Application of Visualization Techniques and Quantitative Optical Diagnostics for the Investigation of Supercritical Jet Atomization

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8th International Symposium on Fluid Control, Measurement and Visualization
Chengdu, China, August 22-25, 2005
conditions in high power cryogenic liquid rocket engines

- propellants: LOX/H2
- pressure: ≈ 11 MPa
- injection temperature: ≈ 100 K
- hot gas temperature: ≈ 3500 K
- propellant injection by about 500 injectors
- atomization by shear-coaxial injection

\[ v_{\text{LOX}} \approx 20 \text{ m/s} \]
\[ v_{\text{H2}} \approx 400 \text{ m/s} \]
thermo-physical properties of oxygen

- $P_{\text{crit,LOX}} = 5.04 \text{ MPa}, T_{\text{crit,LOX}} = 154.6 \text{ K}$
- injection at supercritical pressure and subcritical temperature
  - sensitive dependence of density on temperature
  - maximum value of specific heat
  - minimum thermal diffusivity
  - high compressibility
  - high diffusivity
optical diagnostics at high pressure

high pressure:
- high densities
- high density gradients
- high refractive index gradients

interaction of light with matter at high densities:
- beam steering, beam reflections
- interaction of light with molecules influenced by collisions
  - quenching
  - collisional line broadening
- high signal intensities, non-linear effects

at injection conditions (10 MPa, 100 K):
- \( \rho_{O_2} = 1116 \text{ kg/m}^3 \)
- \( \rho_{H_2} = 23 \text{ kg/m}^3 \)
- \( \rho_{O_2} / \rho_{H_2} = 49 \)

density ratio between supercritical jet and background gas (typically)
- \( \rho_{\text{jet}} / \rho_{\text{gas}} \approx 10^{-16} \)

Gladstone-Dale relationship
- \( n - 1 = k \cdot \rho \)
cold flow tests
cryo-injector test facility

$N_2$-injection at sub- and supercritical conditions:

- $P_{N_2} = 0.1 \ldots 6$ MPa \quad (0.03 < P_r < 1.8)
- $T_{N_2} = 80 \ldots 140$ K \quad (0.64 < T_r < 1.1)

various injection configurations

- free trans-critical jets (LN$_2$)
- shear coaxial injection (LN$_2$/H$_2$ or He)

optical diagnostics

- high speed photography
- spontaneous Raman scattering
cold flow tests

shadowgraphy LN$_2$ free jet injected into N$_2$-gas with increasing pressure

- vanishing surface tension
- reduction length scales of surface irregularities
- increased spreading angle

LN$_2$: 100 K  
GN$_2$: 293 K  
v$_{LN2}$: 5 m/s

Pr = 0.3  0.59  0.85  1.18  1.47  1.77
cold flow tests
shadowgraphy coaxial LN$_2$/He injection

- spray formation at subcritical pressure
- vanishing surface tension at critical point
- turbulent mixing of dense and light fluid components at supercritical pressure

$\begin{align*}
\nu_{\text{LN}_2} &= 5 \text{ m/s} \\
\nu_{\text{He}} &= 100 \text{ m/s} \\
T_{\text{LN}_2} &= 97 \text{ K} & T_{\text{He}} &= 280 \text{ K} \\
P_c &= 1.0 \text{ MPa} & P_r &= 0.3 \\
P_c &= 6.0 \text{ MPa} & P_r &= 1.8
\end{align*}$
cold flow tests
density measurement by spontaneous Raman scattering

inelastic scattering process
- signal photon at different wavelength than exciting photon
- signal is species specific
- \( I_{\text{Raman}} \propto \sigma \cdot \rho \)

high pressure effects:
- signal level benefits from high pressure conditions
- N.B.: at high densities internal field effects: \( \sigma = \sigma(\rho) \)
- high signal levels may result in non-linear effects: use of cw-laser recommended
cold flow tests / Raman scattering
test cases

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raw data

case A4
\( T_{\text{N2}} = 140 \text{ K} \)
\( n_{1,2} = 1.025 \)

case C4
\( T_{\text{N2}} = 100 \text{ K} \)
\( n_{1,2} = 1.157 \)
cold flow tests / Raman scattering
LN$_2$ free jet

Centre line density decay

$$\frac{(\rho_{\text{max}} - \rho_R)/(\rho_I - \rho_R)}{x/D}$$

Centre line temperature decay

$$\frac{(T_{\text{min}} - T_R)/(T_I - T_R)}{x/D}$$

Pseudo boiling due to maximum of specific heat
cold flow tests / Raman scattering
LN$_2$/H$_2$ coaxial injection

- colder N$_2$-jet: less efficient atomization
- increased H$_2$-momentum flux: no pronounced increase in atomization efficiency
- heat exchange between LN$_2$ and H$_2$

$T_{N2}$=140K, $T_{H2}$=270K

$T_{N2}$=118K, $T_{H2}$=270K
hot fire tests at P8 test facility

test bench P8
  - F/G research and technology test bench
  - LOX-supply system
  - GH₂-, LH₂-, CH₄-supply systems

DLR combustor "C"
  - single coax injector head
  - \( P_c \) up to 10 MPa, combustion at supercritical \( O_2^- \) and \( CH_4^- \)-pressures
  - optical access
    - shadowgraphy
    - OH-imaging
    - CARS
hot fire tests
shadowgraphy of LOX/H$_2$ supercritical injection

LOX-jet disintegration:

(a) Subcritical Pressure, 1.5 MPa Combustion

(b) Supercritical Pressure, 10 MPa Combustion

LOX-jet at subcritical (a) and supercritical (b) pressure conditions (from Mayer and Tamura)

- **subcritical:**
  - disintegration into LOX-droplets

- **supercritical:**
  - disintegration into O$_2$ clumps of larger size than typical liquid entities in subcritical case

Visualization of O$_2$-jet disintegration with varying chamber pressure (Mayer and Smith)

results from tests at NAL (Mayer/Tamura) and DLR (Mayer/Smith)
hot fire tests

flame visualization by OH-imaging

- detection of flame emission in spectral range of OH chemiluminescence
- optical components have to be transmittive in UV (standard optics blind below 350nm)
- strong thermal emission of H\textsubscript{2}O at high pressure
hot fire tests

CARS thermometry

Coherent Anti-Stokes Raman spectroscopy
- non-linear 4-wave mixing process
- determination of ro-vib level population
- temperature determination by fitting simulated to experimental spectra

adaptation of laser systems
- modeless dyelaser for increased accuracy

H$_2$-CARS spectra simulation
- broadening coefficients for H$_2$/H$_2$O collisions (V. Smirnov et al., IOFAN, GPI, RAS Moscow)

adaptation of experimental set-up
- hardening of optical mounting against vibrational load at test facility
- remote control

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hot fire tests
CARS at combustor "C" at 6.3 MPa

- beam steering observed, but not prohibitive to signal generation
- reduced signal validation rate
  - in the near injector region
  - in the central spray region
- at high pressures reduced transmission due to $\text{H}_2\text{O}$ condensation in recirculation zone

- spatially and temporally resolved temperature data
  - progress of combustion and state of mixing
hot fire tests
CARS at combustor "C" at 6.3 MPa
conclusions

optical diagnostics in supercritical conditions
  - high densities and density gradients
  - molecular spectroscopic properties change due to collisions

shadowgraphy
  - qualitative characterization of atomization process
  - derivation of geometric jet properties, like jet spreading angle

spectroscopic methods
  - necessary to take collisional interaction into account
  - high signal intensities may favour parasitic non-linear interactions
  - signal may suffer from beam steering
  - quantitative results obtained at pressures up to 6 MPa in reactive cryogenic flow!