial injector.
- Liquid rocket thrust chamber dynamics.

**Major Results**

- Liquid film thickness and swirl cone angle.
- Detailed flow structures, including central recirculation zone, surface instability, etc.
- Response of injector dynamics to external forcing.
LOX/Kerosene Preburner Swirl Injector
(Wu, et al., unpublished data, 2003)

- Kerosene
- LOX
- Retractive chamber
- Secondary injection
  - oxidizer-rich preburner injector
  - damaged inner centrifugal injector
Time Evolution of Swirling Jet

\( p_\infty = 10.0 \text{ MPa}, \ T_\infty = 300 \text{ K}, \ u_{\text{inj}} = 30 \text{ m/s}, \ T_{\text{inj}} = 120 \text{ K}, \ \theta = 30^\circ, \ \text{nitrogen} \)
Time Evolution of Swirling Jet

\( p_\infty = 10.0 \text{ MPa}, \ T_\infty = 300 \text{ K}, \ u_{\text{inj}} = 30 \text{ m/s}, \ T_{\text{inj}} = 120 \text{ K}, \ \theta = 30^\circ, \ \text{nitrogen} \)
Disintegration of Swirling Water Jet
(Inamura, Tamura and Sakamoto, JPP, 2003)

Water Injection, L/D=11.67, K=1.0

• A hollow cone sheet forms around the injector exit.
• The conical sheet fluctuates vigorously and disintegrates into ligaments and droplets at the sheet tip.
• The sheet breakup point approaches the injector as the liquid flow rate increases.
Theoretical Analysis of Swirl Injector (1/2)

**Assumptions**

- Liquid flow is planar two dimensional.
- Effects of the surrounding gas and streamwise pressure gradient on the liquid-film behavior are ignored.
- Momentum of the liquid film is conserved at transition from laminar to turbulent.

\[
\frac{d}{dx} \int_0^\delta (U_i u - u^2)dy = \frac{\tau_w}{\rho_l}
\]

where

\[
\tau_w = \rho_l v_l \left( \frac{\partial u}{\partial y} \right)_{y=0}
\]

and

\[
\delta^* = 5.84 \sqrt{x^*/Re}
\]

\[
Q = U_i h_i = \int_0^\delta u dy + U_i (h - \delta)
\]

\[
h^* = 1 + \left( \frac{3}{10} \right) \delta^*
\]
Theoretical Analysis of Swirl Injector (2/2)

\begin{align*}
& x_0 < x < x_t \\
& h^* = \frac{1.429}{1 + A(x^* - x_0^*)} \quad A = 1.682\left(\frac{\nu_l}{Q}\right) \\
& x_t < x \\
& h^* = 0.02798\left(\frac{x^*}{\text{Re}^{1/4}}\right) + C_1 \quad x_0^* = 0.0598\text{Re} \\
& C_1 = 1.429\{1 + A(x_t^* - x_0^*)\} - 0.0279\left(\frac{x_t^*}{\text{Re}^{1/4}}\right) \\
& x_t < x < x_0 \\
& h^* = 0.02798\left(\frac{x^*}{\text{Re}^{1/4}}\right) + C_3 \\
& C_3 = 1.143 - 0.02798\left(\frac{x_0^*}{\text{Re}^{1/4}}\right) \\
& x_0^* = \frac{1.182 - C_2}{0.2893}\text{Re}^{1/4}
\end{align*}
Limiting Extremes: 2) Diffusion Processes Dominate

- "High" Heating Rates
  - diminished intermolecular forces promote diffusion processes prior to atomization
  - injected jet vaporizes forming continuous fluid in presence of exceedingly large interfacial gradients
  - diffusion flame resides within annular post wake separating oxygen jet from outer hydrogen flow

---

DENSE FLUID CORE
GAS POCKETS
FLAME FRONT

H₂
O₂
H₂

RECIRCULATION ZONES
Burning LOX Jet at Supercritical Pressure

(Mayer, DLR, Germany; Tamura, NAL, Japan)

\[ u_{\text{LOX}} = 30 \text{ m/s}, u_{\text{H}_2} = 300 \text{ m/s}, T_{\text{LOX}} = 100 \text{ K}, T_{\text{H}_2} = 300 \text{ K}, p = 6 \text{ MPa} \]
Combined OH emission and backlighting images (Ph.D thesis of Matthew Juniper)
Modeling and Simulation of Supercritical Combustion

droplet → spray → injector element → full-scale engine
Thank You!
Effect of Pressure on Mean Temperature Distributions

\( (T_\infty = 300 \text{ K}, u_{in} = 15 \text{ m/s}, T_{in} = 120 \text{ K}, D_{in} = 254 \mu\text{m}) \)

For \( p_\infty = 9.3 \text{ MPa} \):

\[
\begin{array}{c}
\text{T (K)} \\
300 \quad 270 \quad 240 \quad 210 \quad 180 \quad 150 \quad 120
\end{array}
\]

For \( p_\infty = 6.9 \text{ MPa} \):

\[
\begin{array}{c}
\text{T (K)} \\
300 \quad 270 \quad 240 \quad 210 \quad 180 \quad 150 \quad 120
\end{array}
\]
Effect of Pressure on Mean Velocity Distributions

\( T_\infty = 300 \text{ K}, \ u_\text{in} = 15 \text{ m/s}, \ T_\text{in} = 120 \text{ K}, \ D_\text{in} = 254 \mu\text{m} \)

\( p_\infty = 9.3 \text{ MPa} \)

\( p_\infty = 6.9 \text{ MPa} \)
Frequency Spectral of Radial Velocity Oscillations

$p = 4.2$ MPa

$p = 6.9$ MPa

$p = 9.3$ MPa
Normalized Density and Temperature Distributions along Radial Direction

\[ T_\infty = 300 \text{K}, \ u_{in} = 15 \text{m/s}, \ T_{in} = 120 \text{K}, \ D_{in} = 254 \mu\text{m} \]

- Thermal diffusivity of nitrogen is relatively lower in the region where the temperature is near the critical temperature.
- Most thermal energy transferred from the hot ambient gaseous nitrogen to the cold jet is used to facilitate volume expansion.
Numerical Challenges

**Challenges**
- machine round-off errors at low speeds
- eigenvalue disparity
- time accuracy
- real-fluid behavior
- robust and efficient numerical treatment

**Solutions**
- pressure decomposition
- preconditioning method
- dual time-stepping integration technique
- partial mass/molar properties
- derivation of numerical Jacobians and thermodynamic properties based on fundamental thermodynamic theories
Normalized Density and Temperature Distributions

\[
(p_\infty = 9.3\text{MPa}, T_\infty = 300\text{K}, u_\text{in} = 15\text{m/s}, T_\text{in} = 120\text{K}, D_\text{in} = 254\mu\text{m})
\]

- Due to the “near critical slow down”, the temperature of nitrogen fluid increases slowly along the jet centerline.
- A self-similar density profile exist when \( x/d > 15 \).