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

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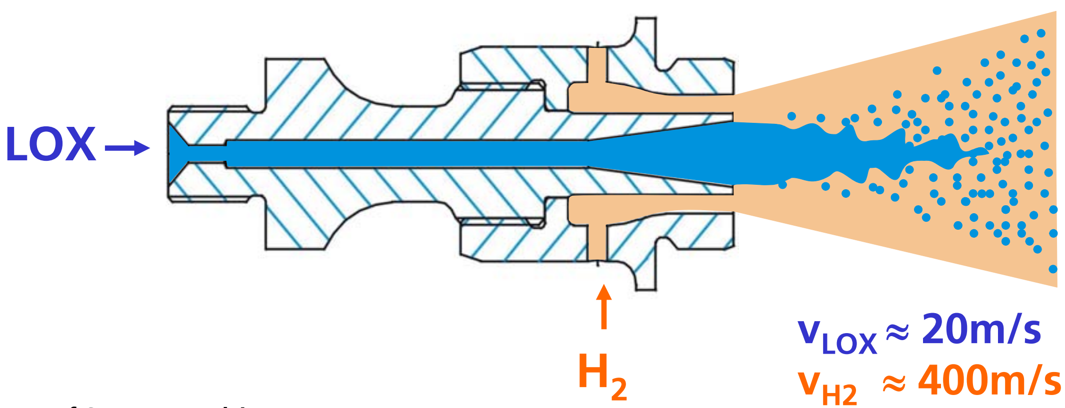
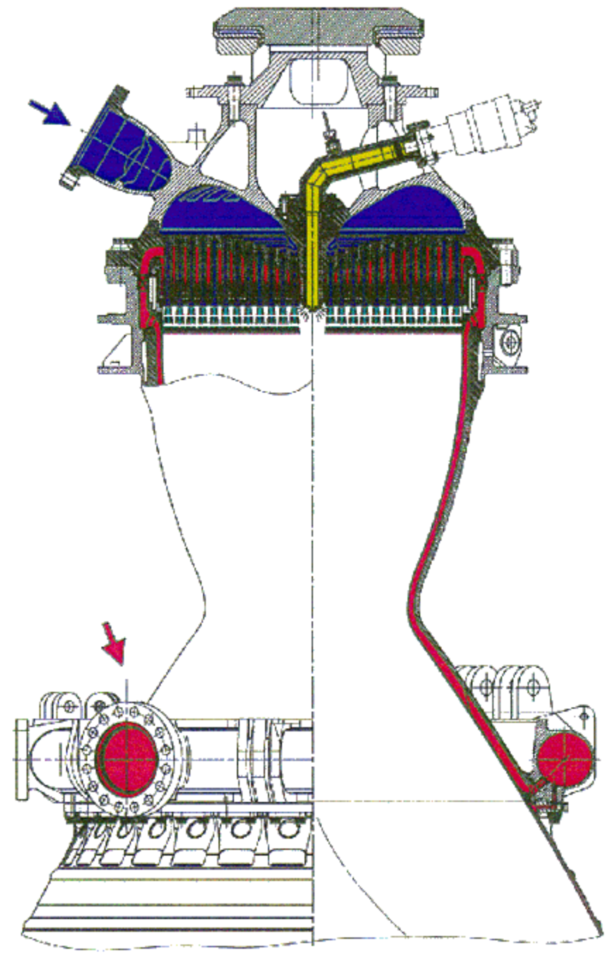
8th International Symposium on Fluid Control, Measurement and Visualization
Chengdu, China, August 22-25, 2005

conditions in high power cryogenic liquid rocket engines

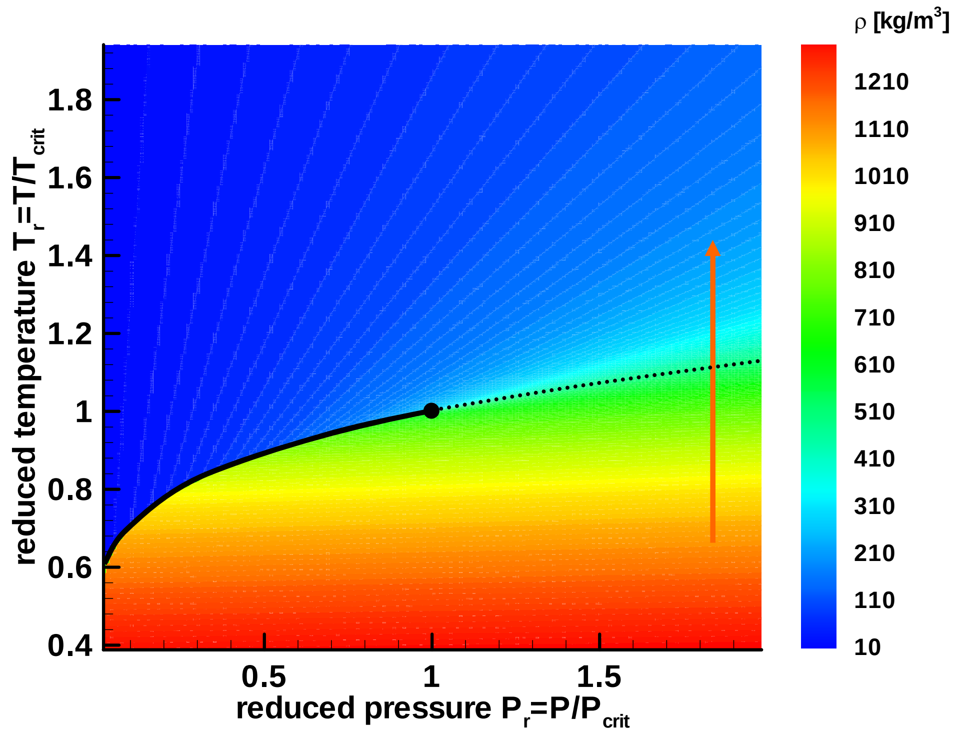
- propellants: LOX/H2
- pressure: ≈ 11 MPa
- injection temperature: ≈ 100 K
- hot gas temperature: ≈ 3500 K
- propellant injection by about 500 injectors
- atomization by shear-coaxial injection

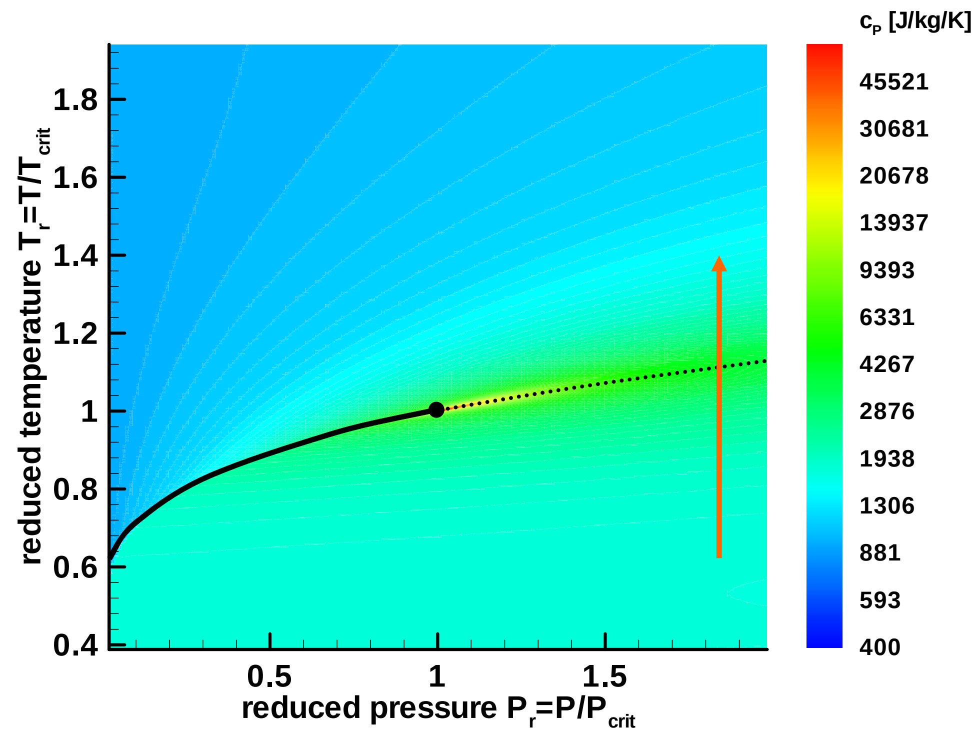




thermo-physical properties of oxygen

- $P_{crit,LOX} = 5.04$ MPa, $T_{crit,LOX} = 154.6$ 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):

- $\rho_{O2} = 1116\ kg/m^3$
- $\rho_{H2} = 23\ kg/m^3$
- $\rho_{O2} / \rho_{H2} = 49$

density ratio between supercritical jet and background gas (typically)

- $\rho_{jet} / \rho_{gas} \approx 10\text{-}16$

Gladstone-Dale relationship

- $n - 1 = k \cdot \rho$

cold flow tests

cryo-injector test facility

N_2-injection at sub- and supercritical conditions:

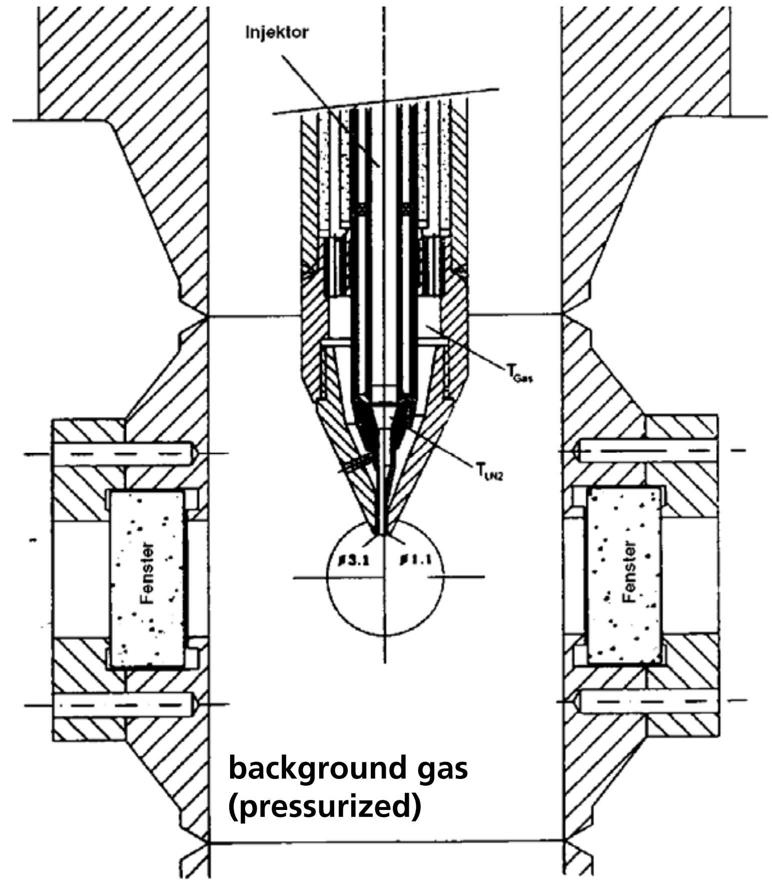
- P_{N2} = 0.1 ... 6 MPa (0.03 < P_r < 1.8)
- T_{N2} = 80 ... 140 K (0.64 < T_r < 1.1)

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



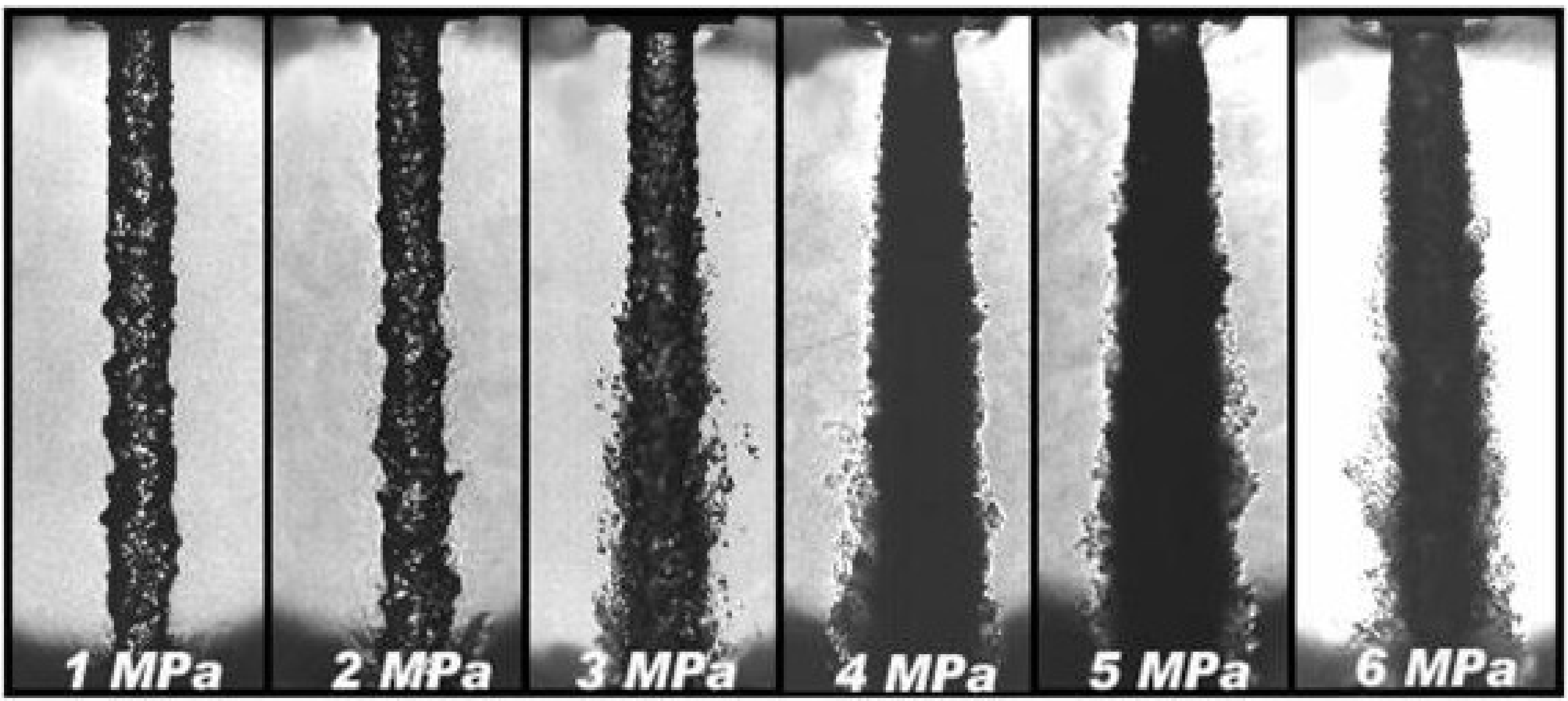
cold flow tests

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}:	5m/s



$P_r = 0.3$ 0.59 0.85 1.18 1.47 1.77

DLR

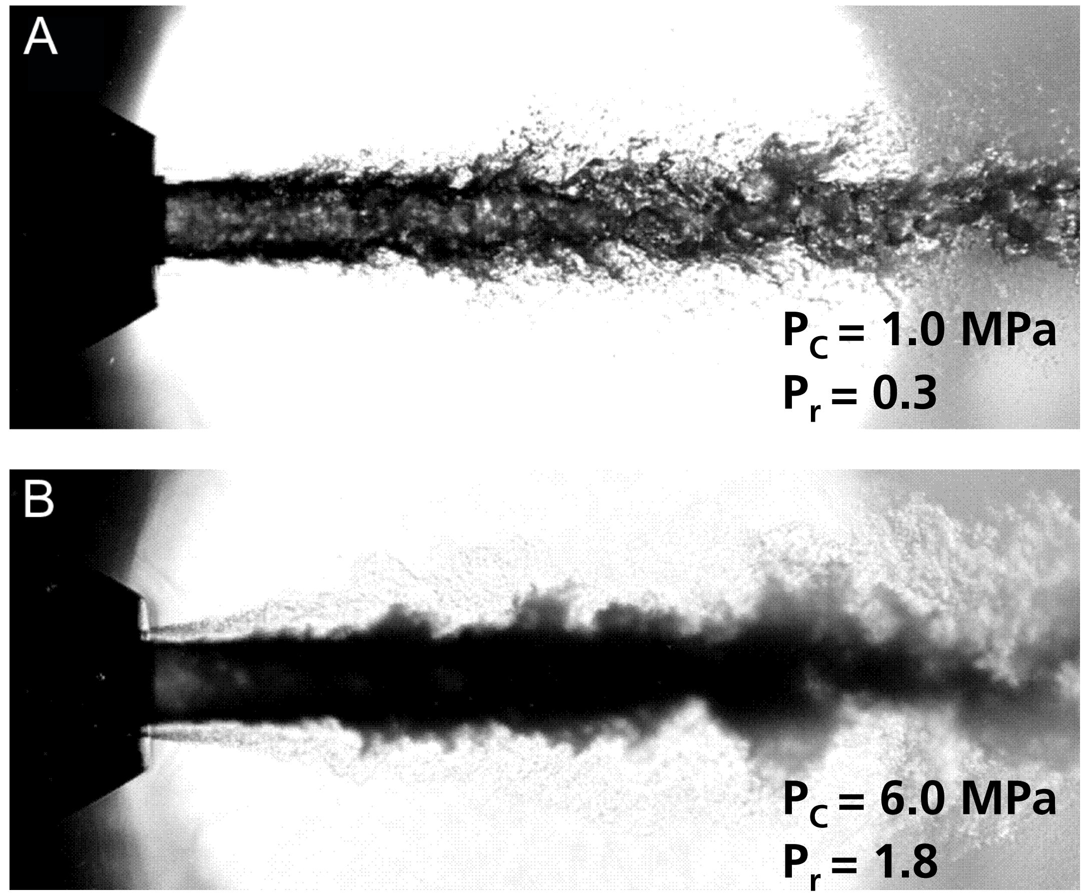
cold flow tests

shadowgraphy coaxial LN_2/He injcetion

v_{LN2} = 5 m/s T_{LN2} = 97 K

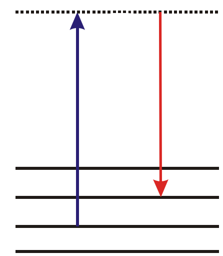
v_{He} = 100 m/s T_{He} = 280 K

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



cold flow tests

density measurement by spontaneous Raman scattering

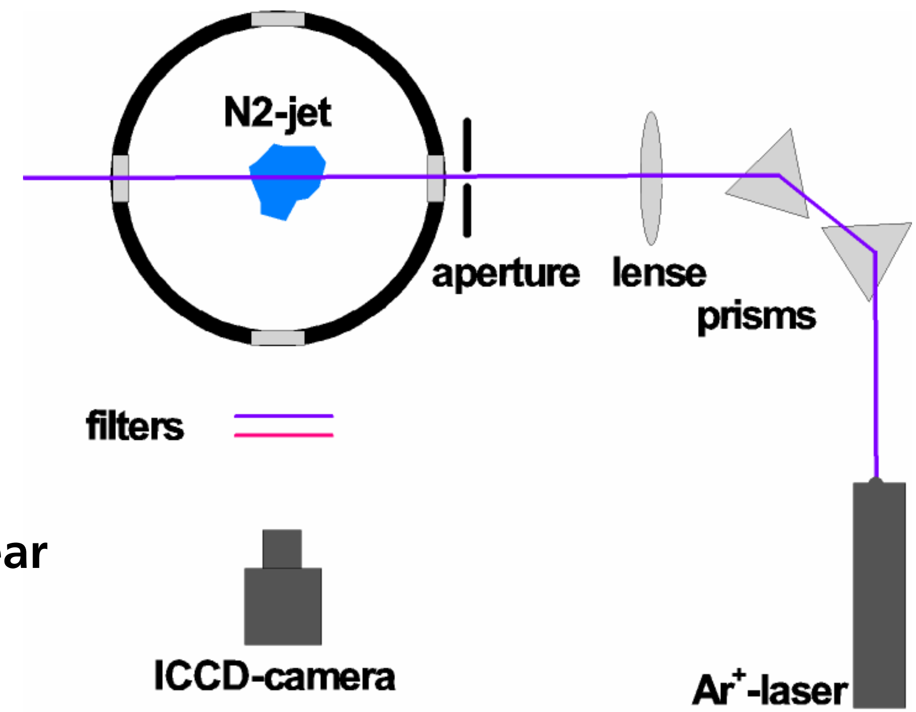


inelastic scattering process

- signal photon at different wavelength than exciting photon
- signal is species specific
- $I_{Raman} \propto \sigma \cdot \rho$

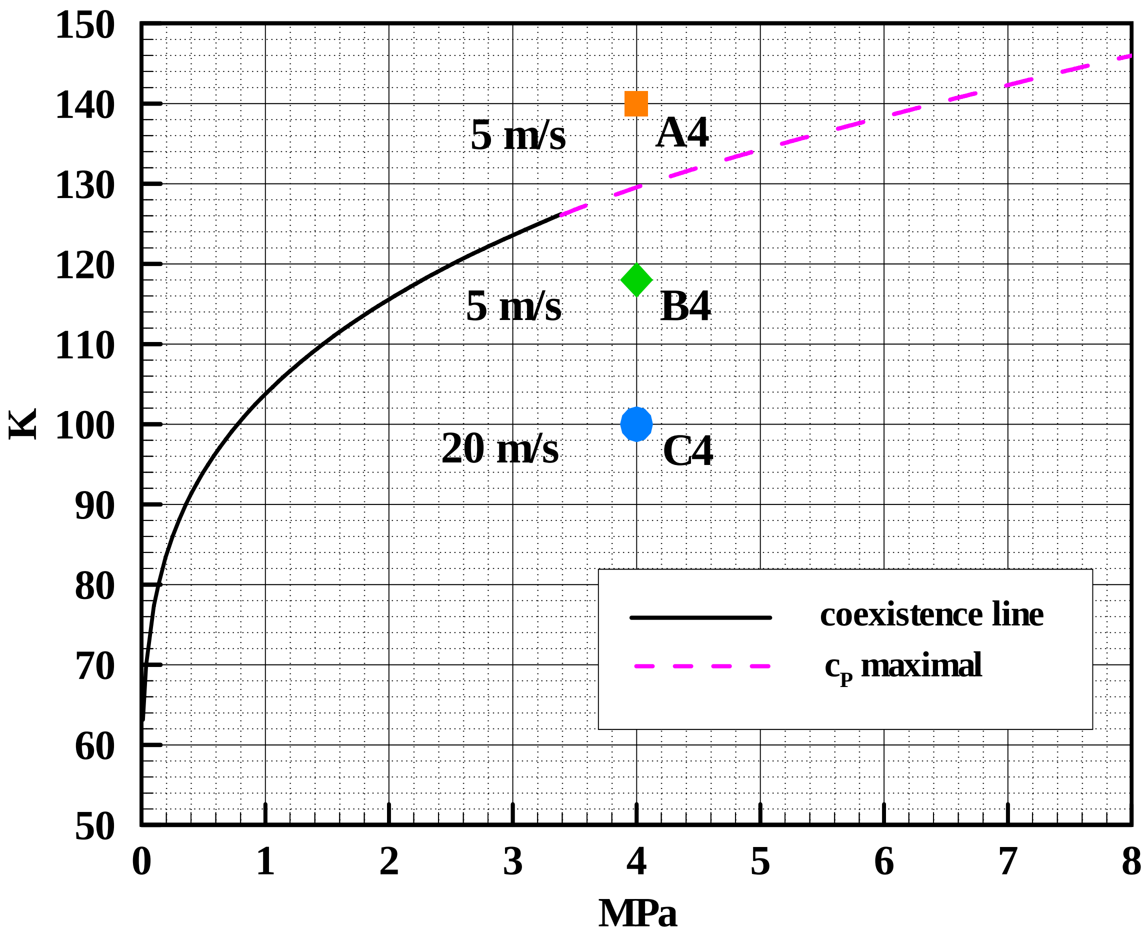
high pressure effects:

- 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

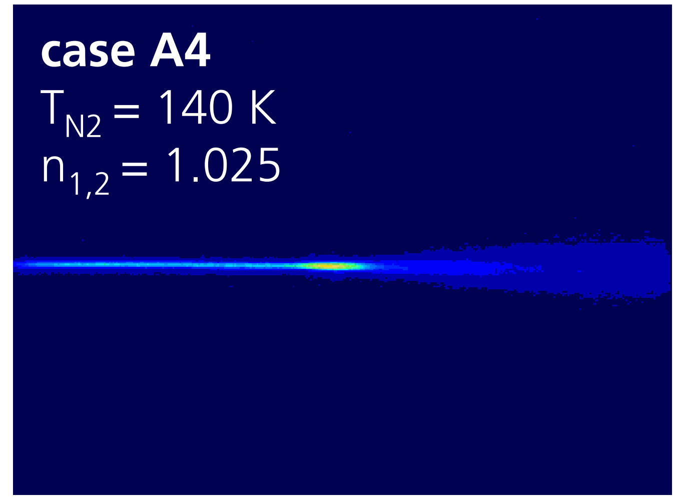


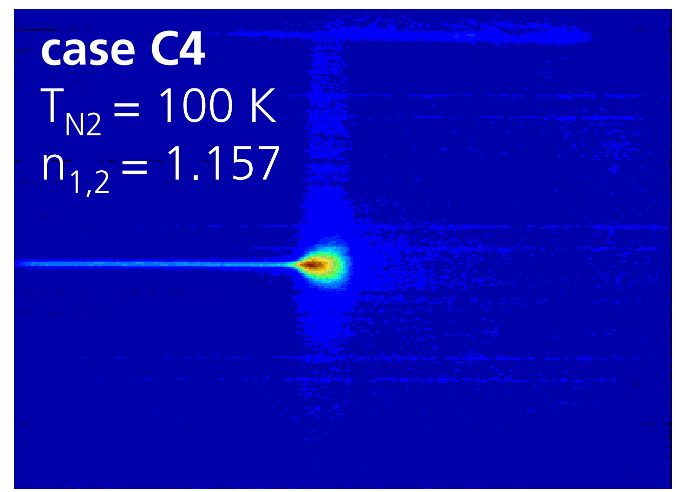
cold flow tests / Raman scattering

test cases



raw data

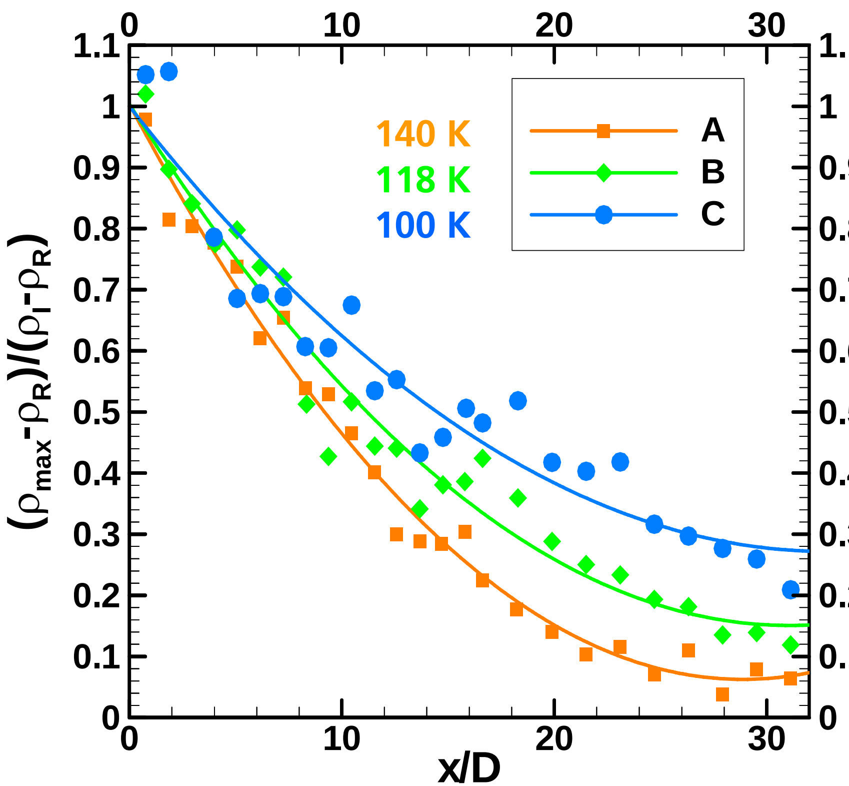




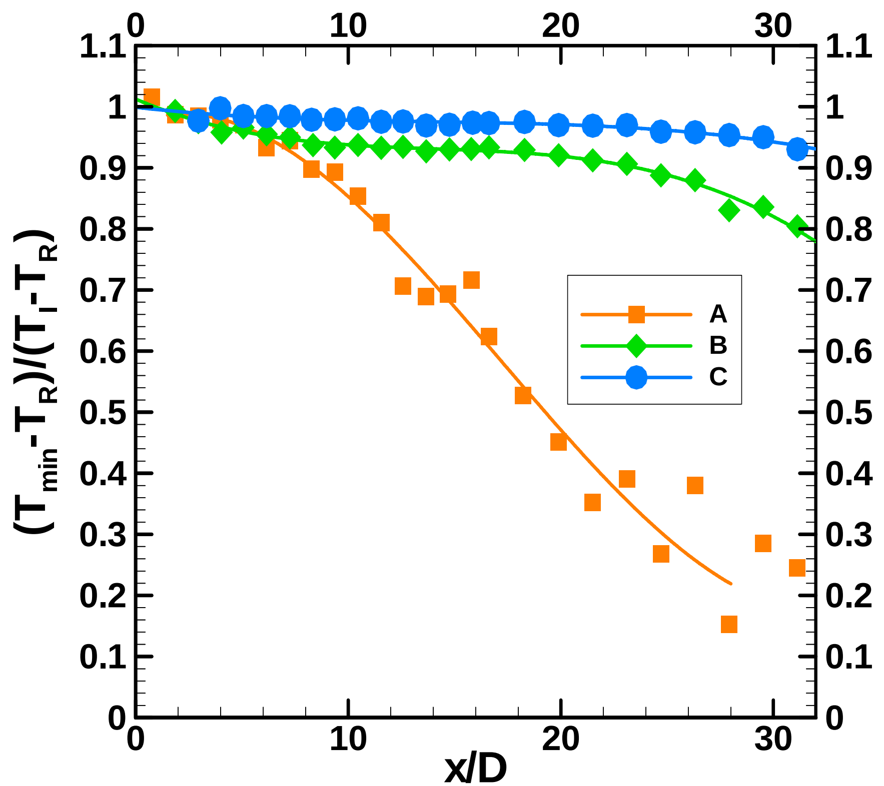
cold flow tests / Raman scattering

LN_2 free jet

centre line density decay



centre line temperature decay



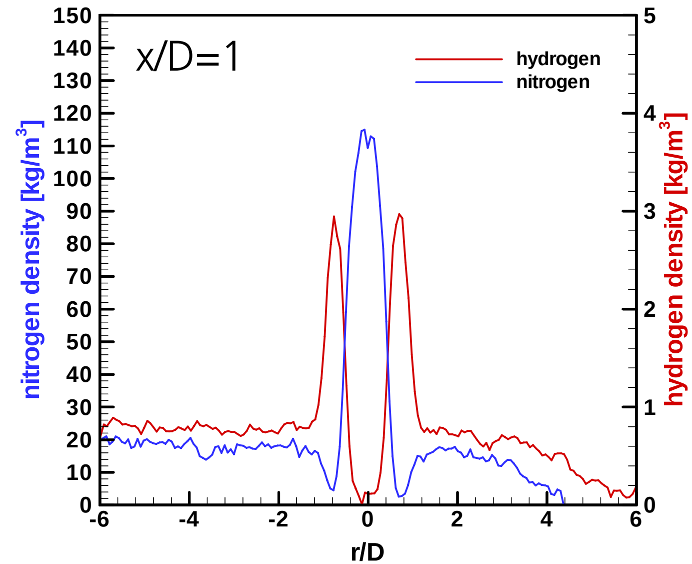
pseudo boiling due to maximum of specific heat

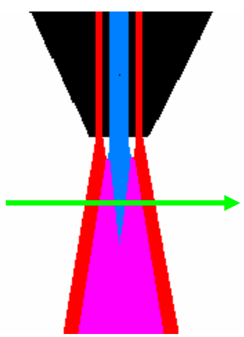
DLR

cold flow tests / Raman scattering

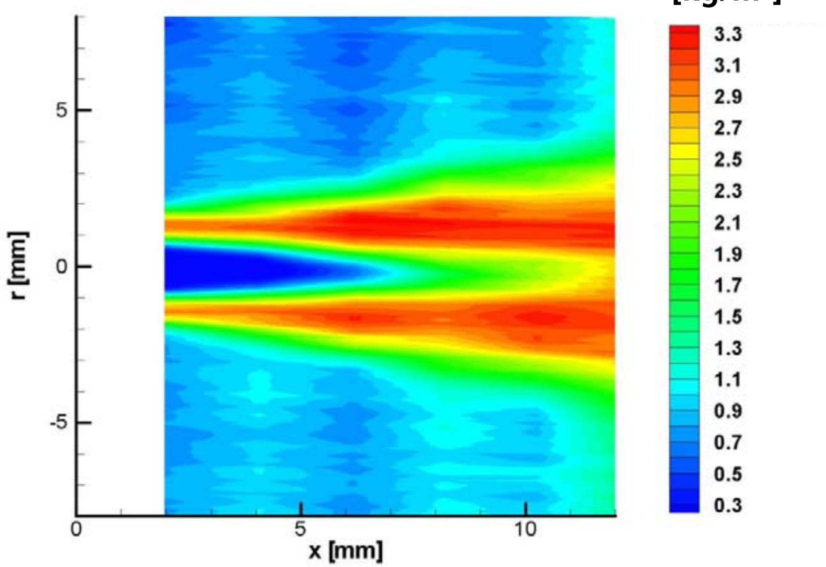
LN_2/H_2 coaxial injection

- 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

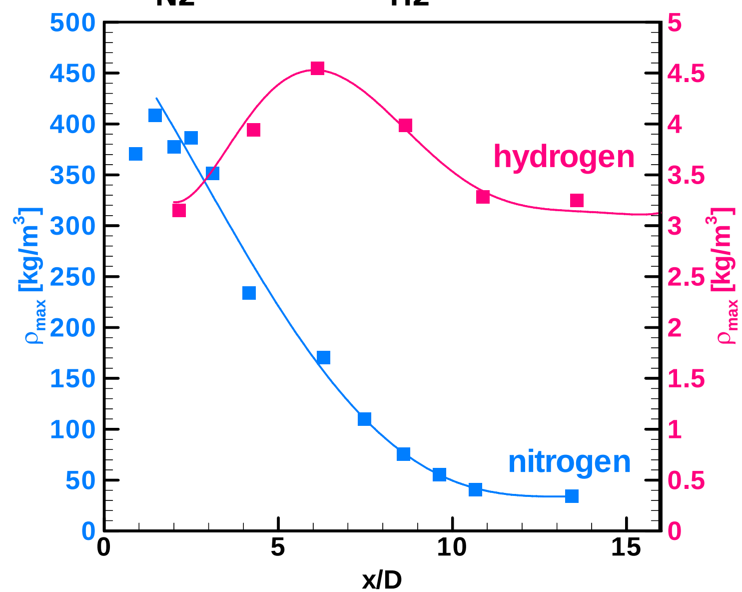




T_{N2}=140K, T_{H2}=270K



T_{N2}=118K, T_{H2}=270K



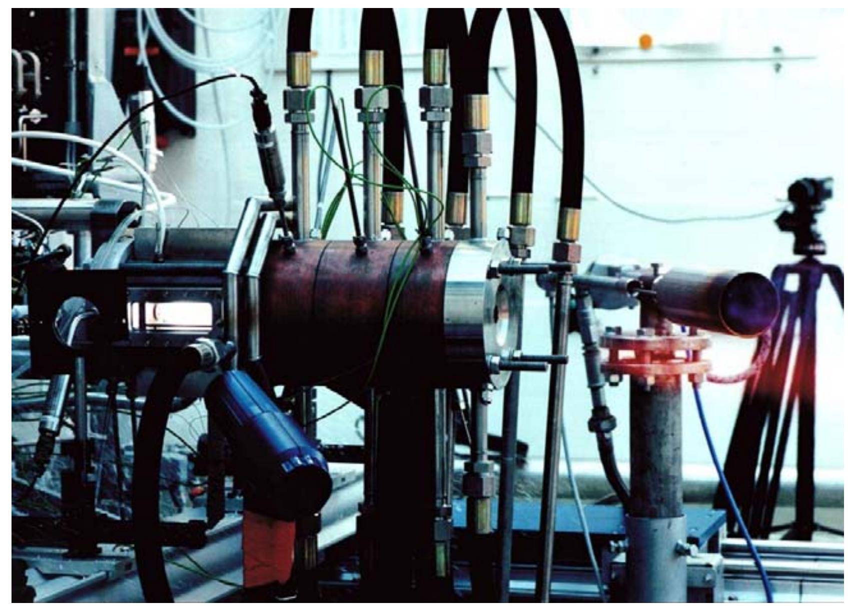
hot fire tests at P8 test facility

test bench P8

- F/G research and technology test bench
- LOX-supply system
- GH_2-, LH_2-, CH_4-supply systems

DLR combustor "C"

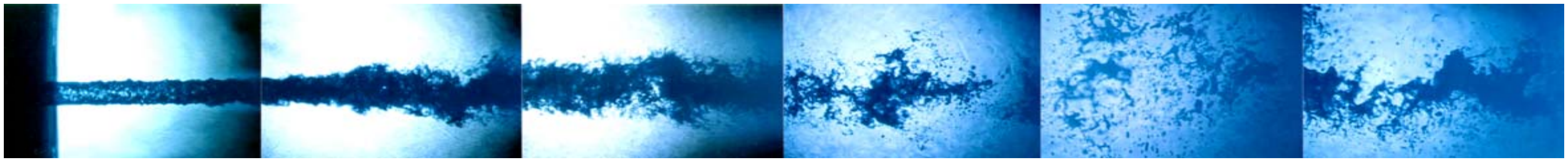
- single coax injector head
- P_C up to 10 MPa, combustion at supercritical O_2- and CH_4-pressures
- optical access
  - shadowgraphy
  - OH-imaging
  - CARS



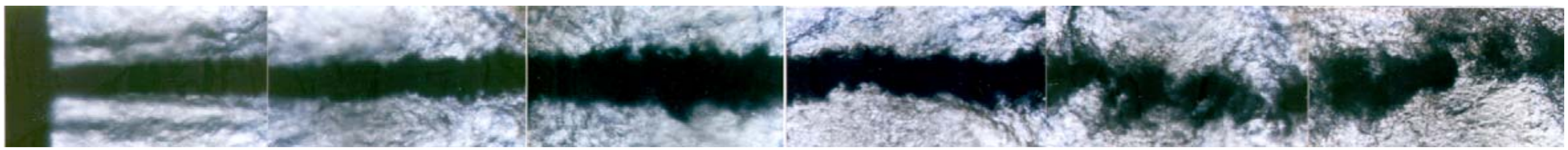
hot fire tests

shadowgraphy of LOX/H_2 supercritical injection

LOX-jet disintegration:



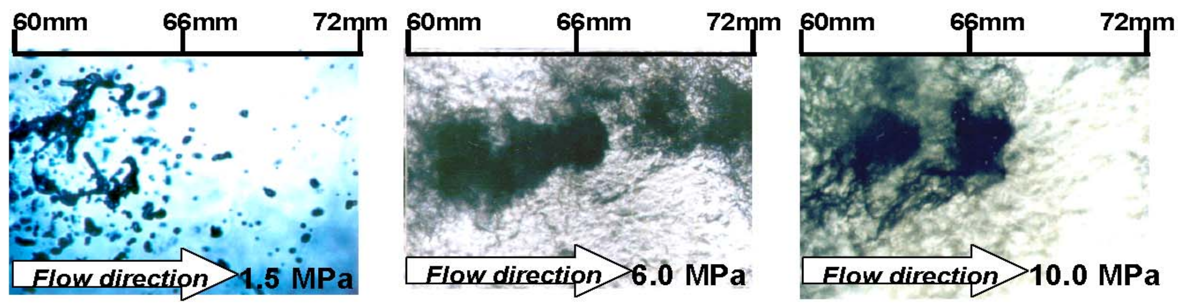
(a) Subcritical Pressure, 1.5 MPa Combustion



(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

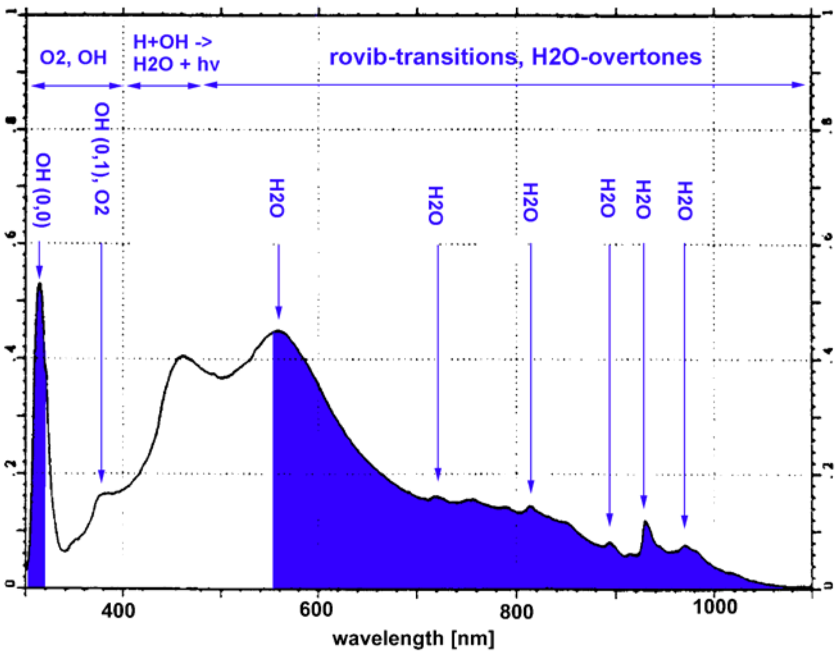


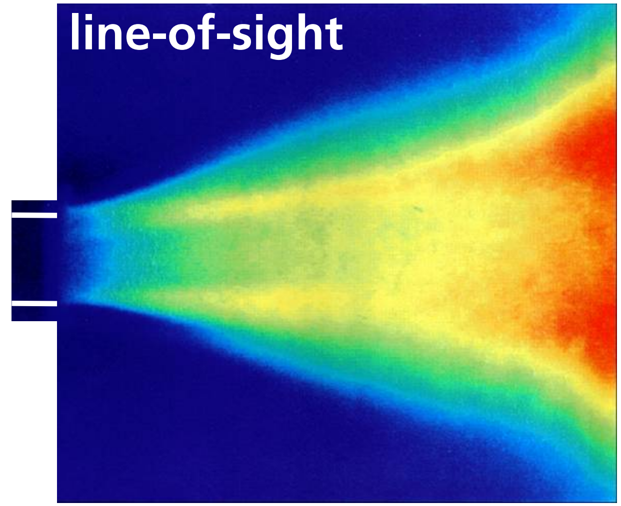
Visualization of O_2-jet disintegration with varying chamber pressure (Mayer and Smith)

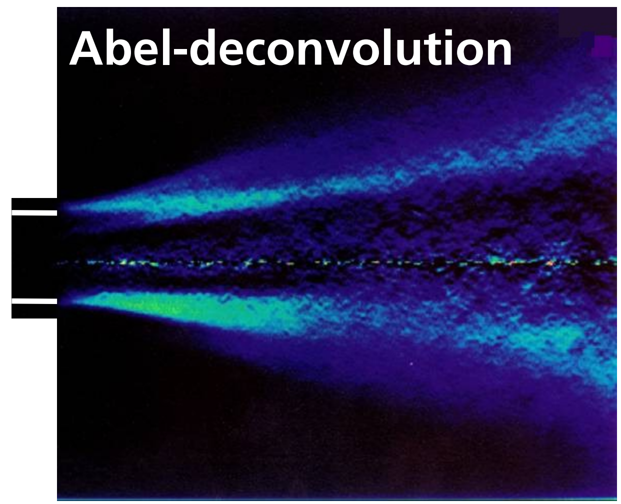
results from tests at NAL (Mayer/Tamura) and DLR (Mayer/Smith)

hot fire tests

flame visualization by OH-imaging



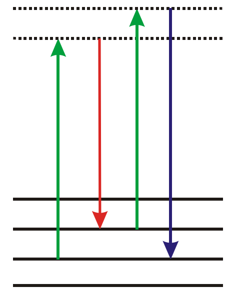




- **detection of flame emission in spectral range of OH chemiluminescence**
- **optical components have to be transmittive in UV** (standard optics blind below 350nm)
- **strong thermal emission of H_2O at high pressure**

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

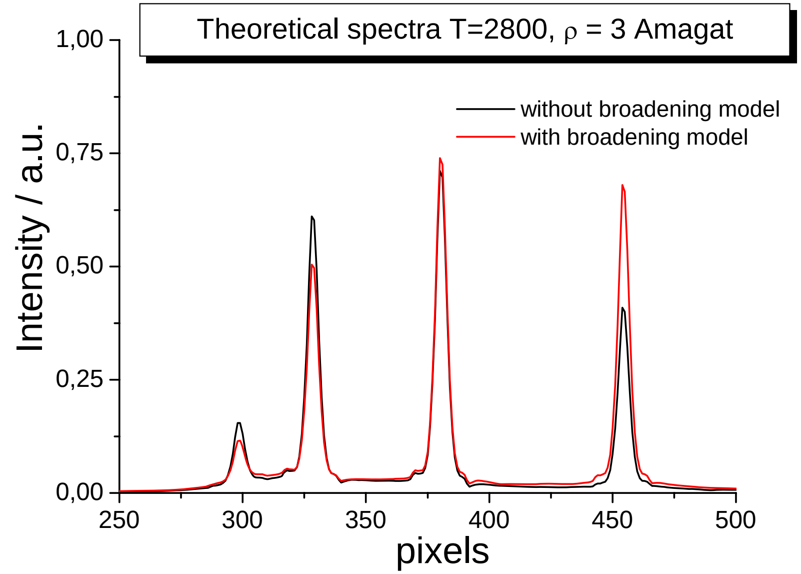
- modeless dyelaser for increased accuracy

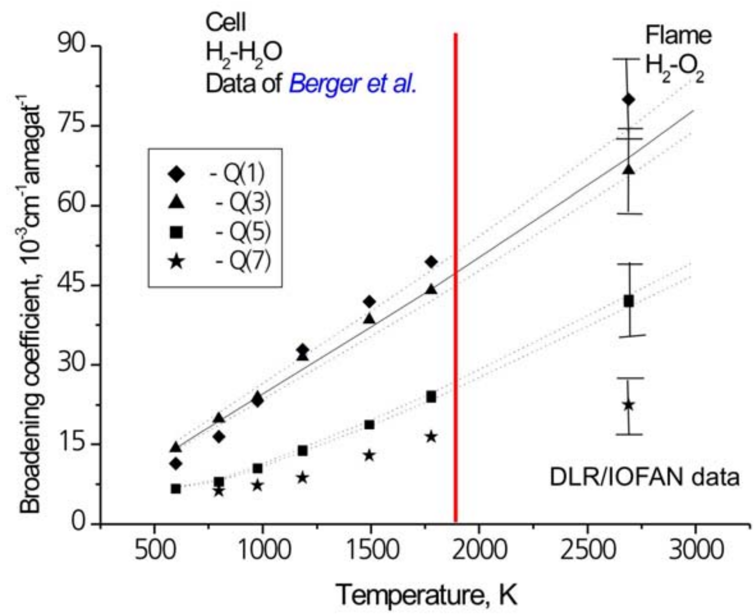
H_2-CARS spectra simulation

- broadening coefficients for H_2/H_2O 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

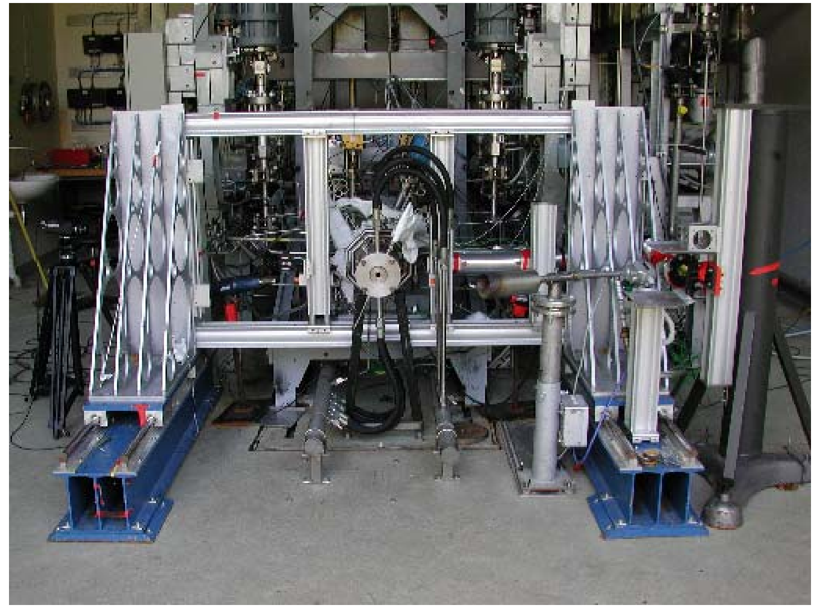




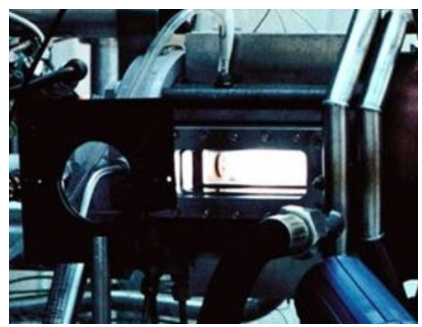
hot fire tests

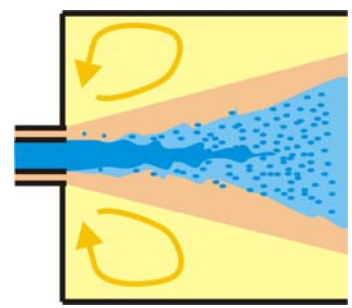
CARS at combustor "C" at 6.3 MPa

- **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 H_2O condensation in recirculation zone**



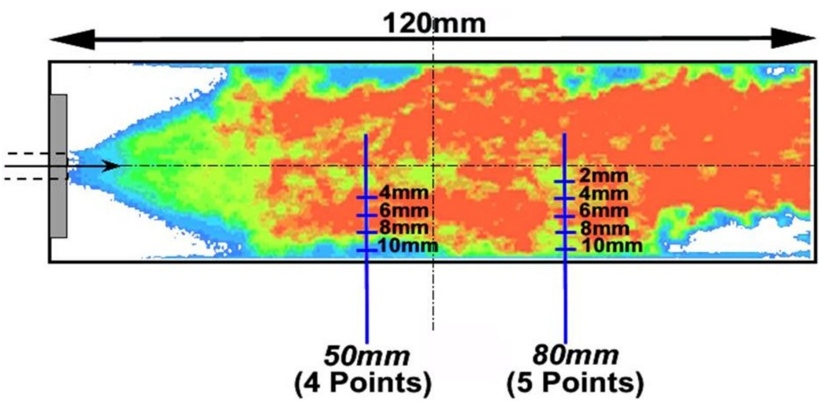
- **spatially and temporally resolved temperature data**
  - progress of combustion and state of mixing

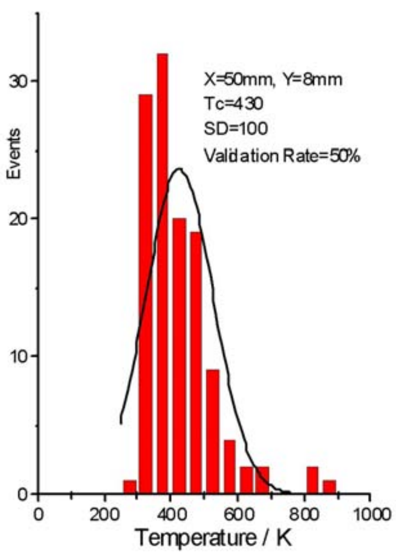


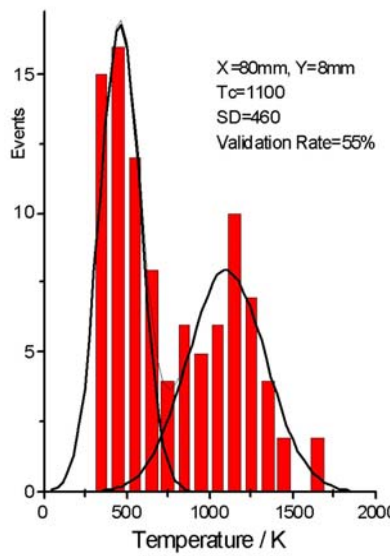


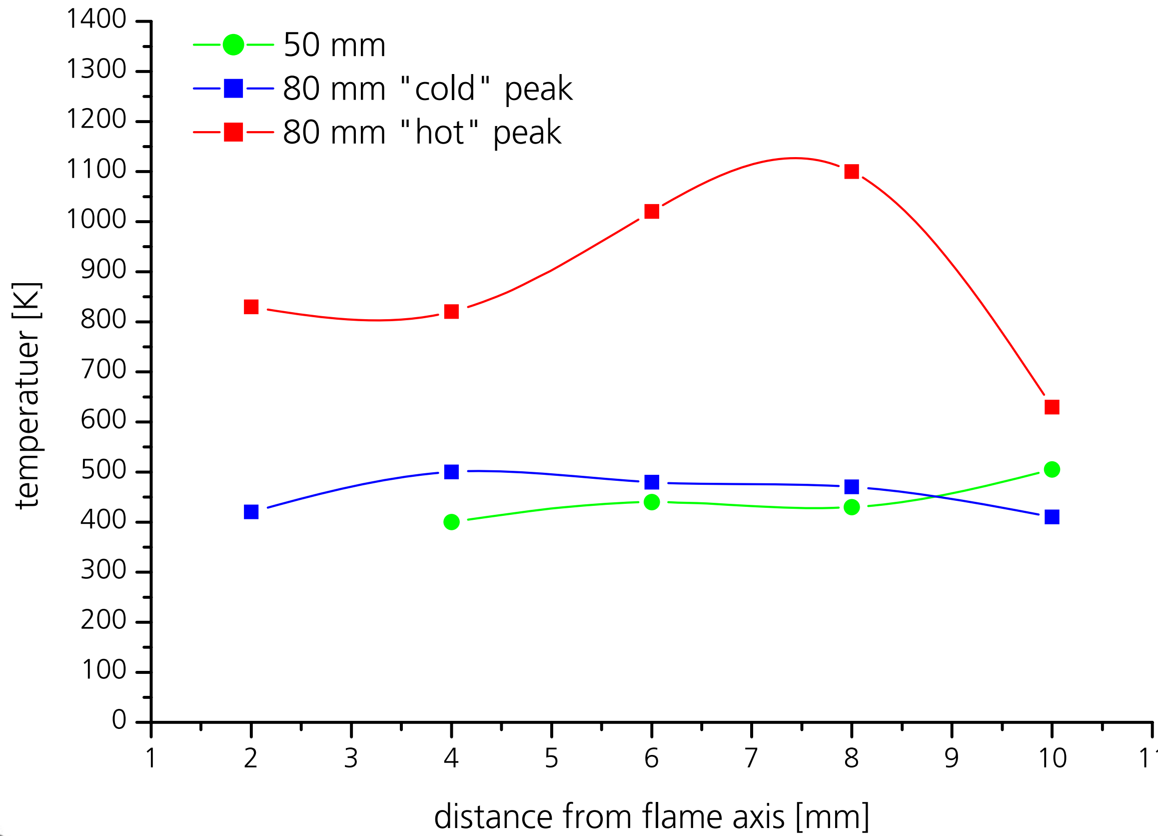
hot fire tests

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!