



# High-Pressure Combustion Chamber Dynamics

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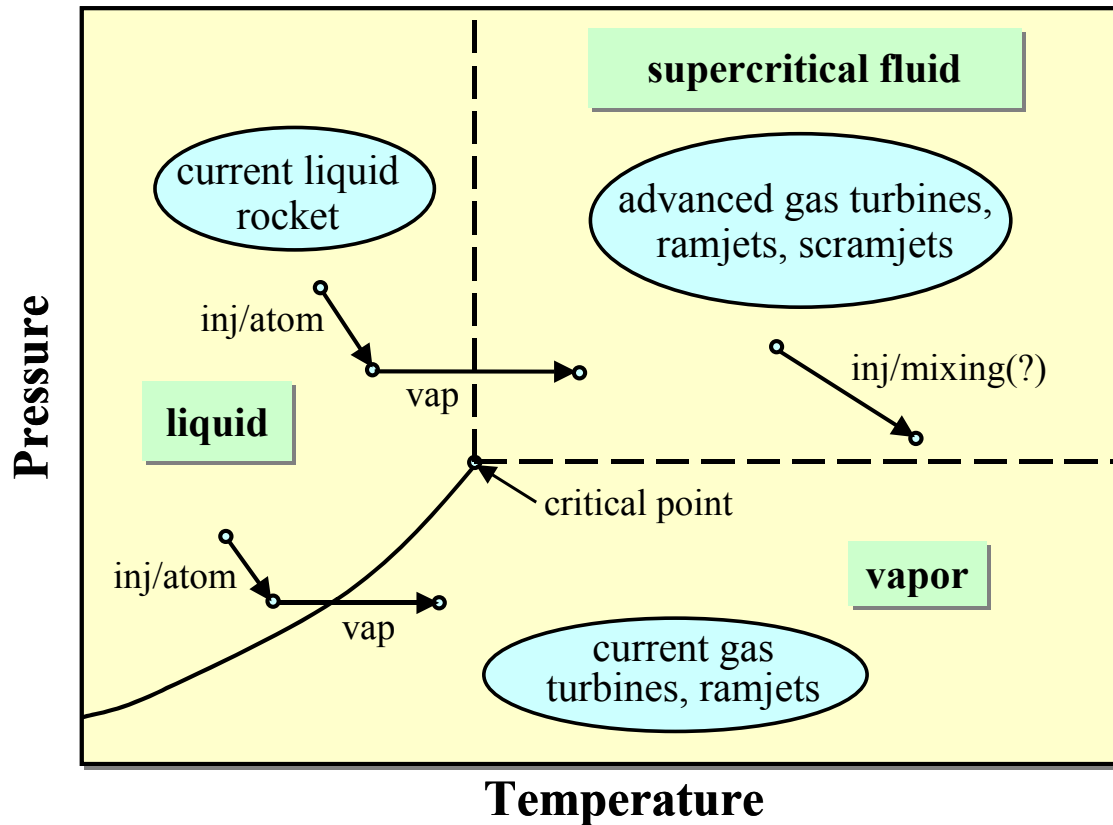
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# Why Supercritical Combustion Research?

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





# Liquid Rocket Chamber Conditions

## Critical Properties of Propellants

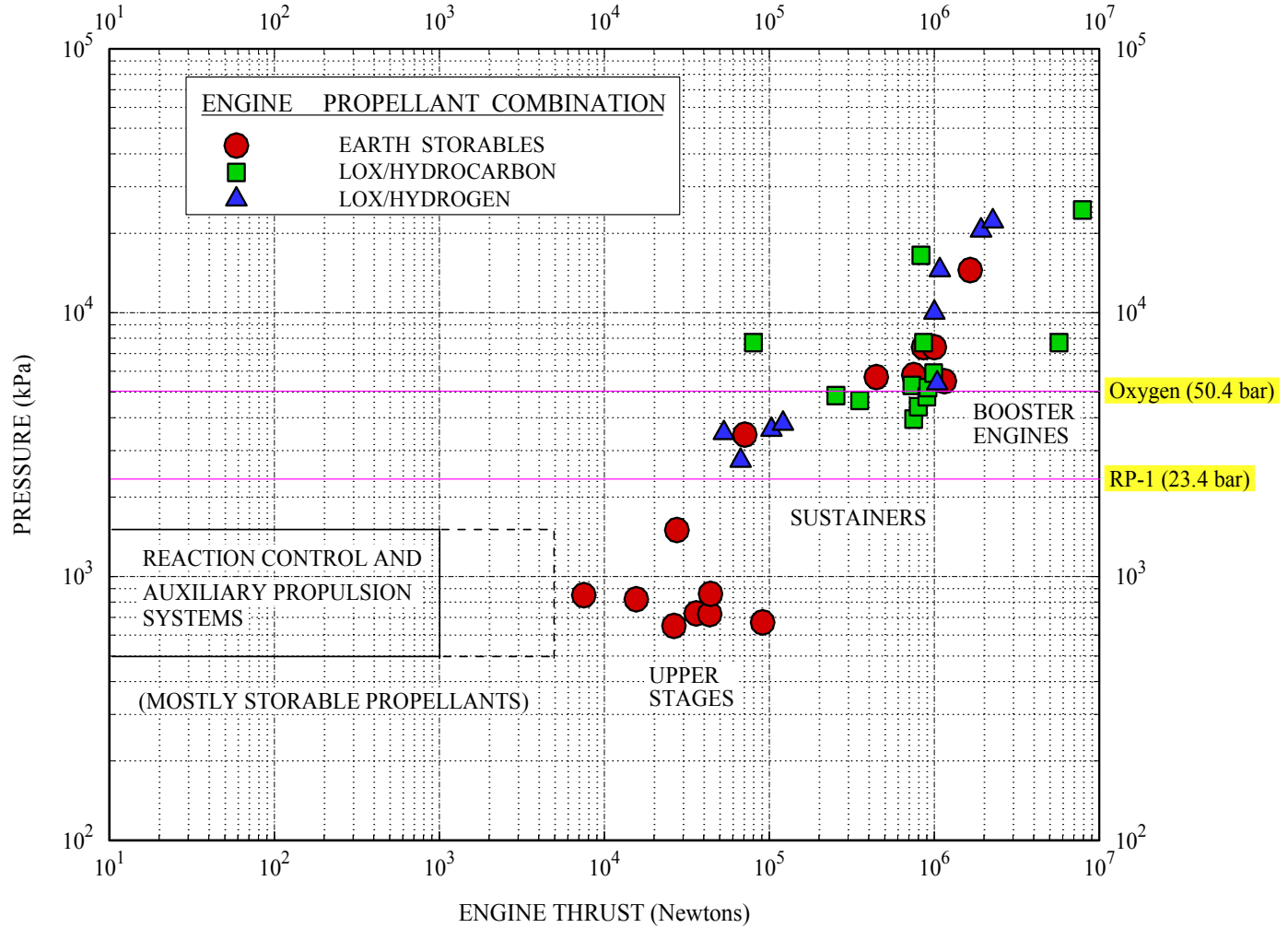
	Pcr (MPa)	Tcr (K)
H <sub>2</sub>	1.3	33.3
Oxygen	5.04	154.4
RP-1	2.344	685.95

## F-1 Engine (Saturn V)

	Fuel Inj.	Oxy Inj.	Cham.
T (K)	294.3	89.5	3546
P (MPa)	7.9	8.8	7.8

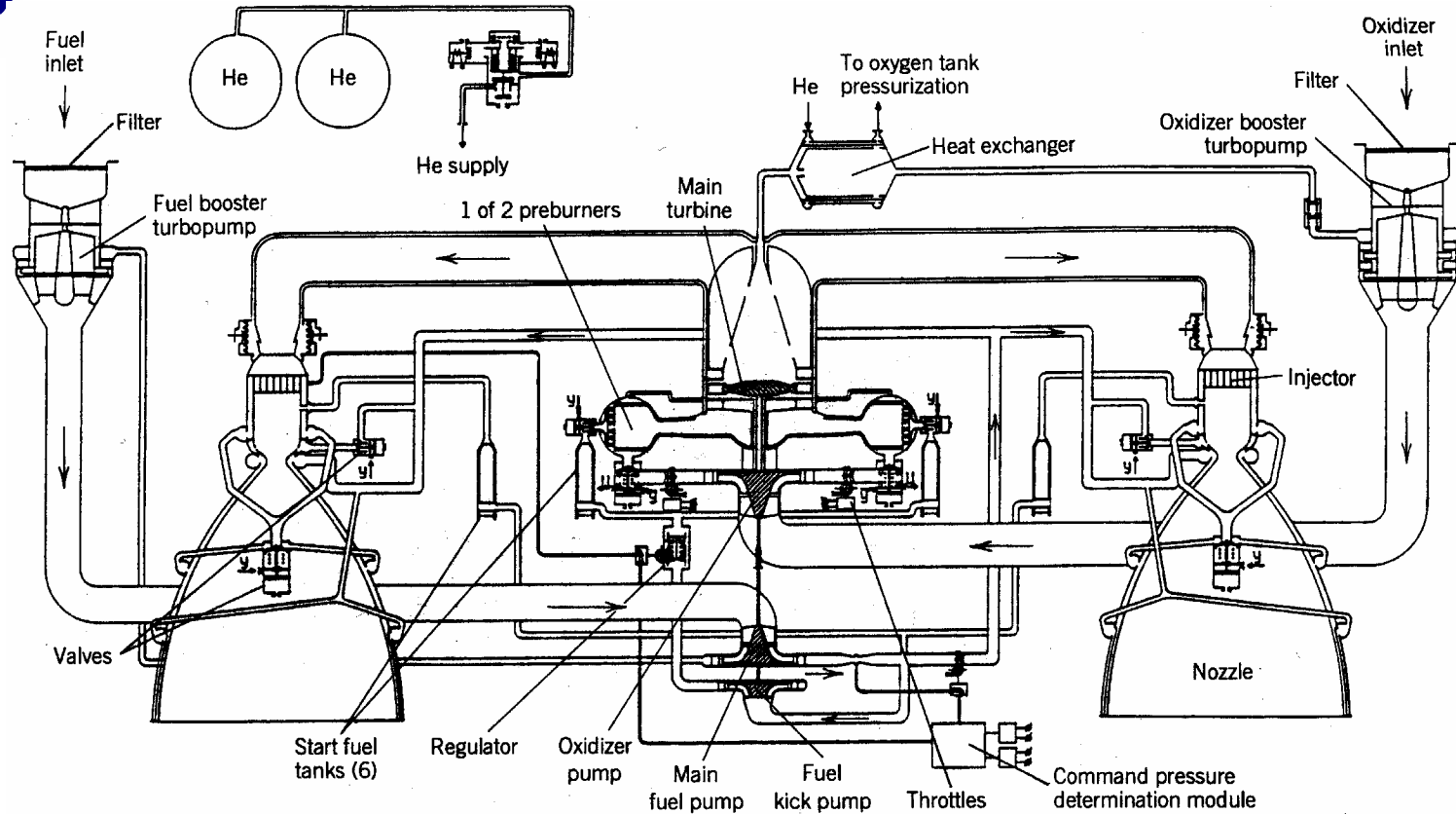
## Space Shuttle Main Engine

	Fuel Inj.	Oxy Inj.	Cham.
T (K)	879.0	126.0	3700
P (MPa)	24.8	33.0	22.58





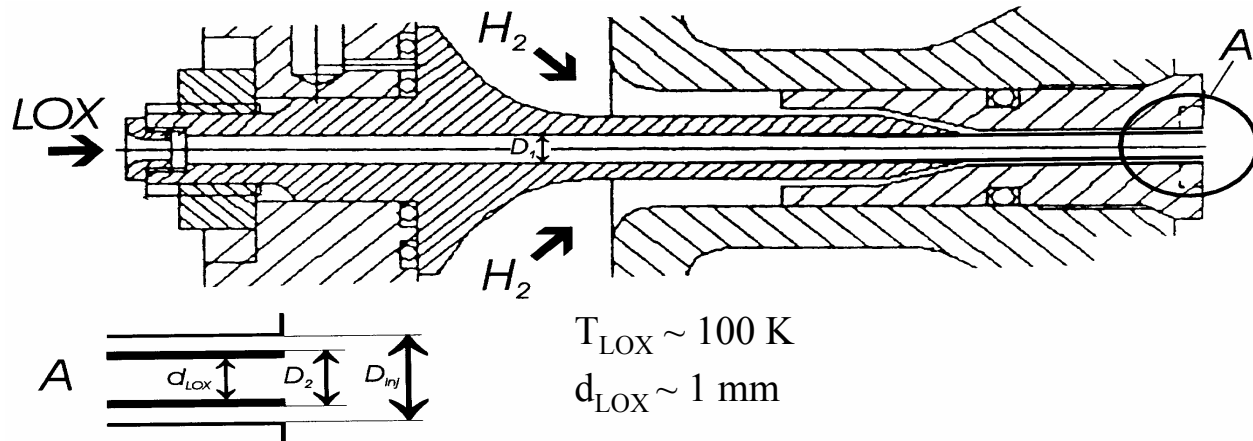
# Flow Diagram of RD-170 Engine

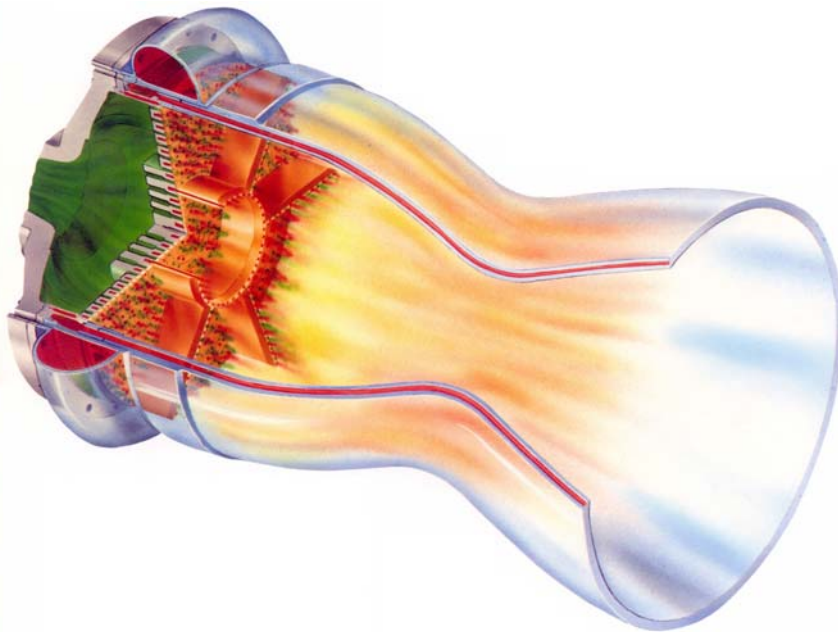
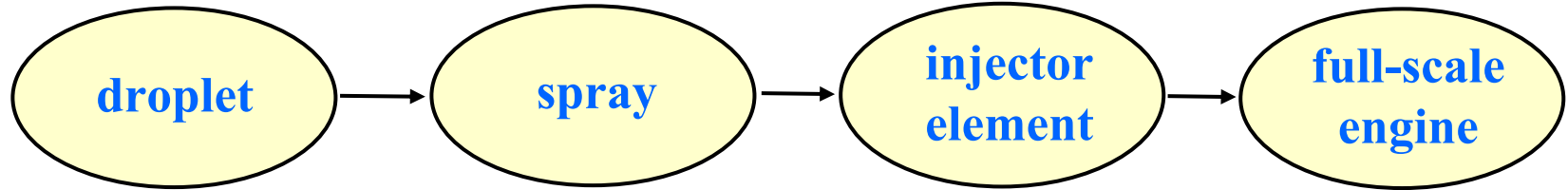


- Energia booster and Zenit first stage, up to 10 flights.
- LOX/kerosene, one main two boost turbopumps
- 806 ton thrust (vacuum), 337 seconds of  $I_{sp}$ , O/F ratio of 2.63
- Chamber pressure 250 bar, turbine inlet pressure 519 bar and temperature 772 K



- 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)

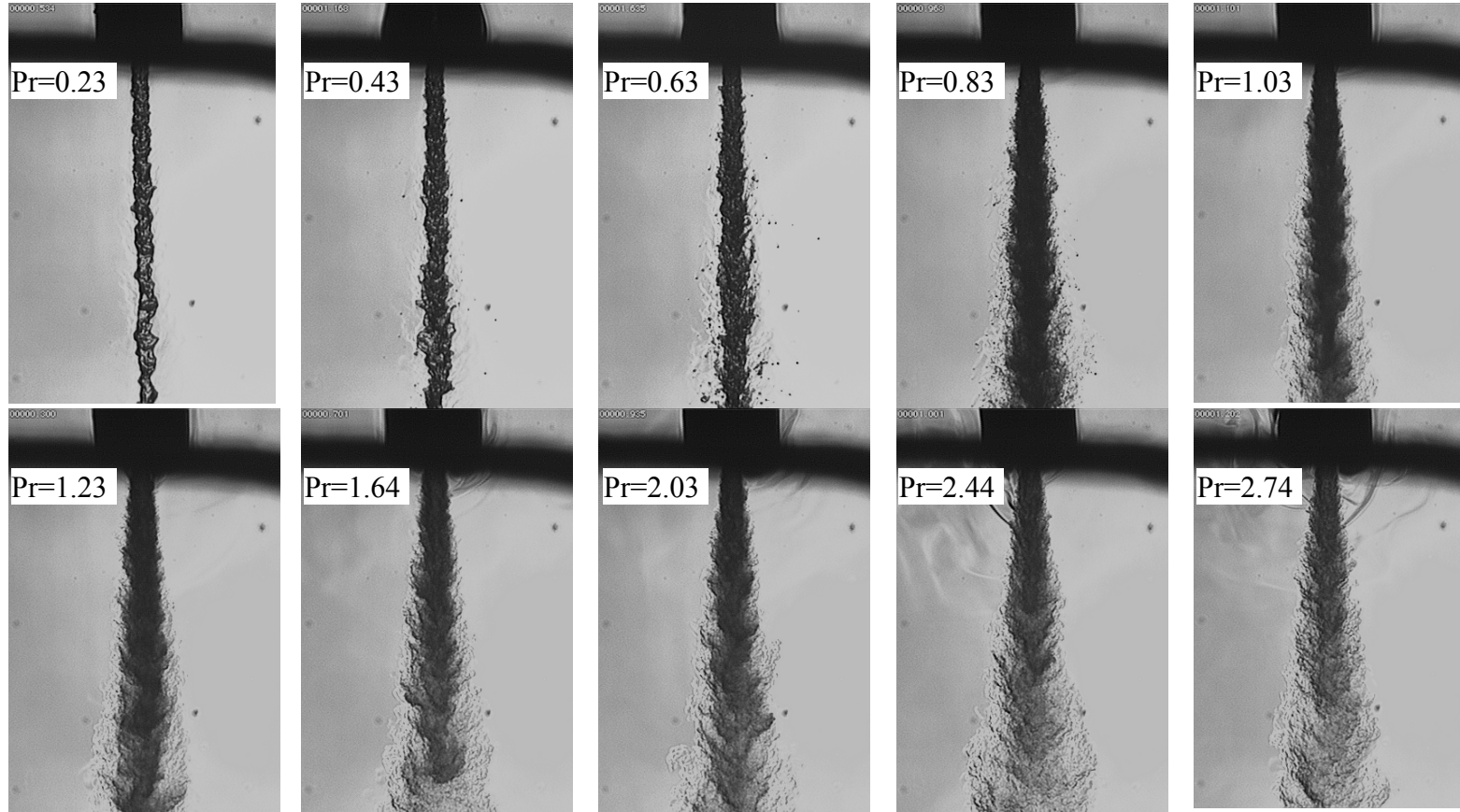




- Oefelein / DoE Sandia Lab. (USA)
- Bellan / NASA JPL (USA)
- Farmer / U. of Nevada (USA)
- Habiballah, et al. / ONERA (France)
- Yang / Penn State (USA)



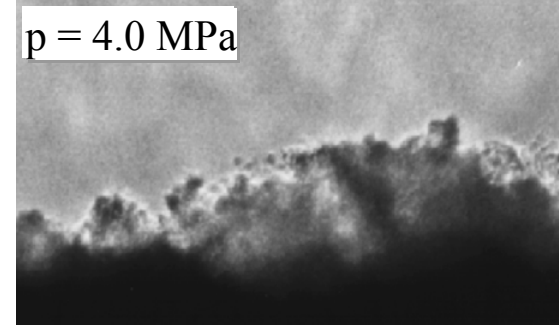
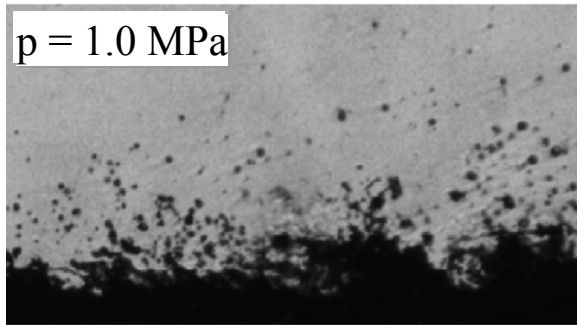
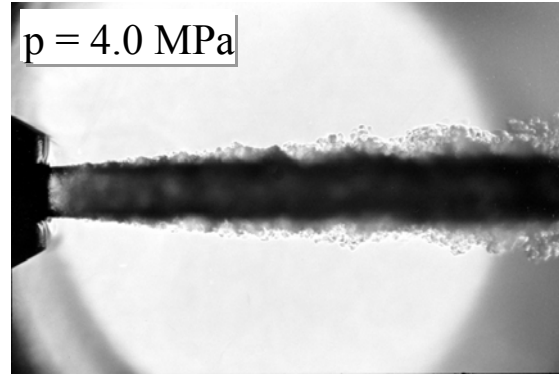
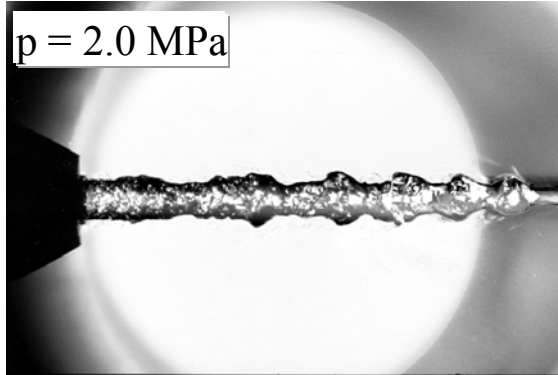
$p_{cr} = 3.39 \text{ MPa}$ ,  $T_{cr} = 126 \text{ K}$ ,  $T_{\infty} = 300 \text{ K}$ ,  $T_{in} = 99 \sim 120 \text{ K}$   
 $u_{in} = 10 \sim 15 \text{ m/s}$ ,  $D_{in} = 0.254 \text{ mm}$ ,  $Re = 25,000 \sim 75,000$







# Characteristics of Supercritical Fluid Jet

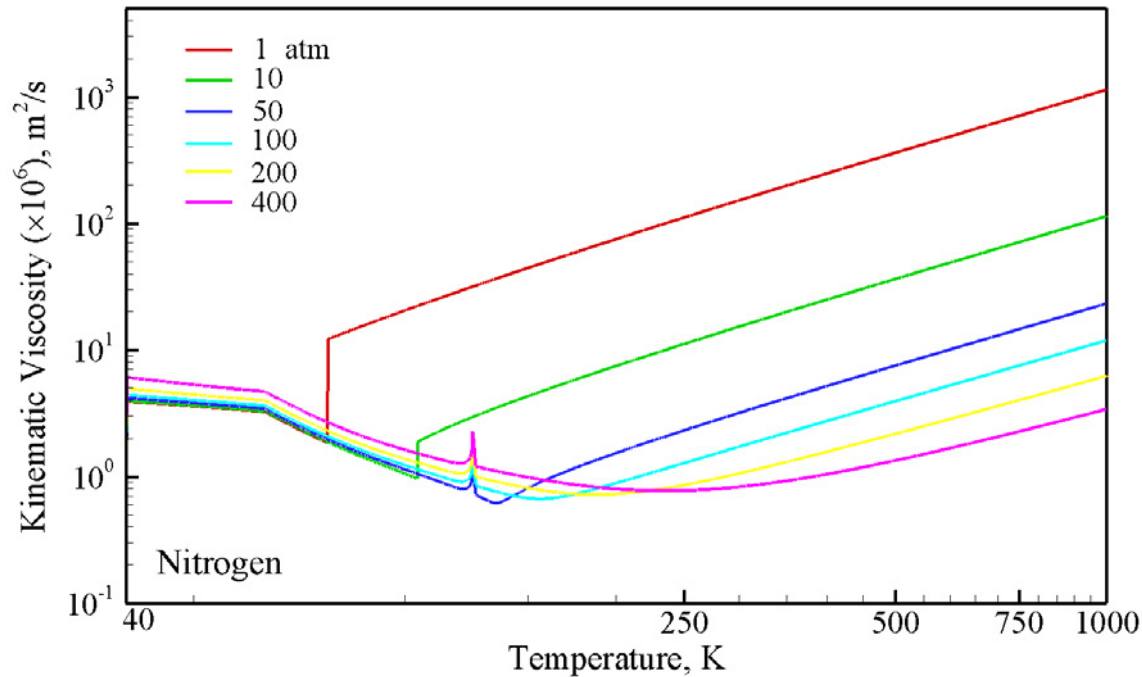


Mayer et al.  
*AIAA 1996-2620*  
 $T_{\text{LN}_2} = 105 \text{ K}$   
 $T_{\text{GN}_2} = 300 \text{ K}$   
 $u_{\text{LN}_2} = 10 \text{ m/s}$   
 $D_{\text{in}} = 1.9 \text{ mm}$

- **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**



# 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)



• Favre-filtered conservation equations

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

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

$$\frac{\partial (\bar{\rho} \tilde{E} + q)}{\partial t} + \frac{\partial [(\bar{\rho} \tilde{E} + \bar{P}) \tilde{u}_j - \overline{u_i \tau_{ij}}]}{\partial x_j} = - \frac{\partial (K_j + Q_j + q_j)}{\partial x_j}$$

• Closure requirements

- Thermodynamic and transport properties  $Z, C_p, \mu, \lambda, D_{im}$
- Subgrid-scale turbulence interaction  $R, L, C$
- Chemical kinetics  $\bar{\dot{\omega}}_i$



# Equations of State

- Soave-Redlich-Kwong (SRK)

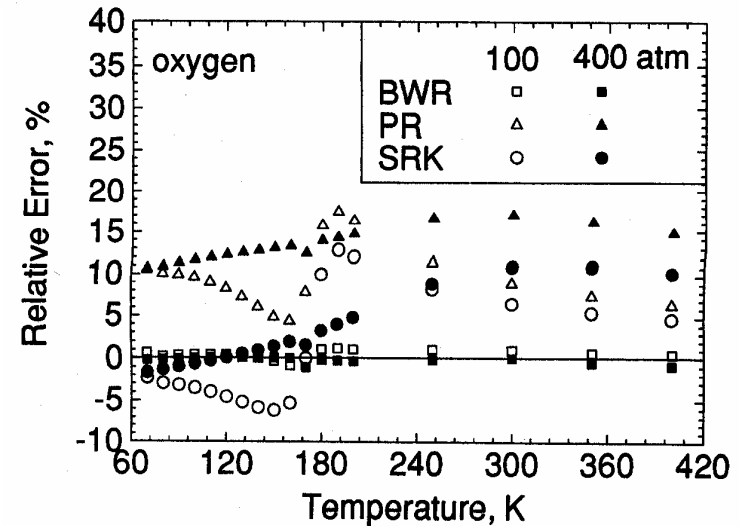
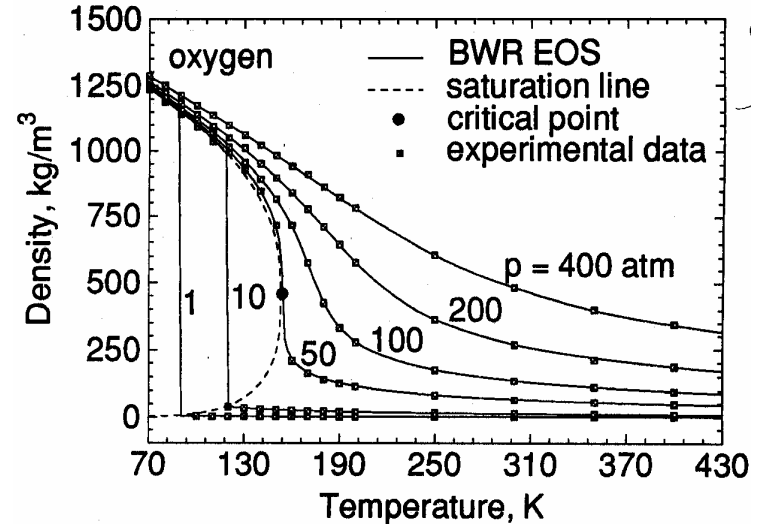
$$p = \frac{RT}{v-b} - \frac{a}{v(v+b)}$$

- Peng-Rubinson (PR)

$$p = \frac{RT}{v-b} - \frac{a}{v(v+b)+b(v-b)}$$

- Benedict-Webb-Rubin (BWR)

$$p = \sum_{n=1}^9 a_n \rho^n + \sum_{n=10}^{15} a_n \rho^{2n-17} e^{-\gamma \rho^2}$$





- Sensible enthalpy:  $h(\rho, T) = h^0(T) + \Delta h_{exc}(\rho, T)$
  - Internal energy:  $u(\rho, T) = u^0(T) + \Delta u_{exc}(\rho, T)$
  - Specific heat  $C_p(\rho, T) = C_p^0(T) + \Delta C_{p,exc}(\rho, T)$
- $\Delta h_{exc}, \Delta u_{exc}, \Delta C_{p,exc} =$  dense fluid corrections  
 $h^0(T), u^0(T), C_p^0(T), =$  values in dilute-gas limit

Pressure-explicit type of EOS:

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

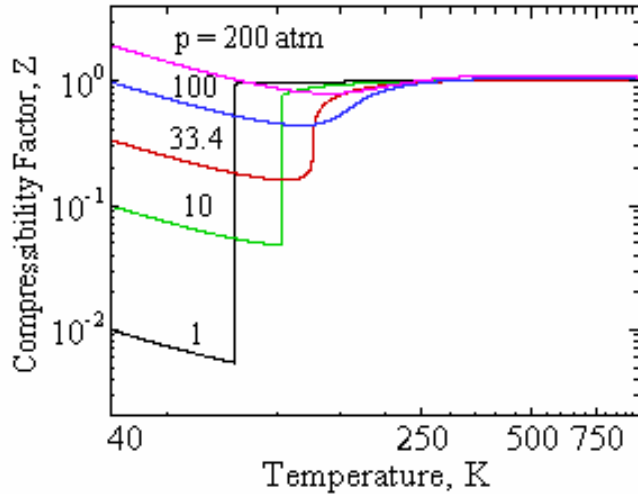
$$\Delta u_{exc} = \int_0^\rho \left[ \frac{p}{\rho^2} - \frac{T}{\rho^2} \left( \frac{\partial p}{\partial T} \right)_\rho \right] d\rho$$

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

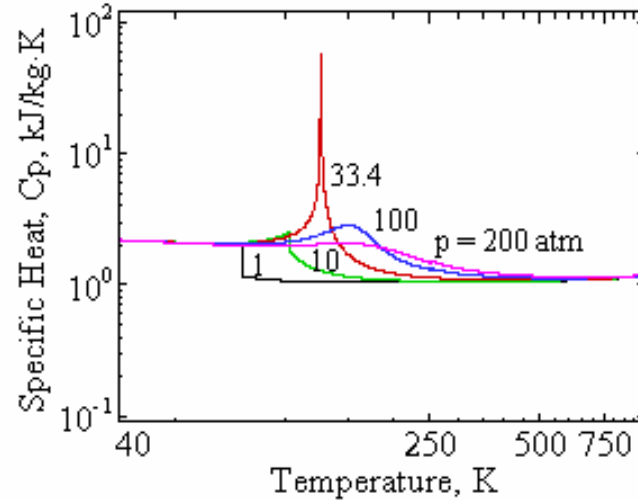


# Thermophysical Properties of Nitrogen

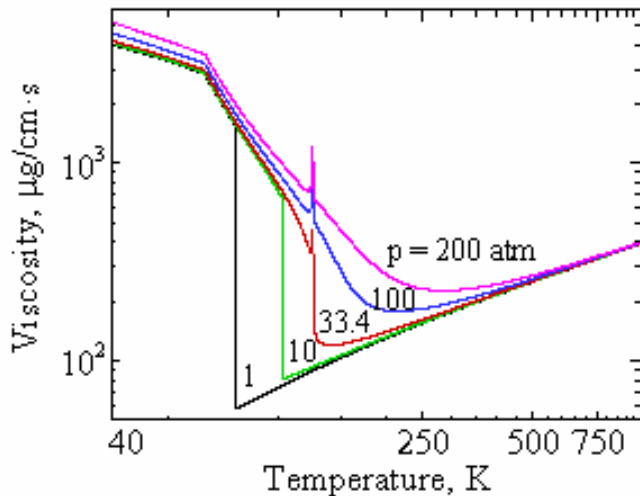
• compressibility factor



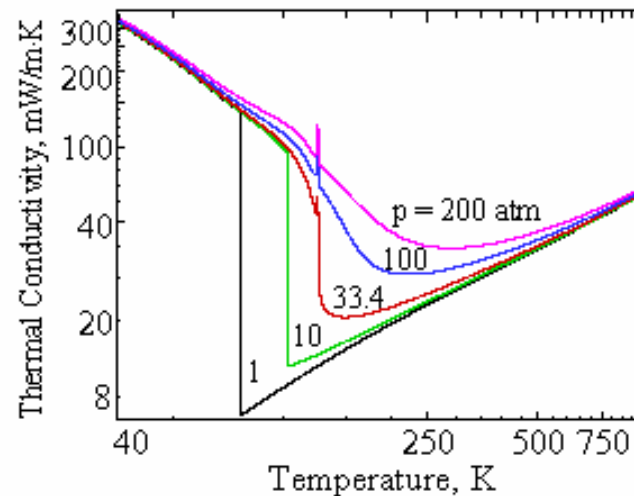
• specific heat



• dynamic viscosity



• thermal conductivity





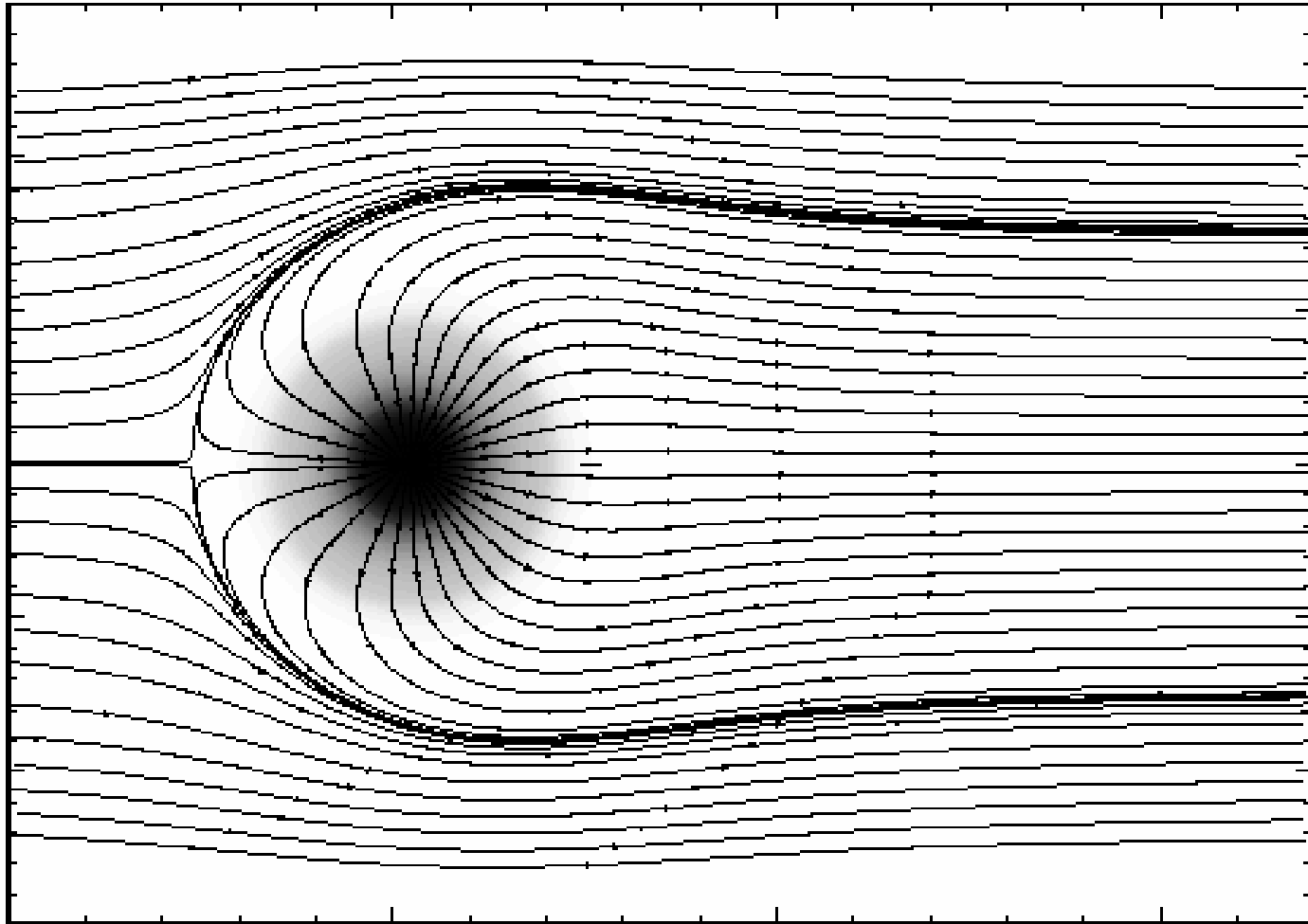
# Droplet Vaporization and Combustion in Quiescent and Convective Environments

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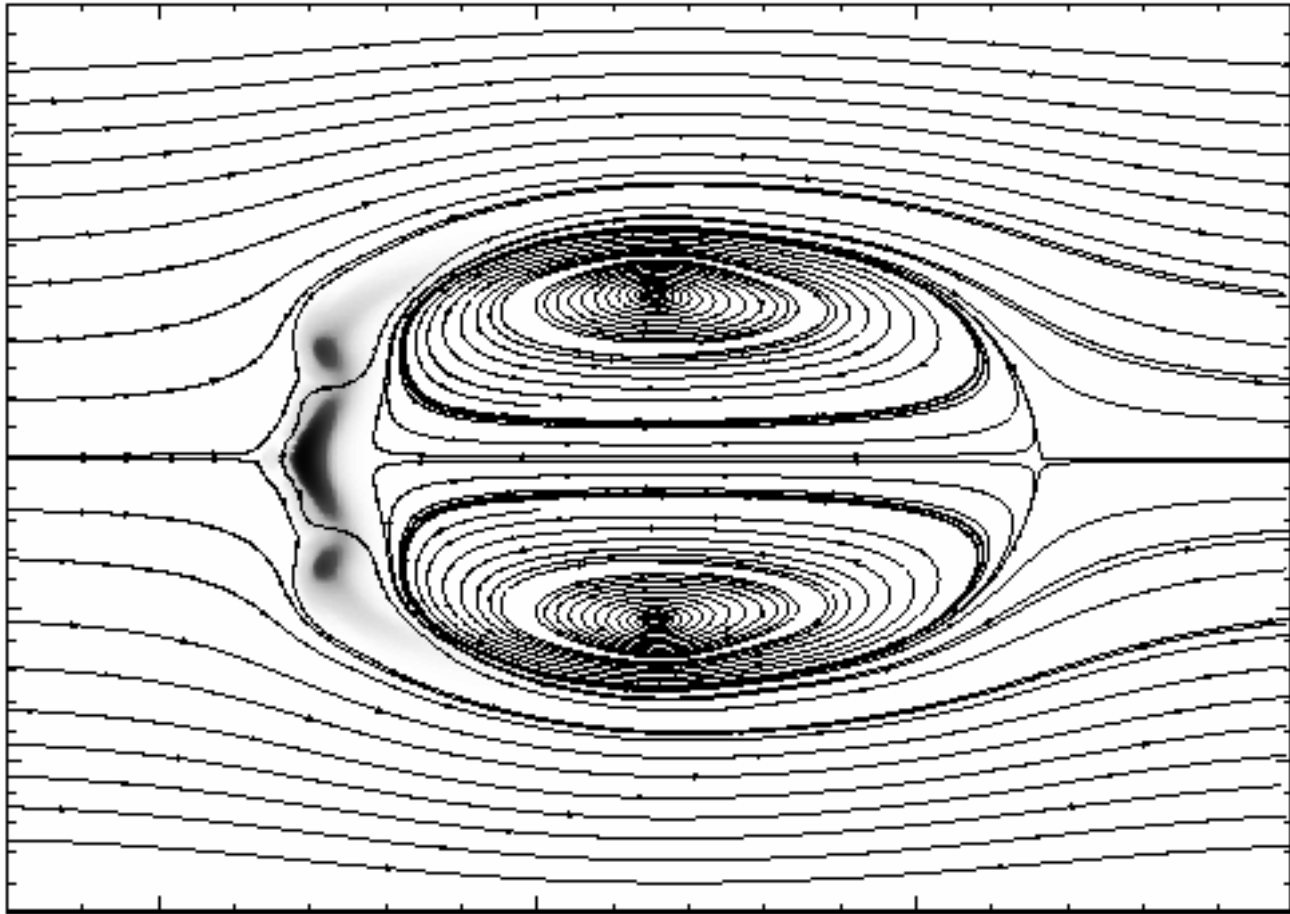
- **Liquid oxygen (LOX) droplet vaporization & combustion in hydrogen and water**  
 $5 < p_{\infty} < 300 \text{ atm}$   
 $500 < T_{\infty} < 2500 \text{ K}$   
 $50 < D_0 < 300 \mu\text{m}$
- **Hydrocarbon droplet vaporization & combustion in air and oxygen**  
 $5 < p_{\infty} < 200 \text{ atm}$   
 $300 < T_{\infty} < 2500 \text{ K}$   
 $100 < D_0 < 1000 \mu\text{m}$
- **Unsymmetrical dimethylhydrazine (UDMH) droplet vaporization and decomposition combustion**  
 $1 < p_{\infty} < 180 \text{ atm}$



# Spherical Mode (100 atm, 0.2 m/s; $t=610 \mu\text{s}$ )







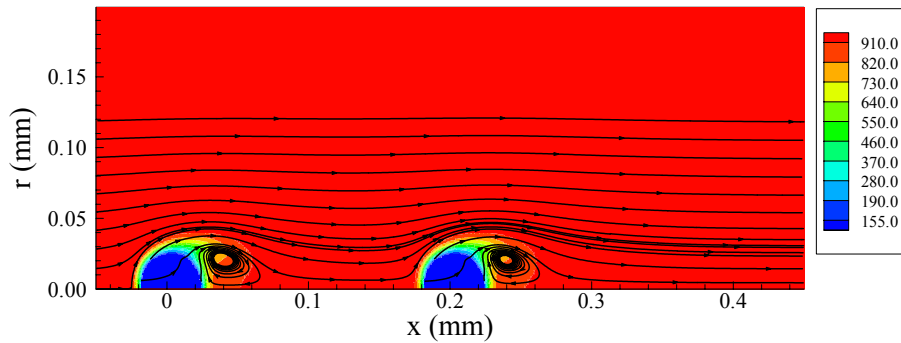


# Flow and Temperature Fields

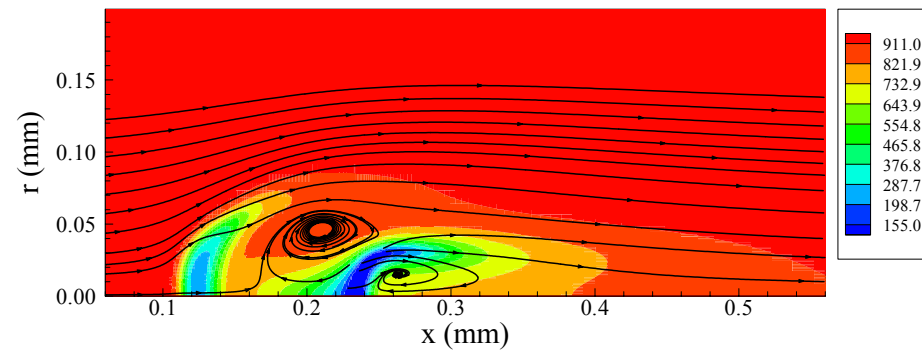
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$P_\infty = 100 \text{ atm}$ ,  $T_\infty = 1000 \text{ K}$ ,  $u_\infty = 20 \text{ m/s}$ ,  $T_0 = 100 \text{ K}$ ,  $d_0 = 50 \text{ }\mu\text{m}$ ,  $H/R = 8$

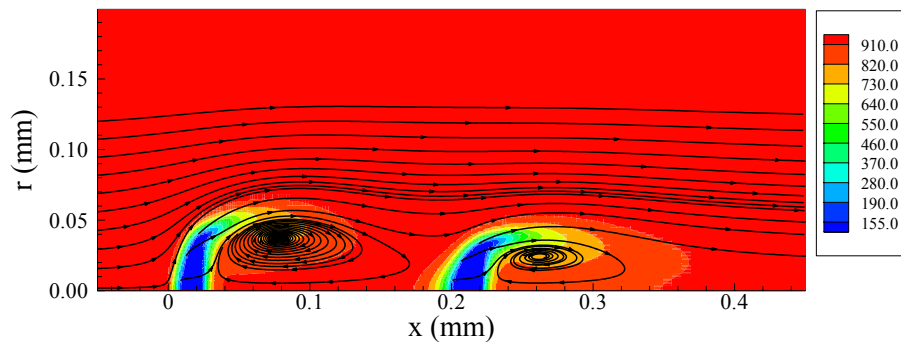
$t = 8 \text{ }\mu\text{s}$



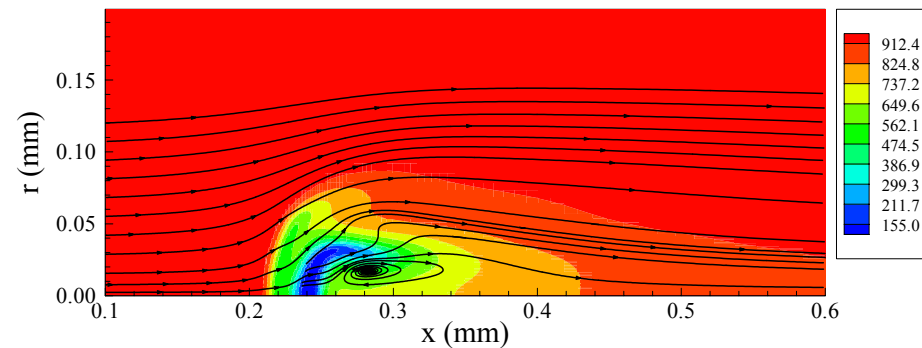
$t = 90 \text{ }\mu\text{s}$

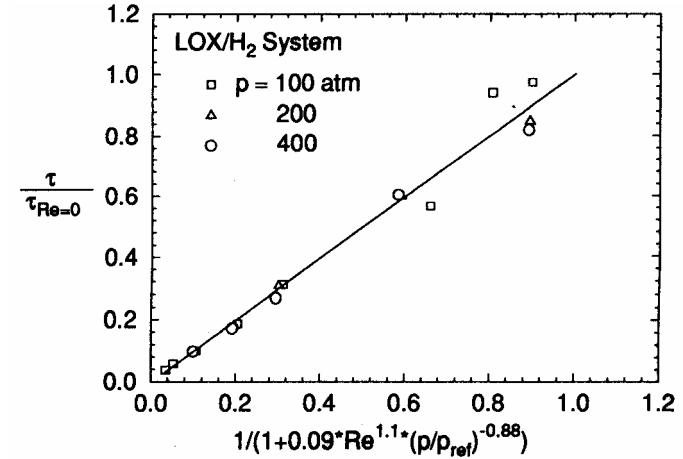
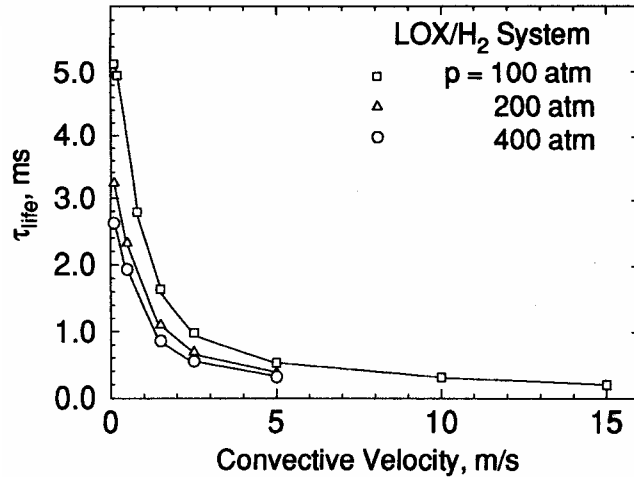


$t = 40 \text{ }\mu\text{s}$



$t = 110 \text{ }\mu\text{s}$





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

- **atmospherical condition**

- Ranz and Marshall's correlation

$$\frac{\tau_f}{\tau_{f,Re=0}} \propto \frac{h_{Re=0}}{h} = \frac{1}{1 + 0.3 Re^{1/2} Pr^{1/3}}$$

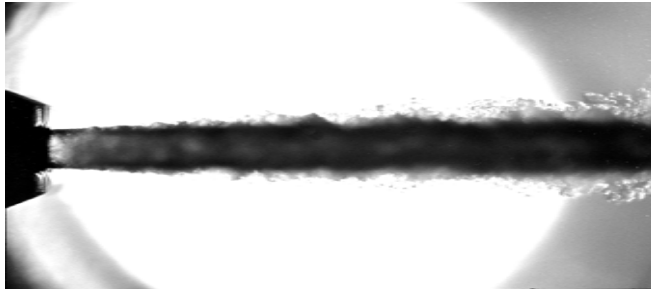
- **supercritical condition**

- LOX/hydrogen system

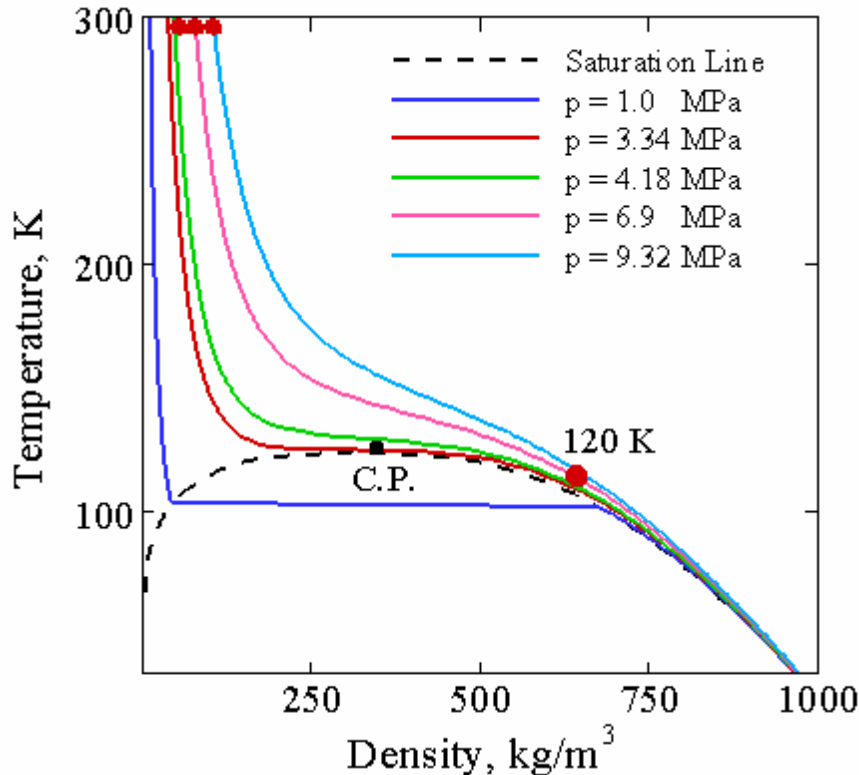
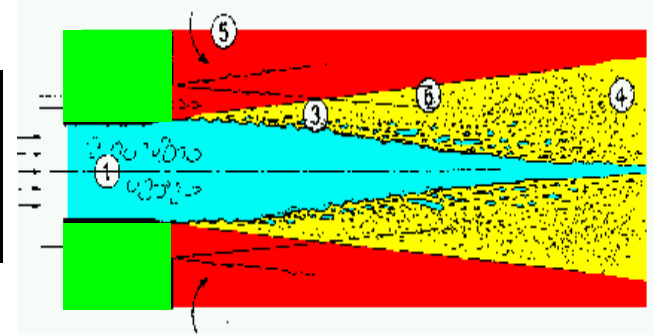
$$\frac{\tau_f}{\tau_{f,Re=0}} \propto \frac{h_{Re=0}}{h} = \frac{1}{1 + 0.15634 Re^{1.1} Pr_{O_2}^{-0.88}}$$



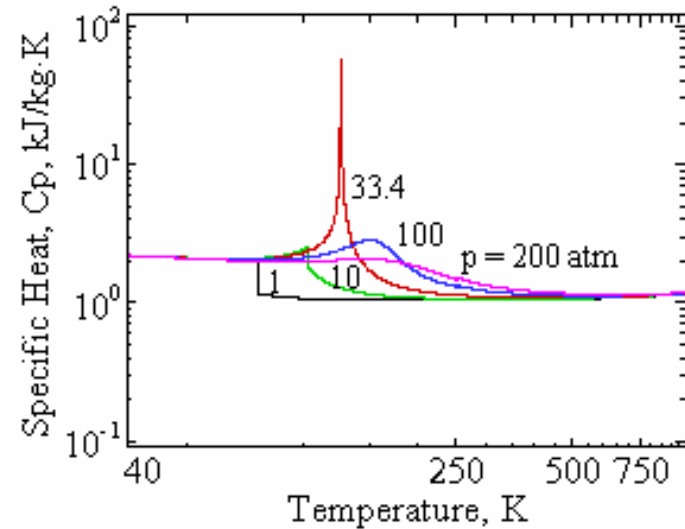
# Supercritical Fluid Injection



$p_{ch} = 4.0 \text{ MPa}$   
 $T_{LN2} = 105 \text{ K}$   
 $T_{GN2} = 300 \text{ K}$   
 $u_{LN2} = 10 \text{ m/s}$   
 $D_{in} = 1.9 \text{ mm}$

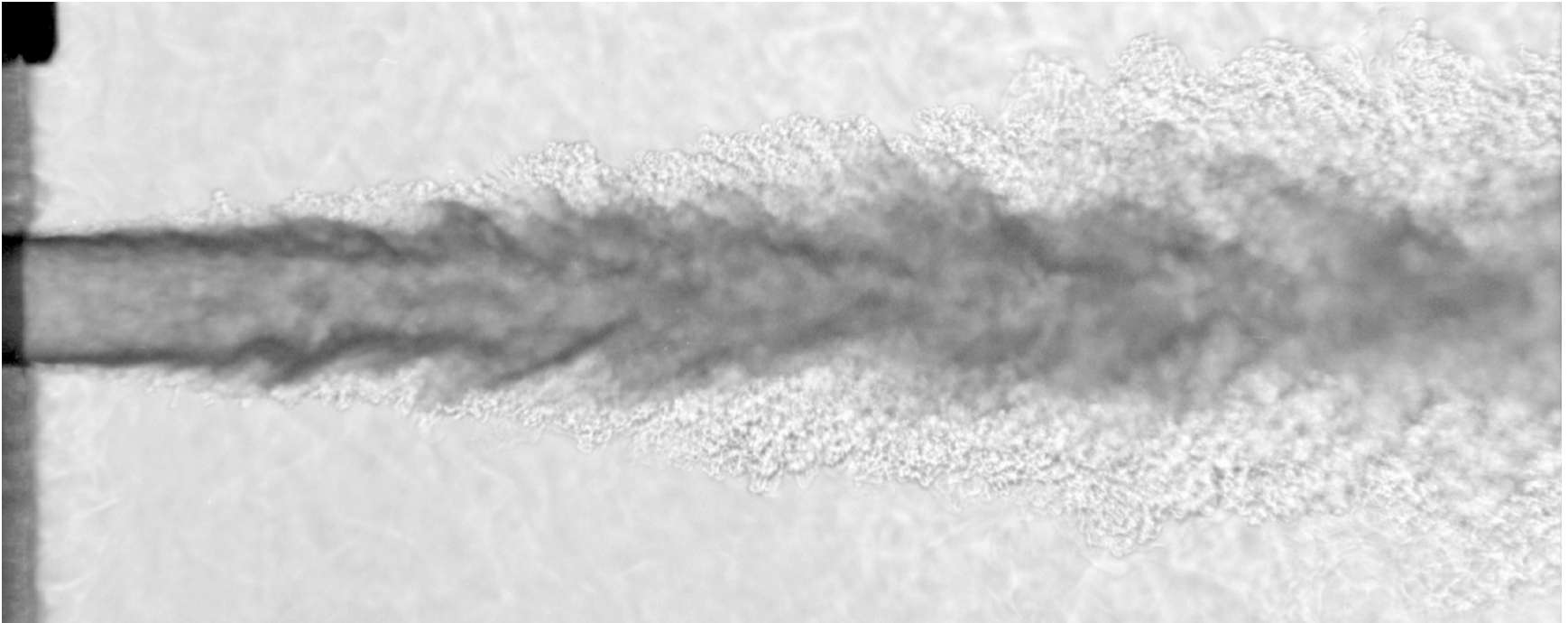


$p_{\infty} = 3.4 - 10.0 \text{ MPa}$ ,  $T_{\infty} = 300 \text{ K}$ ,  
 $T_{inj} = 120 \text{ K}$ ,  $D_{inj} = 0.254 \text{ mm}$ ,  
 $u_{inj} = 15 \text{ m/s}$ ,  $Re = 20000 - 40000$



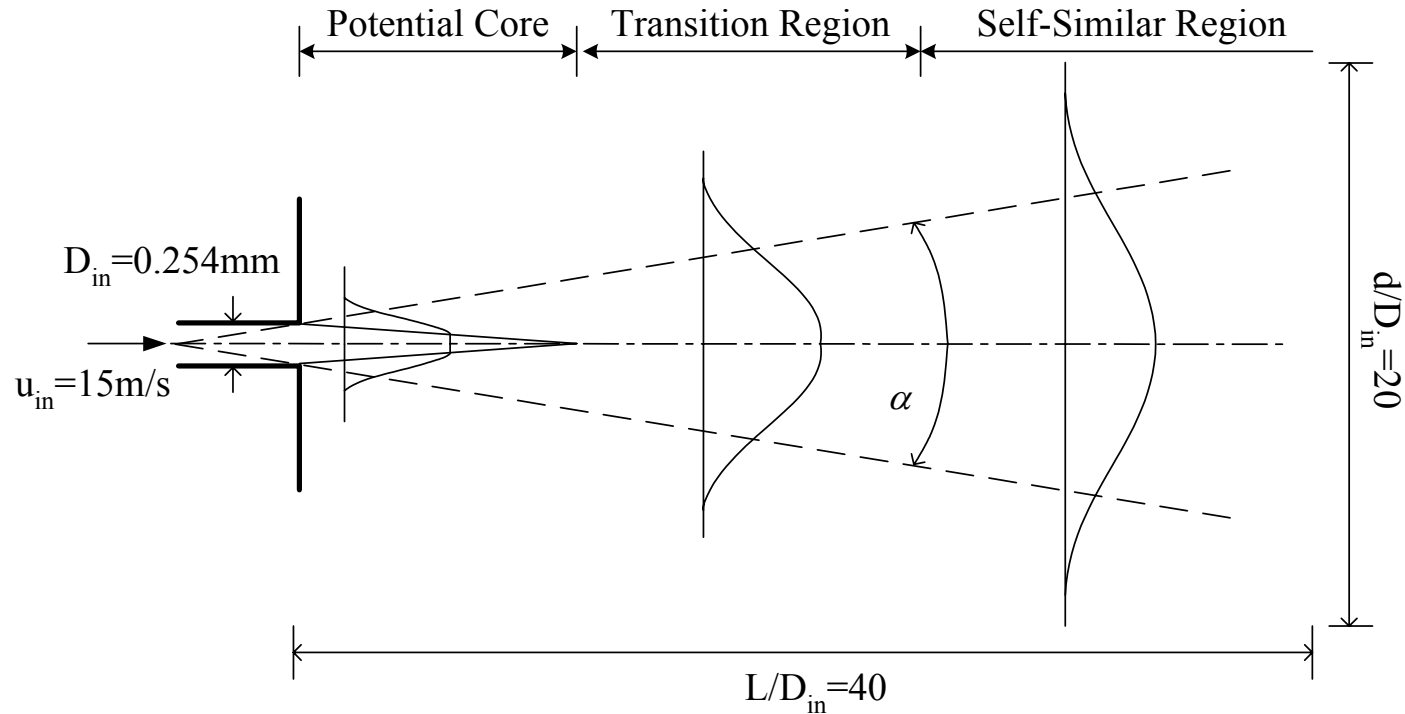


( $p_\infty = 6.0$  MPa,  $T_\infty = 300$  K,  $u_{in} = 4.9$  m/s,  $T_{in} = 132$  K,  $D_{in} = 2.2$  mm)





# 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  $D_{in} = 0.254 \text{ mm}$
- $3 < \lambda_t < 5 \text{ } \mu\text{m}$



total grids

$$225 \times 75 \times 72 = 1,215,000$$

mean grid spacing in  
near injector region

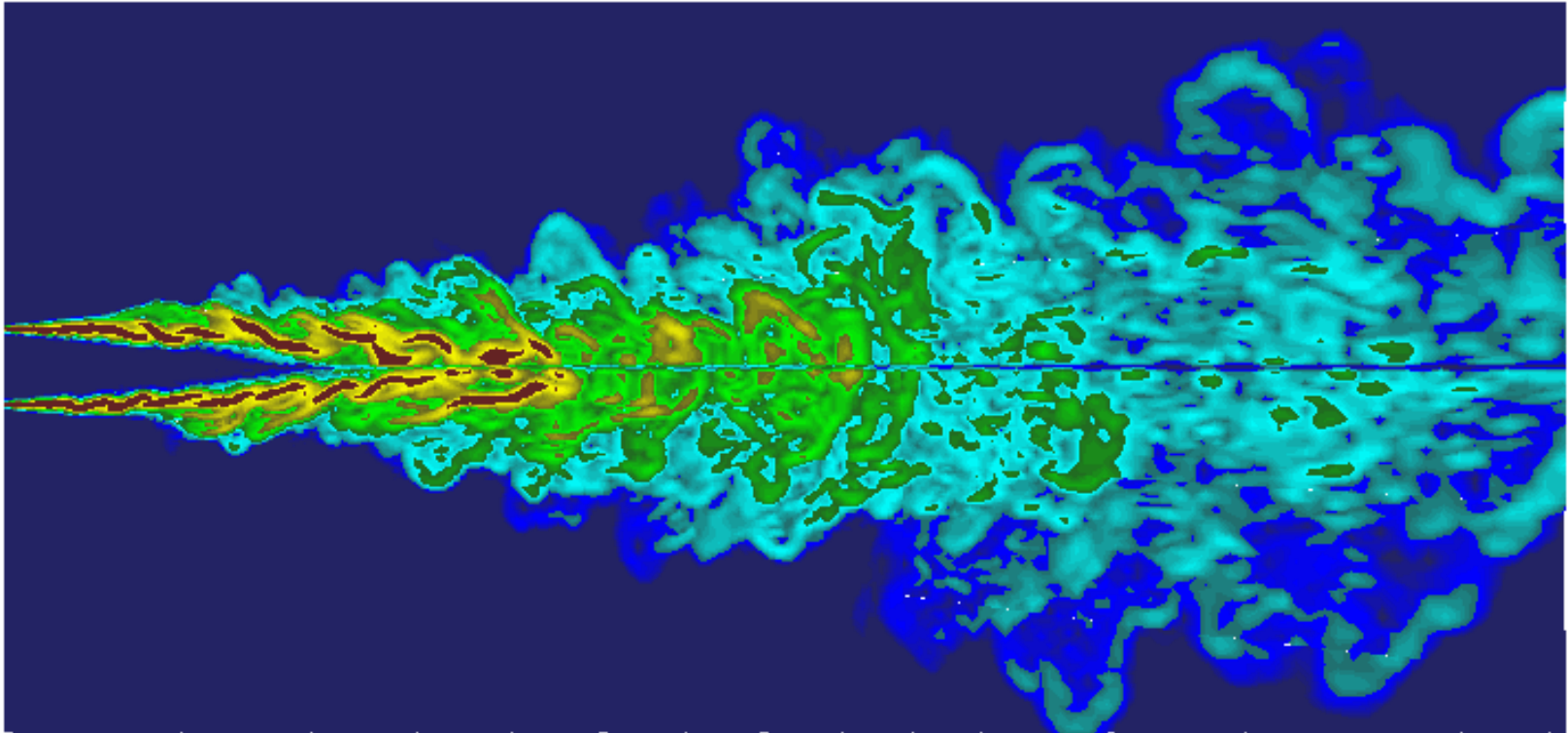
$$\Delta = 5 \text{ } \mu\text{m}$$



# Density Gradient Field

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



$|\nabla\rho| \text{ (kg/m}^4\text{)}$



1.0000E+04   3.9401E+04   1.5524E+05   6.1167E+05   2.4100E+06

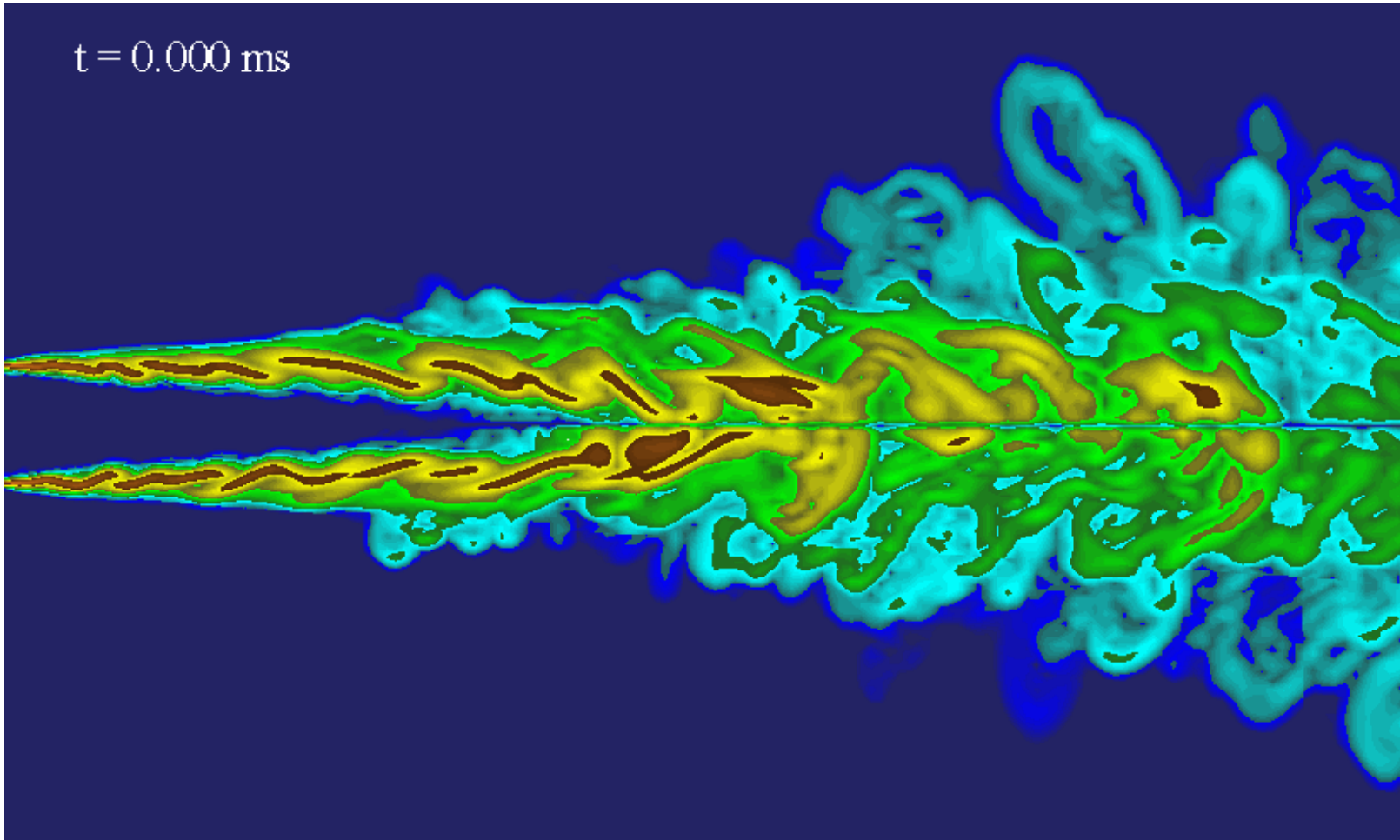




# Time Evolution of Density Gradient Field

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

$t = 0.000 \text{ ms}$

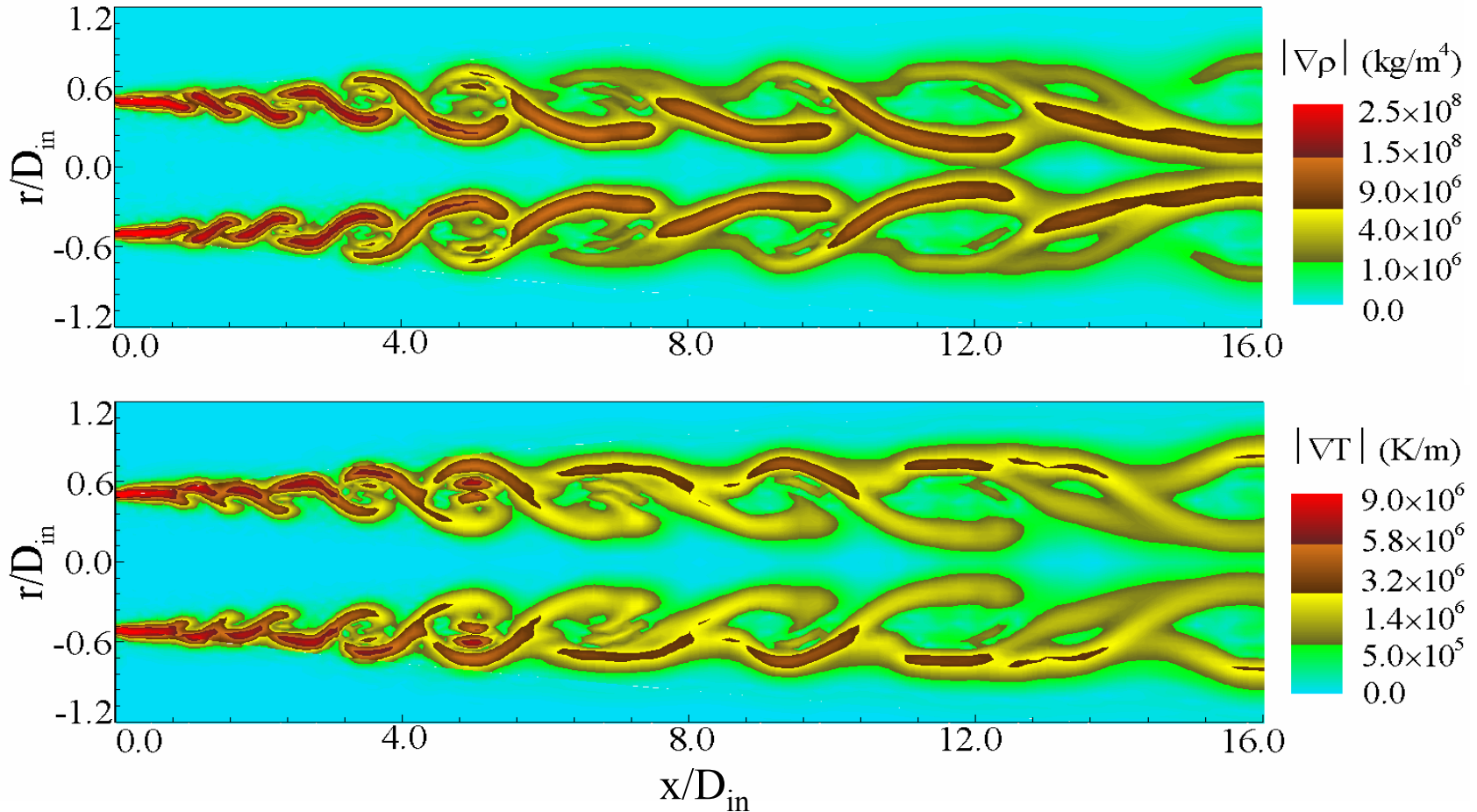




# Snapshots of Density and Temperature Gradient Fields

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$(p_\infty = 9.3\text{MPa}, T_\infty = 300\text{K}, u_{in} = 15\text{m/s}, T_{in} = 120\text{K}, t = 1.550\text{ms}, D_{in} = 254\mu\text{m})$





# Most Energy Containing POD Modes of Axial Velocity

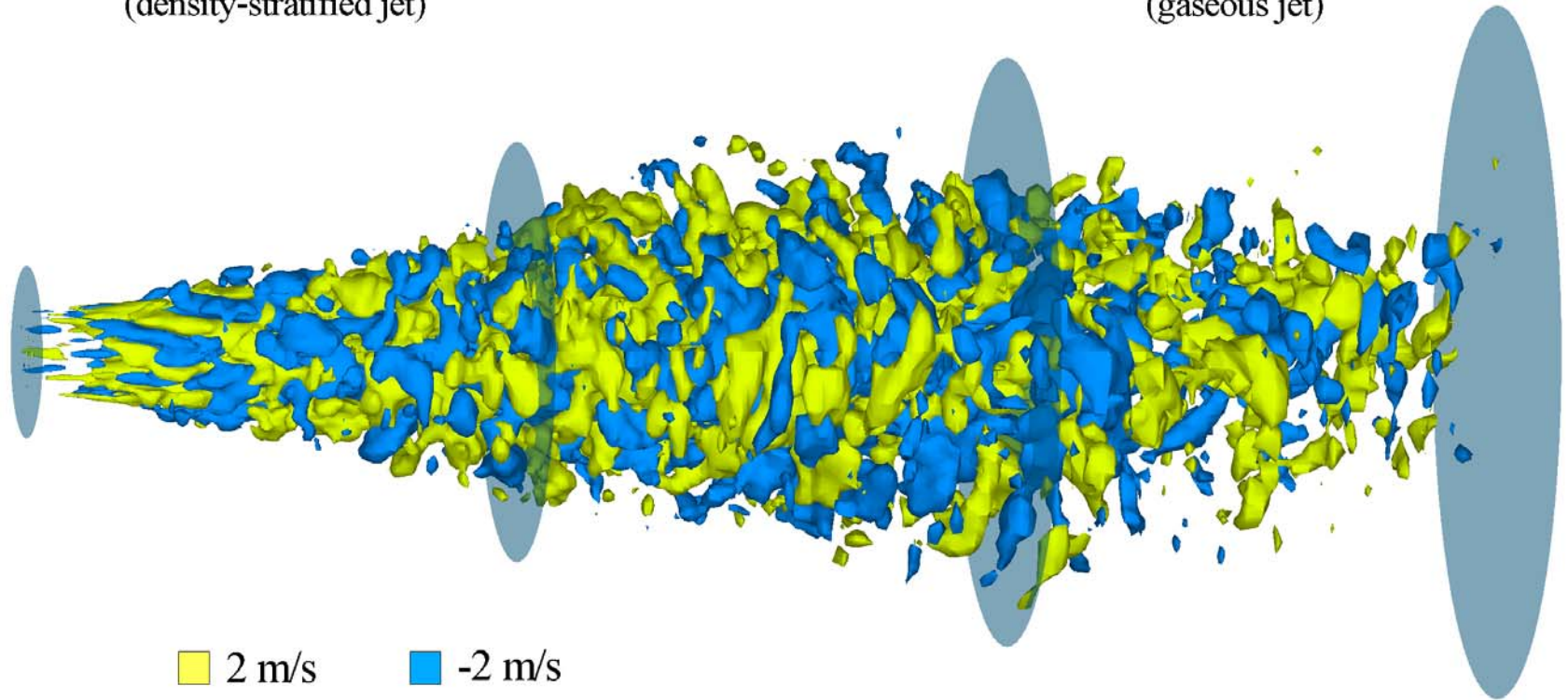
1 8 5 5 Department of Mechanical & Nuclear Engineering

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

pre-burst region  
(density-stratified jet)

burst region

post-burst region  
(gaseous jet)

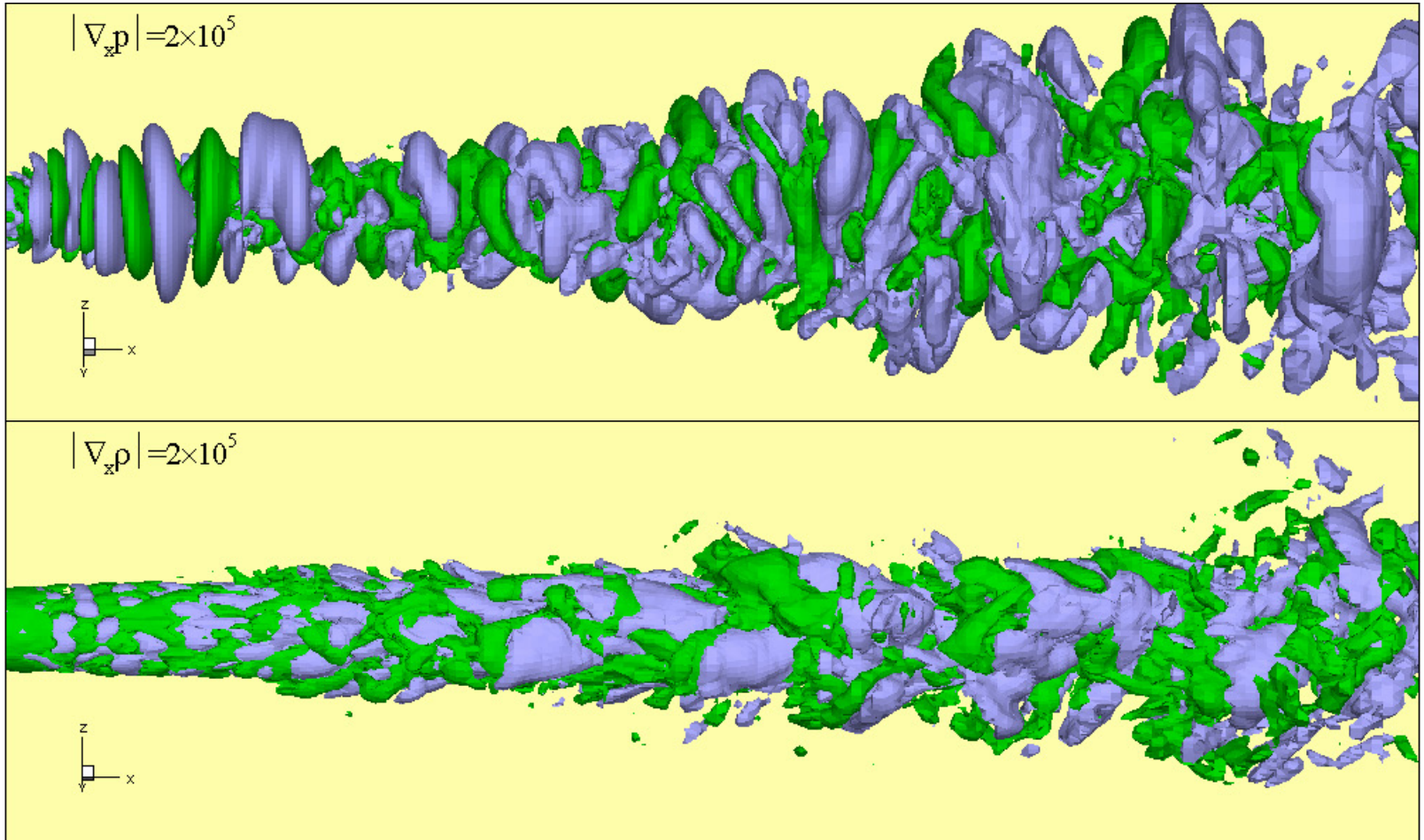




# Iso-Surfaces of Pressure and Density Gradients

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

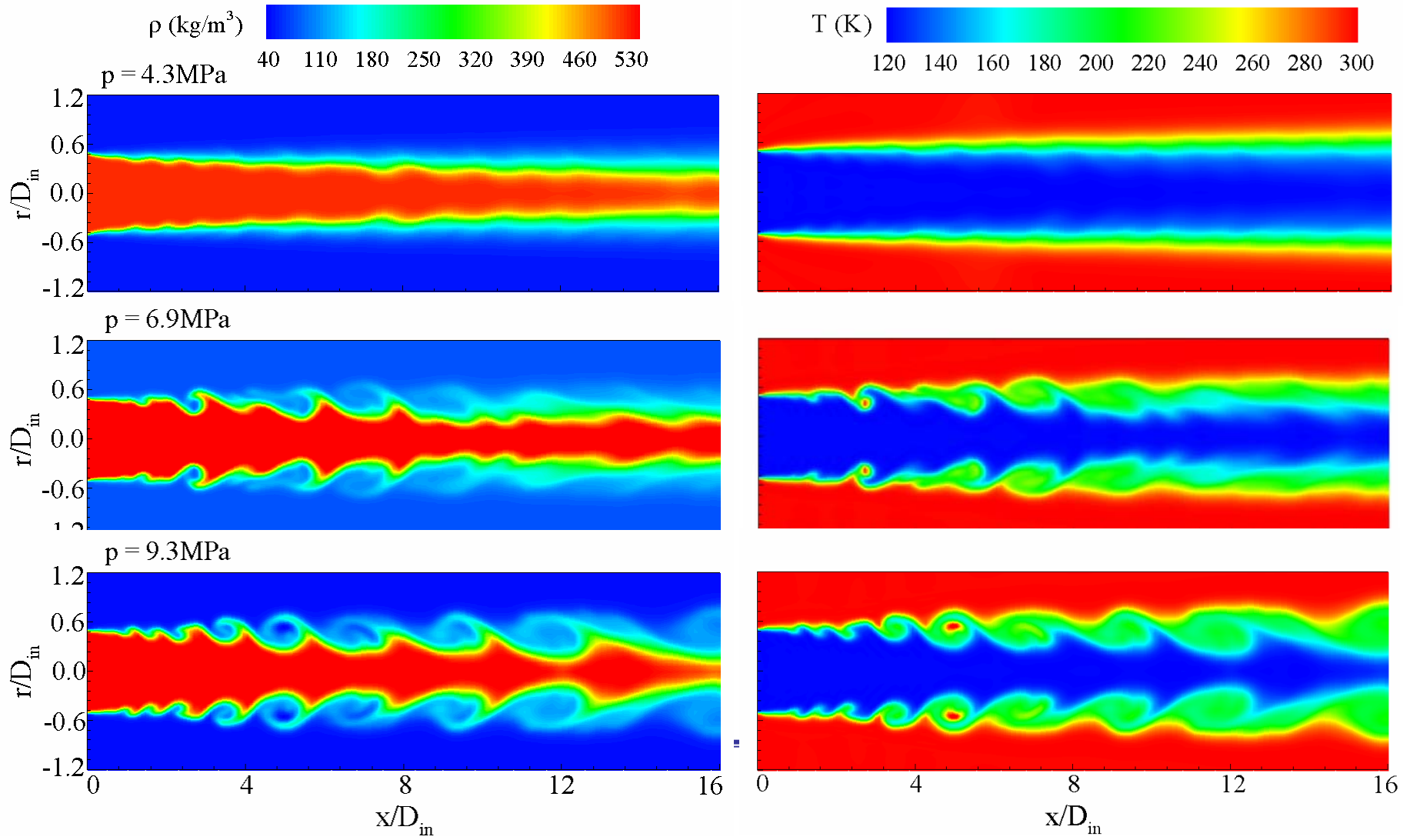




# Effect of Pressure on Density and Temperature Fields

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



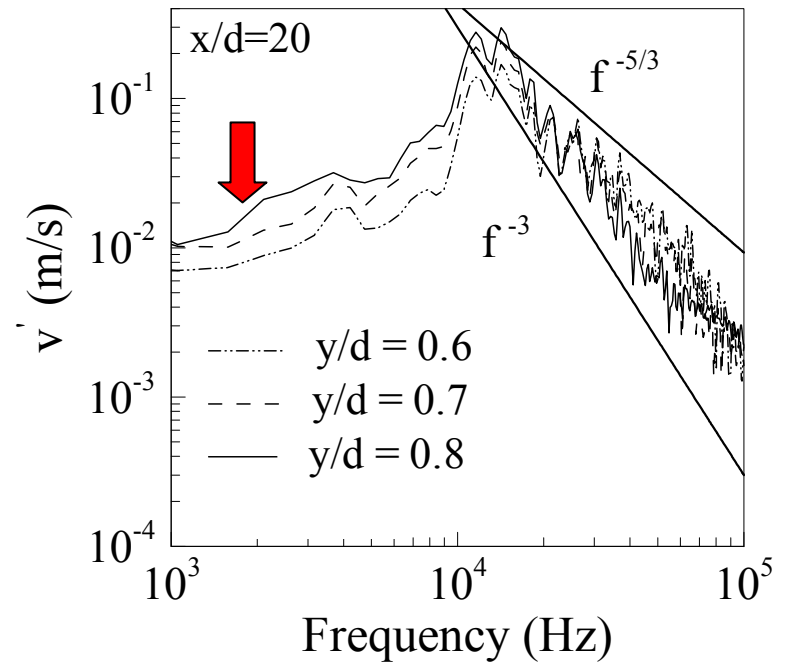
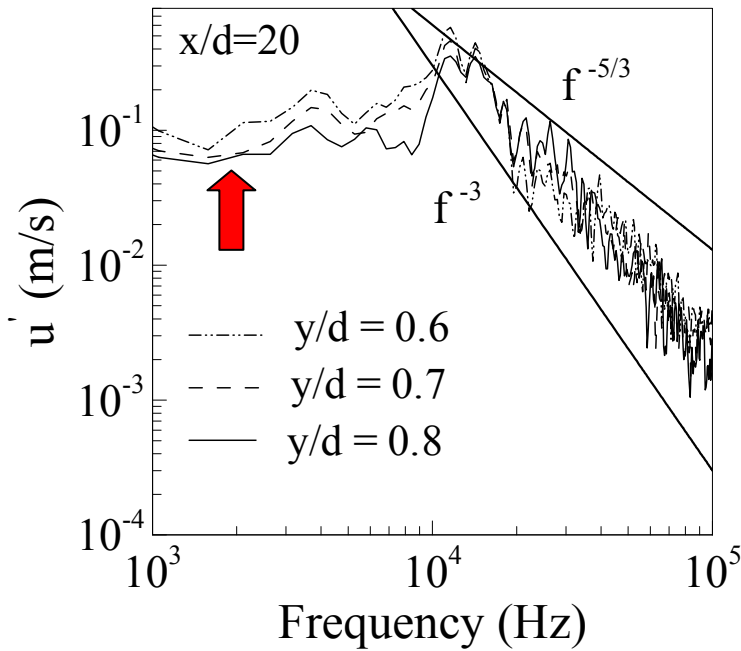




# Power Spectral Densities of Velocity Fluctuations

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

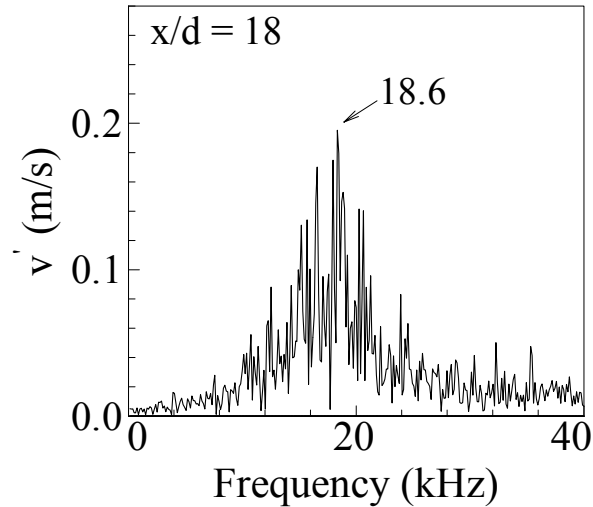
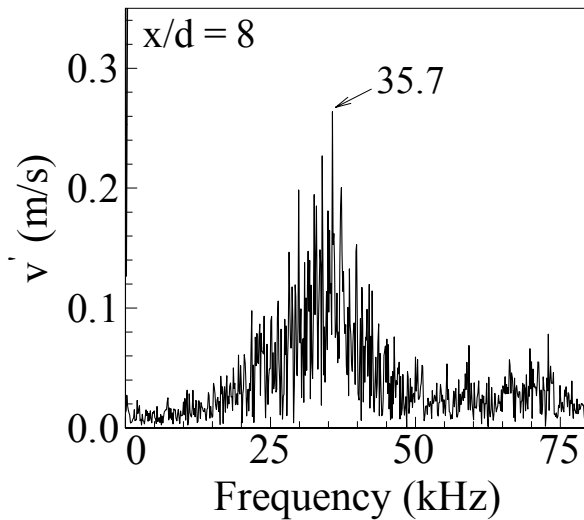
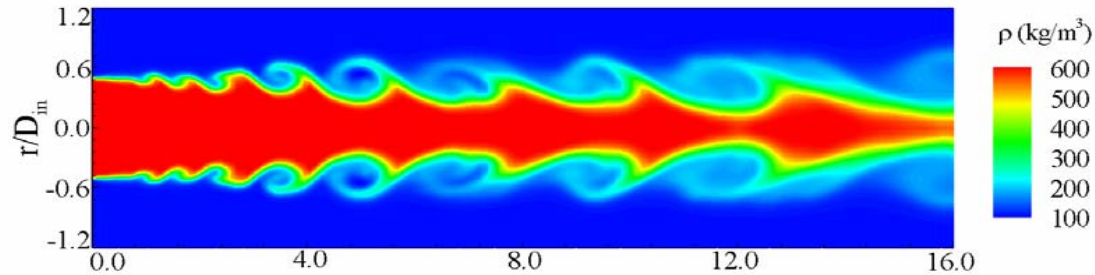


Large density-gradient regions act like a solid wall that amplifies the axial turbulent fluctuation but damps the radial one.



# Vortex Shedding Frequency

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



## 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

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

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

choose

$$St_j = 0.046$$

then

$$f_1 = 34500$$

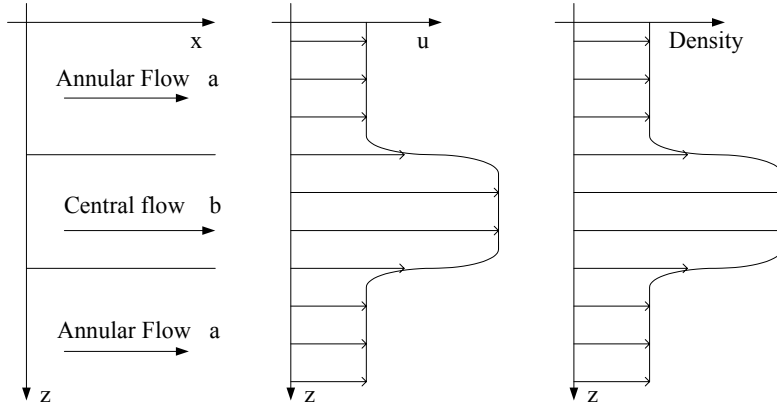
$$f_2 = 17250$$



# Linear Stability Analysis of Real Fluid Jet

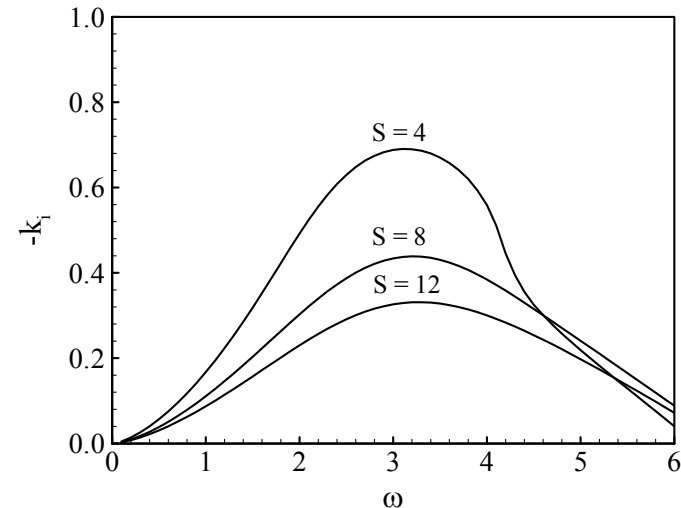
## Approach

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



## Conclusions

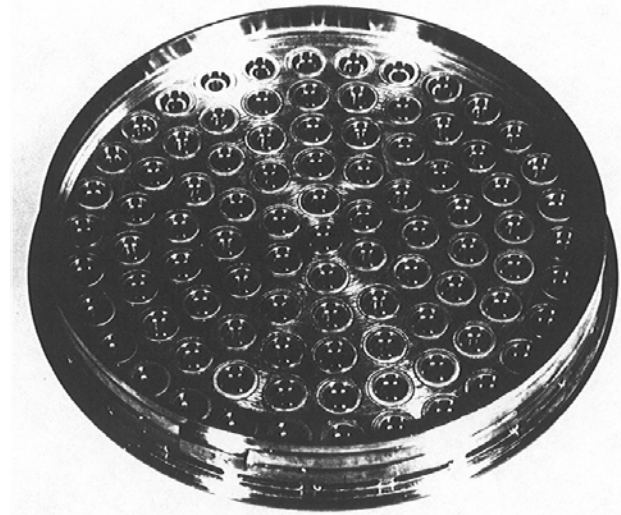
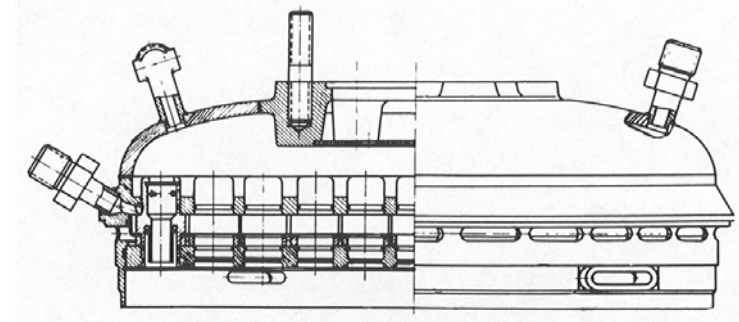
- As the density ratio increases, the spatial growth rate of the interfacial instability wave decreases. ➡ Density stratification tends to stabilize the mixing layer.
- Density stratification has little effect on the frequency of the most unstable mode.





# Bi-Propellant Swirl Co-Axial Injector

Component	Geometrical characteristic	Spray-cone angle	Pressure drop	flow rate
oxidizer	2	80	0,426	172,9
fuel	24,5	135	0,696	64,8
oxidizer	-	-	0,426	172,3
fuel	-	-	0,696	64,8

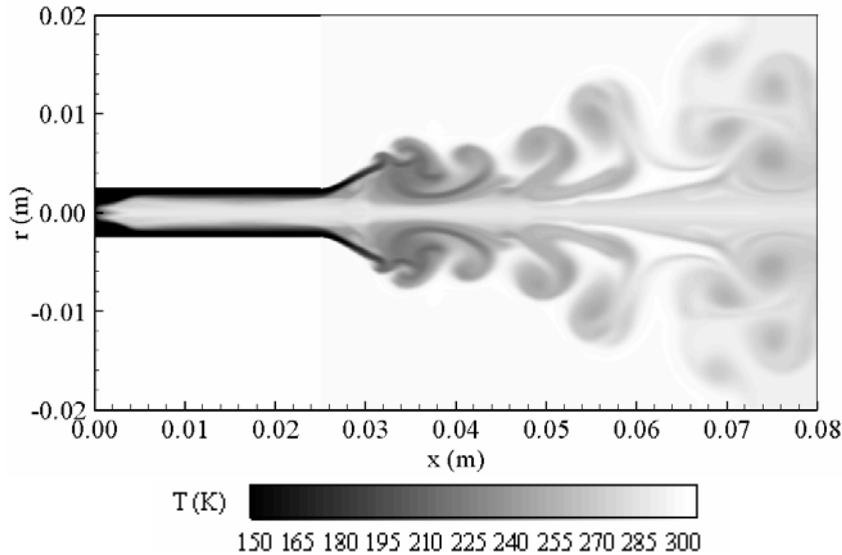
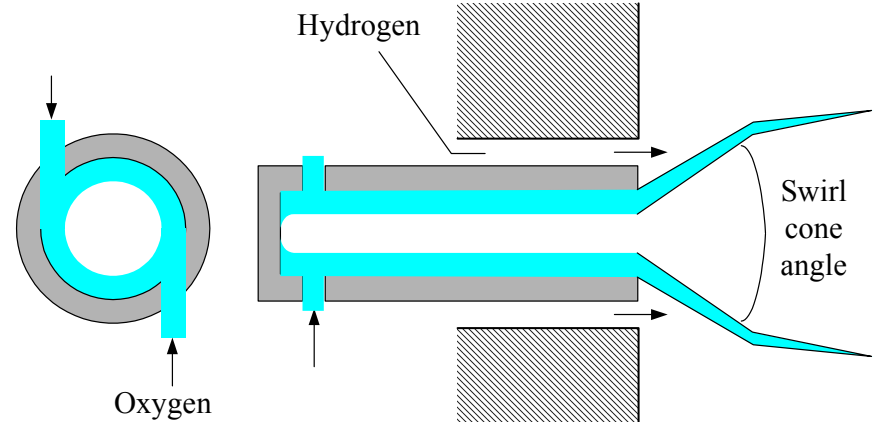






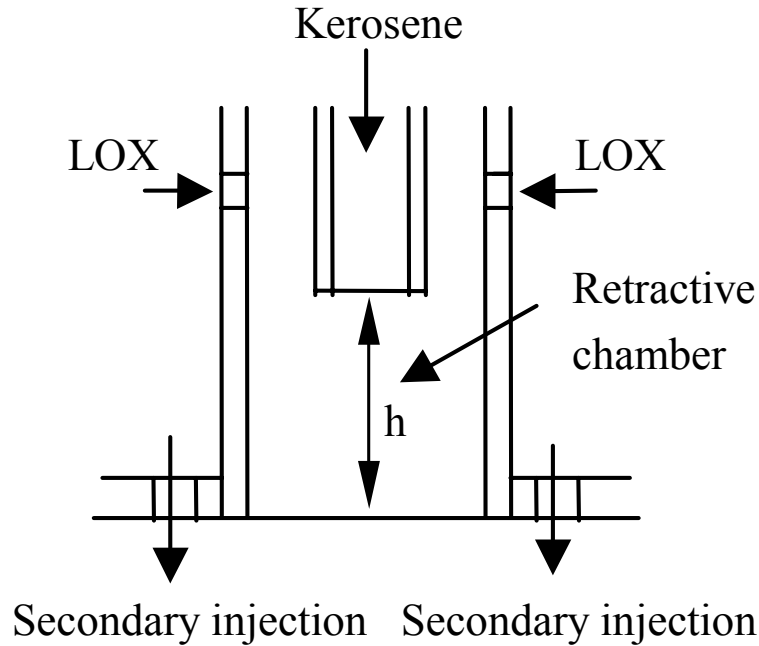
## Issues

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

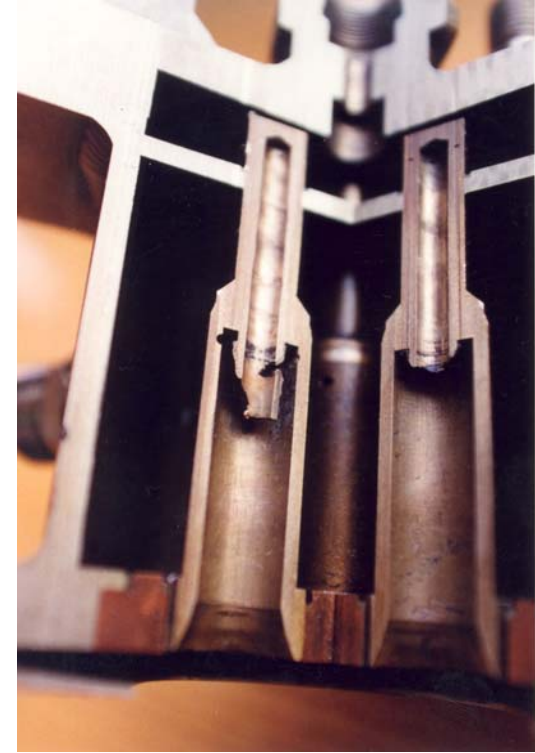


## Major Results

- Liquid film thickness and swirl cone angle.
- Detailed flow structures, including central recirculation zone, surface instability, etc.
- Response of injector dynamics to external forcing.



oxidizer-rich preburner injector



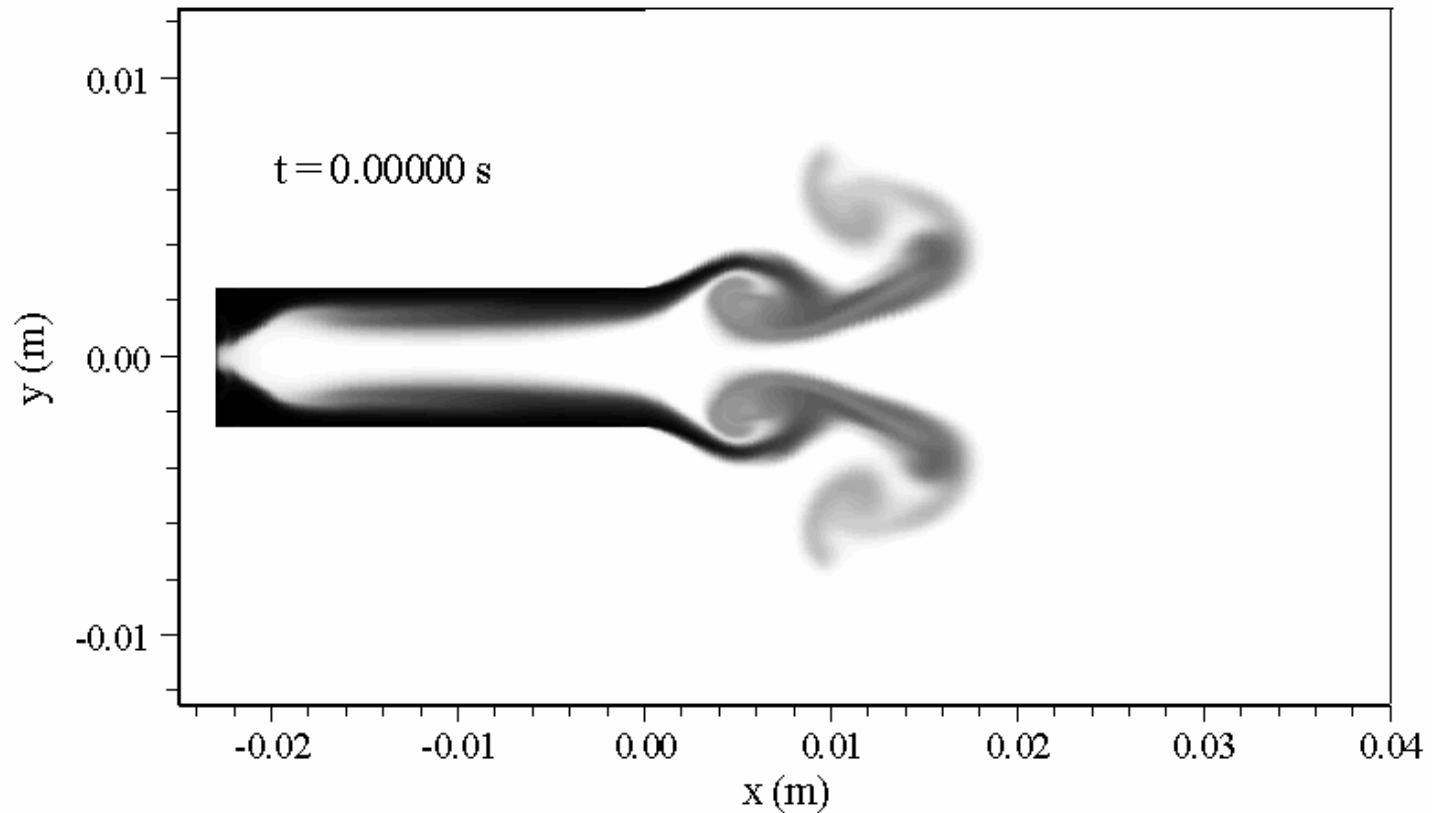
damaged inner centrifugal injector



# Time Evolution of Swirling Jet

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( $p_\infty=10.0$  MPa,  $T_\infty=300$  K,  $u_{inj}=30$  m/s,  $T_{inj}=120$  K,  $\theta=30^\circ$ , nitrogen )

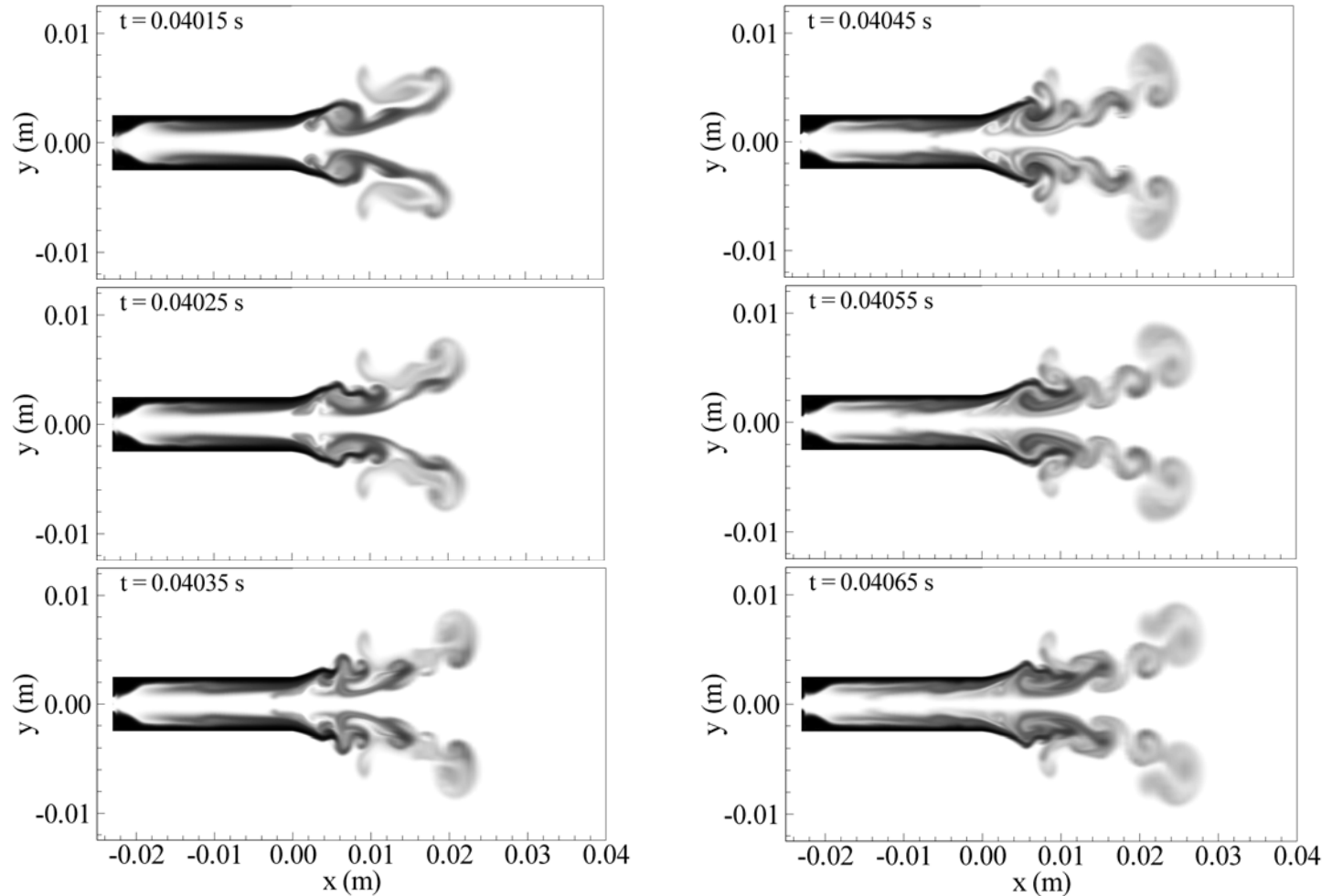




# Time Evolution of Swirling Jet

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( $p_\infty = 10.0$  MPa,  $T_\infty = 300$  K,  $u_{inj} = 30$  m/s,  $T_{inj} = 120$  K,  $\theta = 30^\circ$ , nitrogen)



Temperature (K)

120 140 160 180 200 220 240 260 280 300

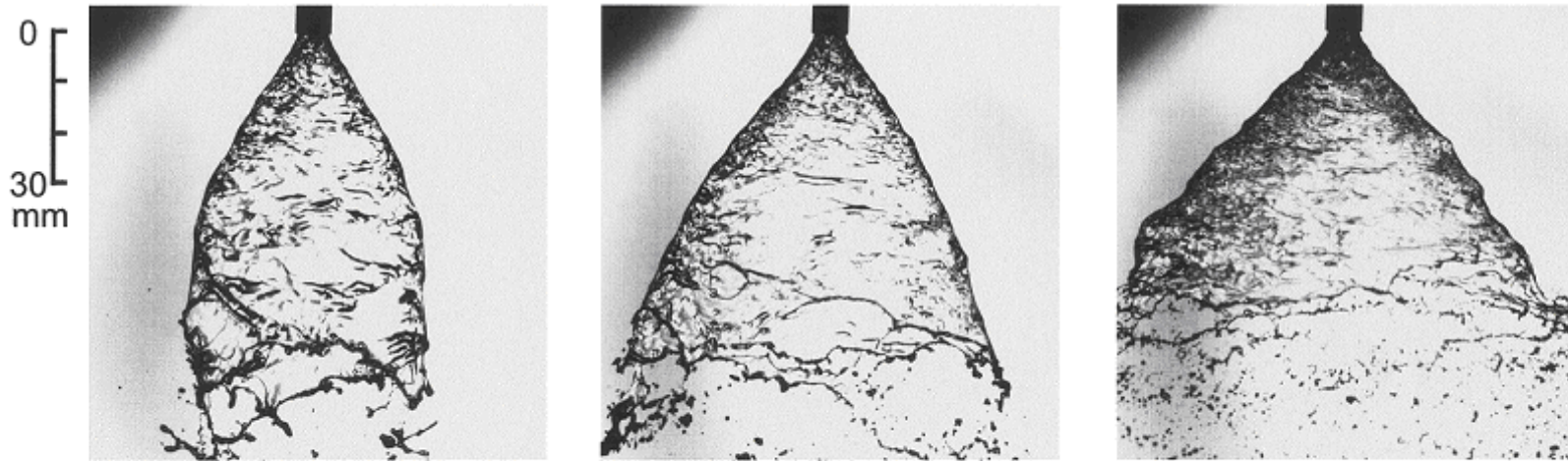


# Disintegration of Swirling Water Jet

(Inamura, Tamura and Sakamoto, JPP, 2003)

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



(1)  $M_l = 26.1$  g/s

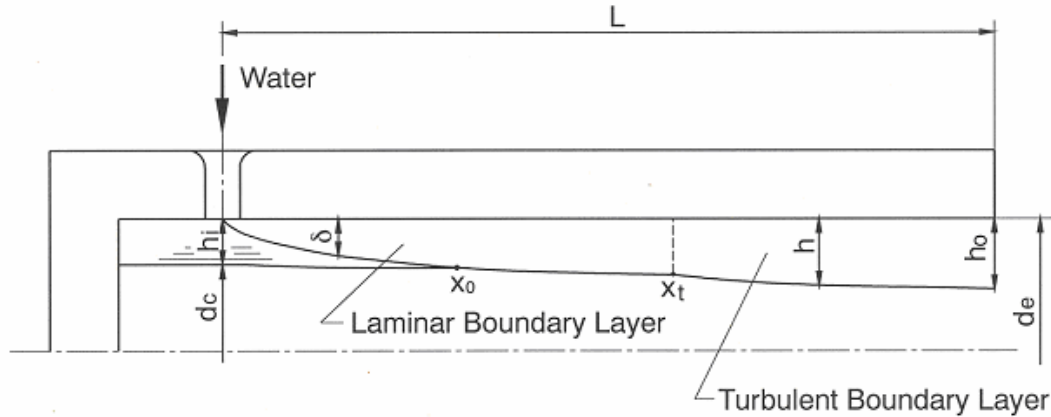
(2)  $M_l = 32.5$  g/s

(3)  $M_l = 48.6$  g/s

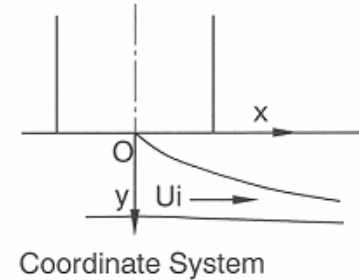
- A hollow cone sheet forms around the injector exit.
- The conical sheet fluctuates vigorously and disintegrates into ligaments and droplets at the sheet tip.
- The sheet breakup point approaches the injector as the liquid flow rate increases.



# Theoretical Analysis of Swirl Injector (1/2)



( Inamura et al. *JPP*, 2003 )



$$x < x_0$$

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

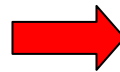
where

$$\tau_w = \rho_l \nu_l \left( \frac{\partial u}{\partial y} \right)_{y=0}$$

and

$$\delta^* = 5.84 \sqrt{x^* / \text{Re}}$$

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



$$h^* = 1 + (3/10) \delta^*$$



# Theoretical Analysis of Swirl Injector (2/2)

$$x_0 < x < x_t$$

$$h^* = 1.429 / \{1 + A(x^* - x_0^*)\} \quad A = 1.682(v_l / Q)$$

$$x_t < x$$

$$h^* = 0.02798(x^* / \text{Re}^{1/4}) + C_1 \quad x_0^* = 0.0598 \text{Re}$$

$$C_1 = 1.429\{1 + A(x_t^* - x_0^*)\} - 0.0279(x_t^* / \text{Re}^{1/4})$$

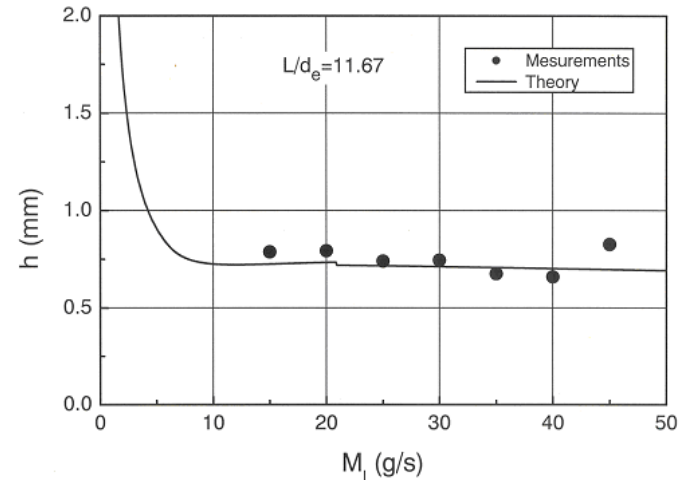
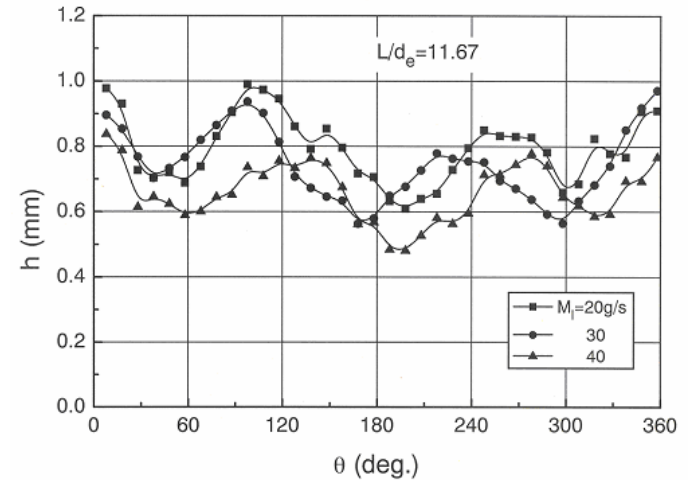
$$x_t < x < x_0$$

$$h^* = 0.02798(x^* / \text{Re}^{1/4}) + C_3$$

$$C_3 = 1.143 - 0.02798(x_0^* / \text{Re}^{1/4})$$

$$x_0^* = \{(1.182 - C_2) / 0.2893\} \text{Re}^{1/4}$$

## Film Thickness at Post Exit

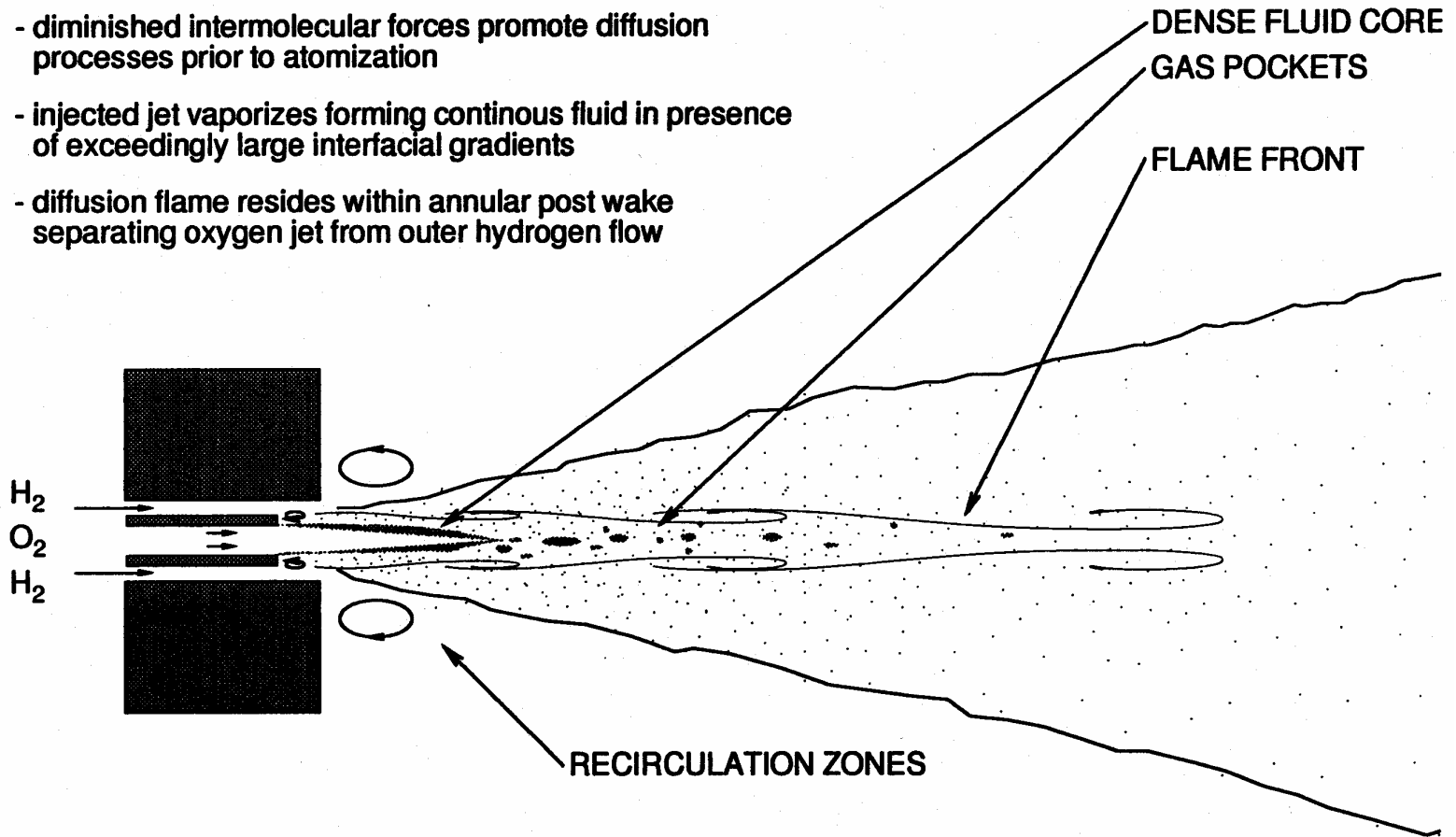




# Limiting Extremes: 2) Diffusion Processes Dominate

- "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





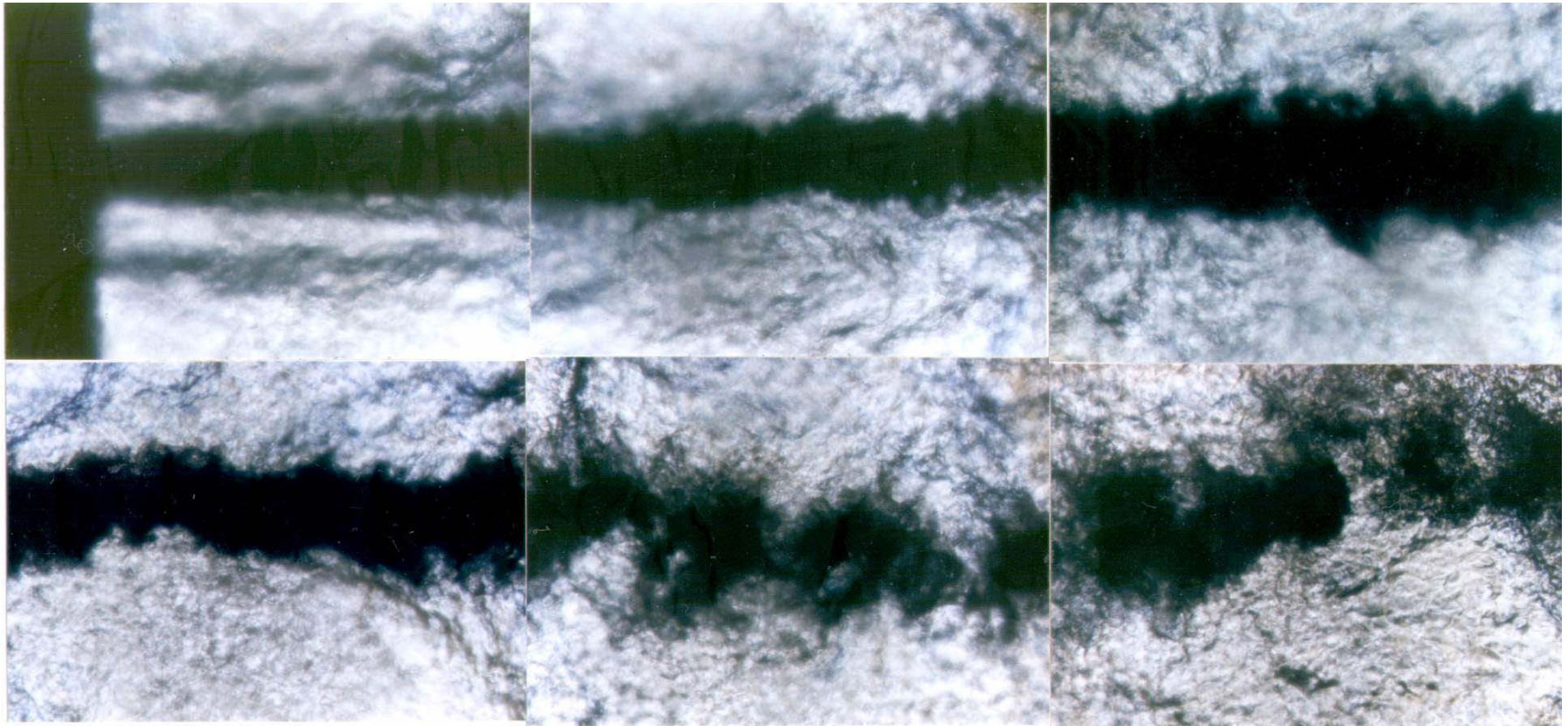


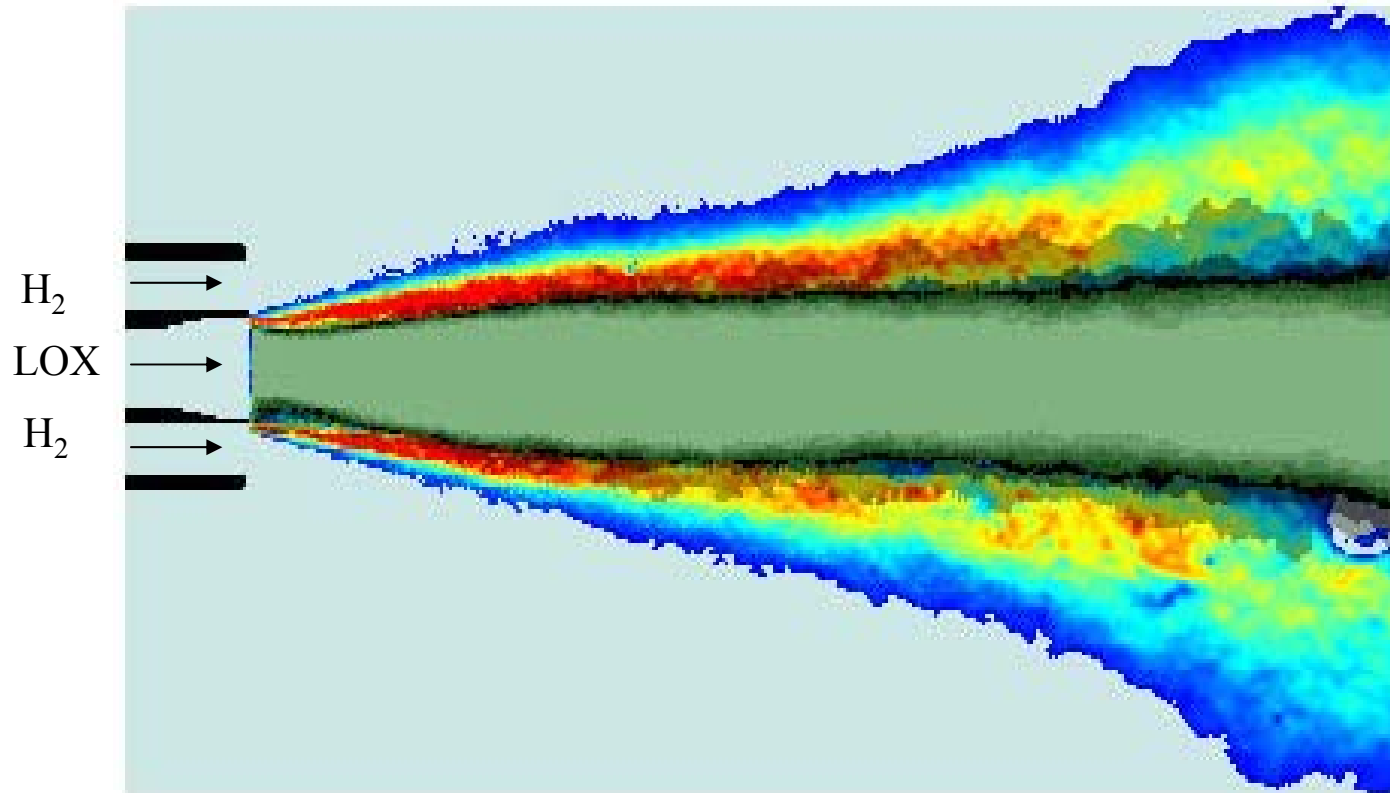
# Burning LOX Jet at Supercritical Pressure

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

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$(u_{\text{LOX}} = 30 \text{ m/s}, u_{\text{H}_2} = 300 \text{ m/s}, T_{\text{LOX}} = 100 \text{ K}, T_{\text{H}_2} = 300 \text{ K}, p = 6 \text{ MPa})$

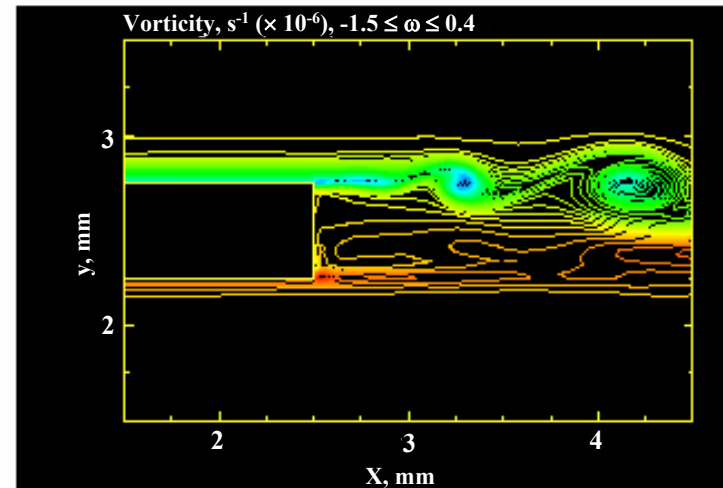
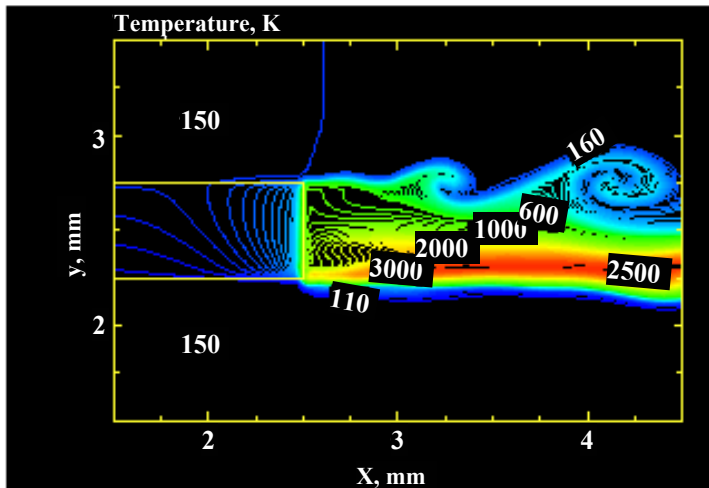
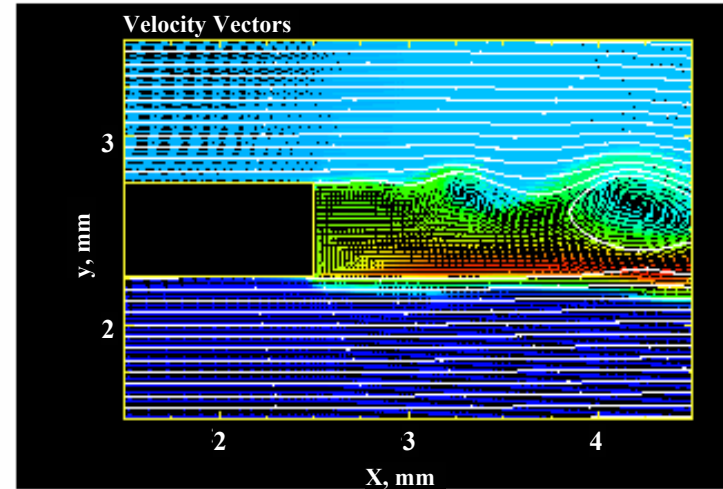
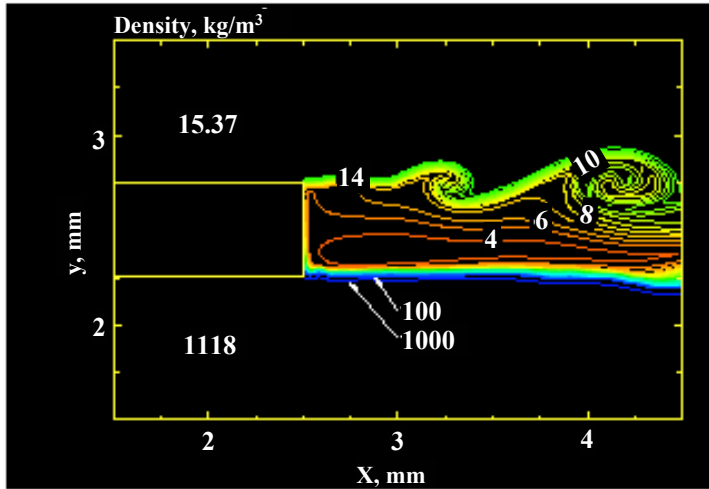




Combined OH emission and backlighting images (Ph.D thesis of Matthew Juniper)

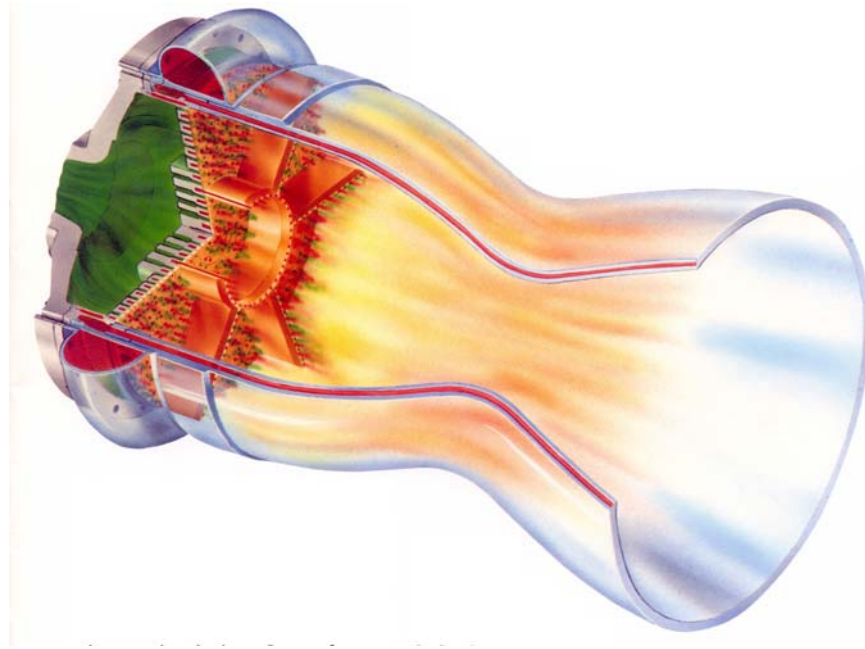
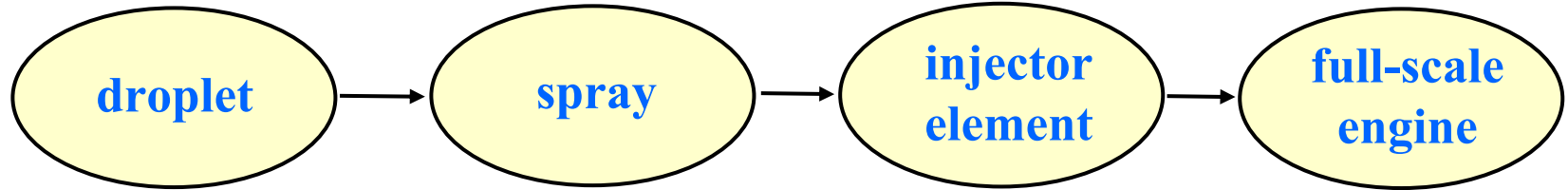


# LOX/Hydrogen Shear-Coaxial Injector Dynamics





# Modeling and Simulation of Supercritical Combustion



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**Thank You!**

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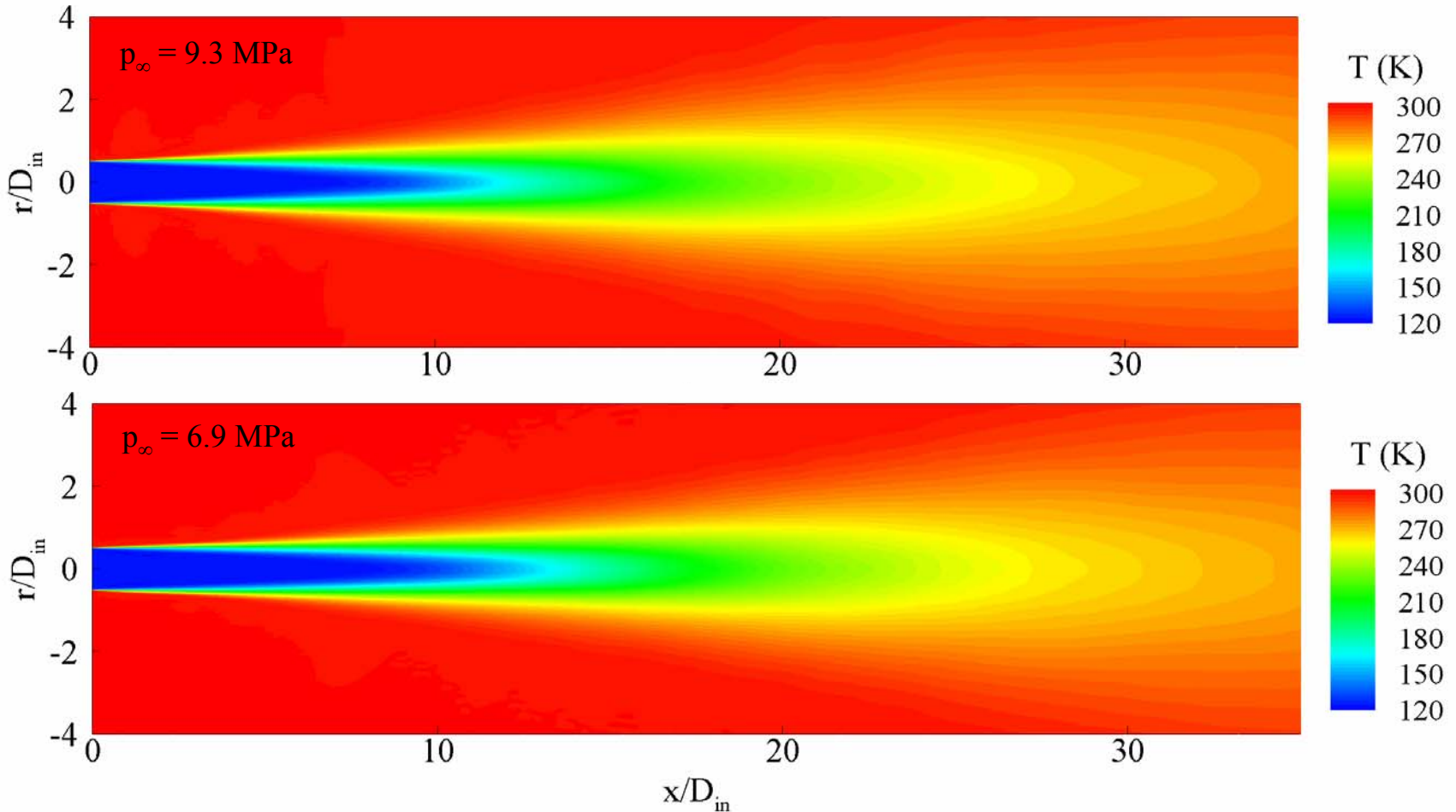
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# Effect of Pressure on Mean Temperature Distributions

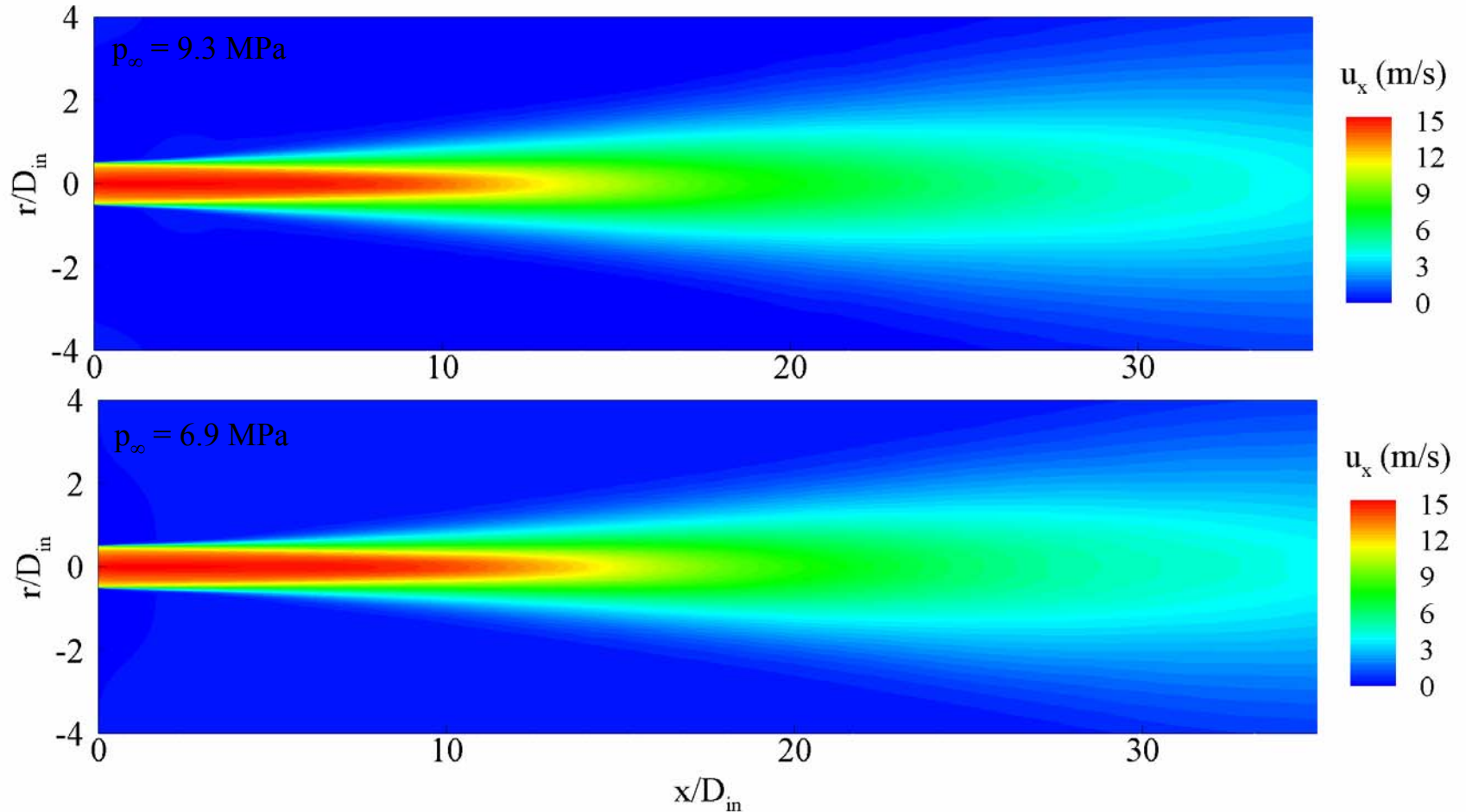
$(T_\infty = 300 \text{ K}, u_{in} = 15 \text{ m/s}, T_{in} = 120 \text{ K}, D_{in} = 254 \mu\text{m})$





# Effect of Pressure on Mean Velocity Distributions

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

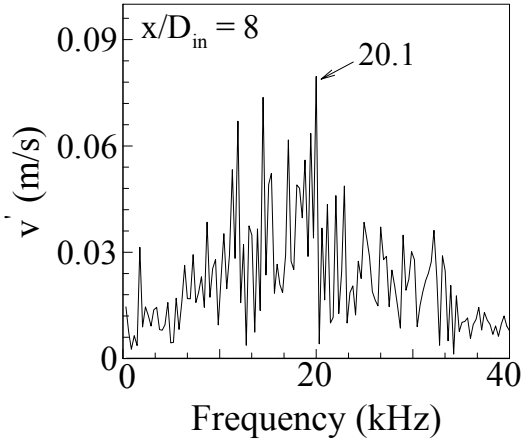




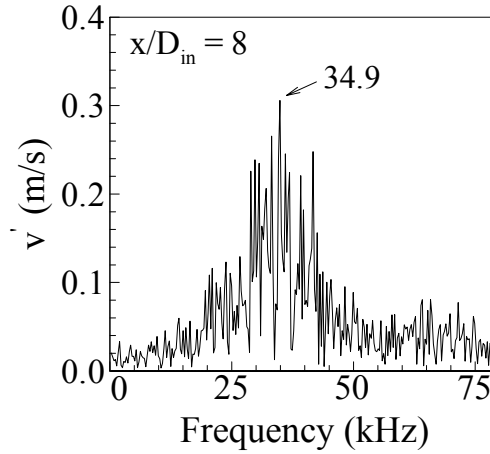


# Frequency Spectral of Radial Velocity Oscillations

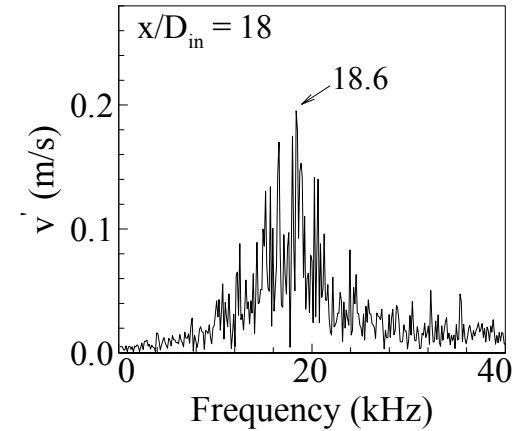
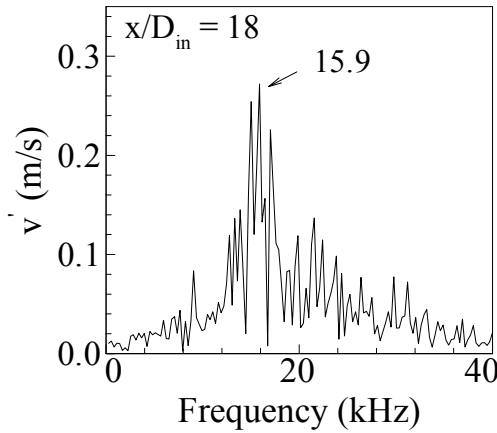
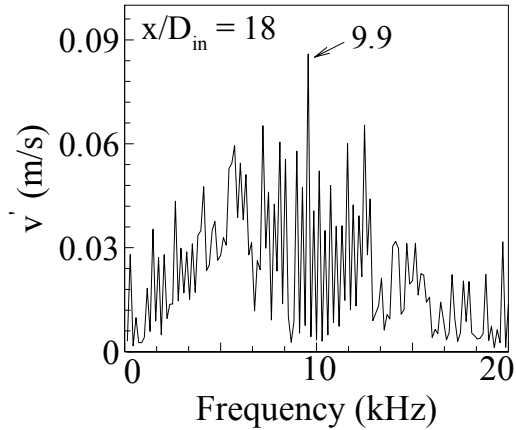
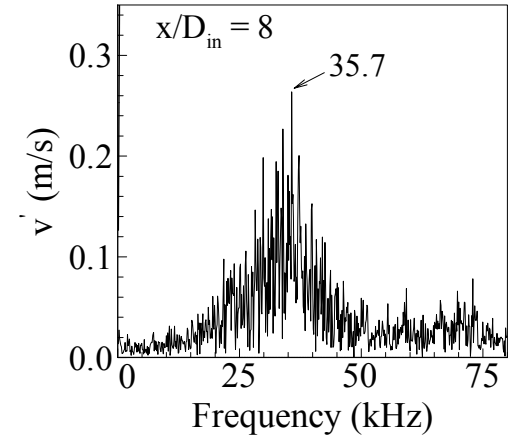
$p = 4.2 \text{ MPa}$



$p = 6.9 \text{ MPa}$



$p = 9.3 \text{ MPa}$

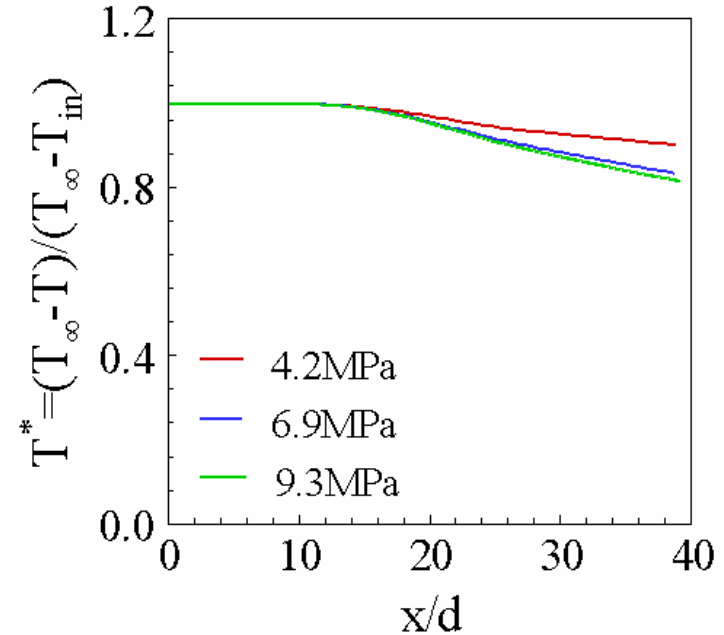
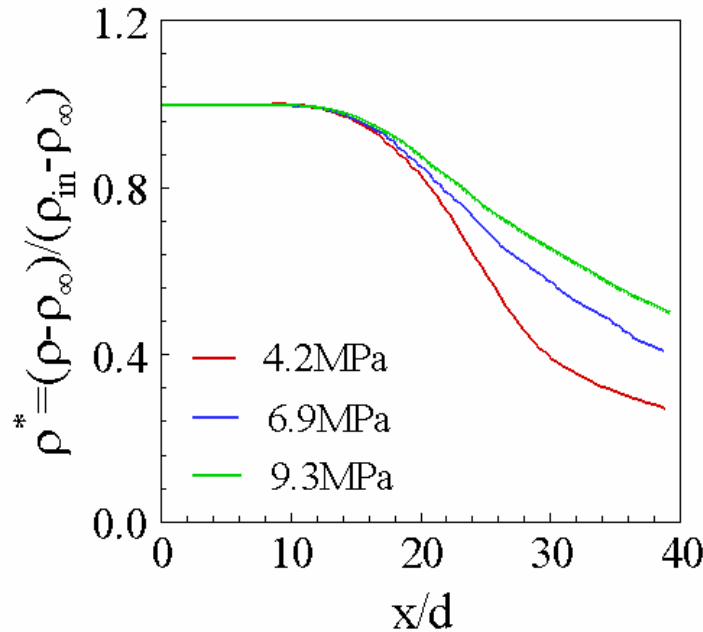




# Normalized Density and Temperature Distributions along Radial Direction

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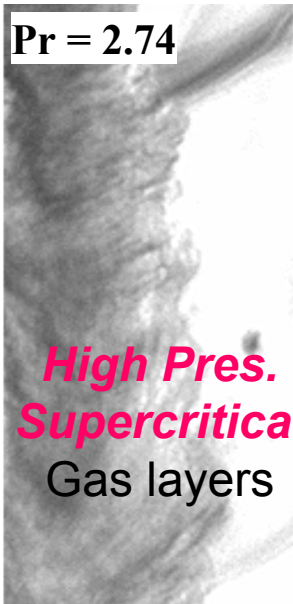
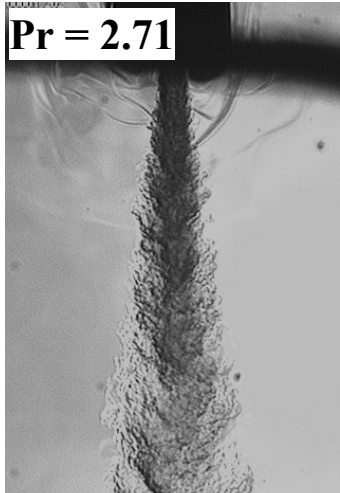
$$T_{\infty} = 300\text{K}, u_{in} = 15\text{m/s}, T_{in} = 120\text{K}, D_{in} = 254\mu\text{m}$$



- 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

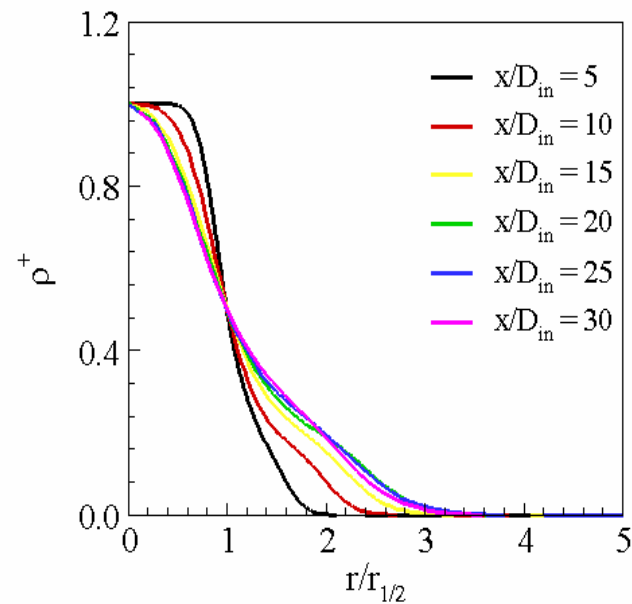
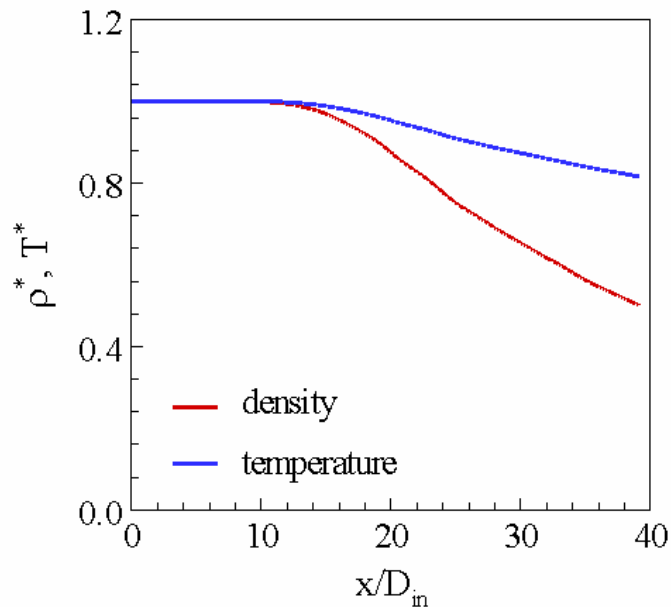
- machine round-off errors at low speeds
- eigenvalue disparity
- time accuracy
- real-fluid behavior
- robust and efficient numerical treatment

## 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



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



- 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  $x/d > 15$ .

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