Atomization and Combustion in LOX/H_2- and LOX/CH_4-Spray Flames Spray

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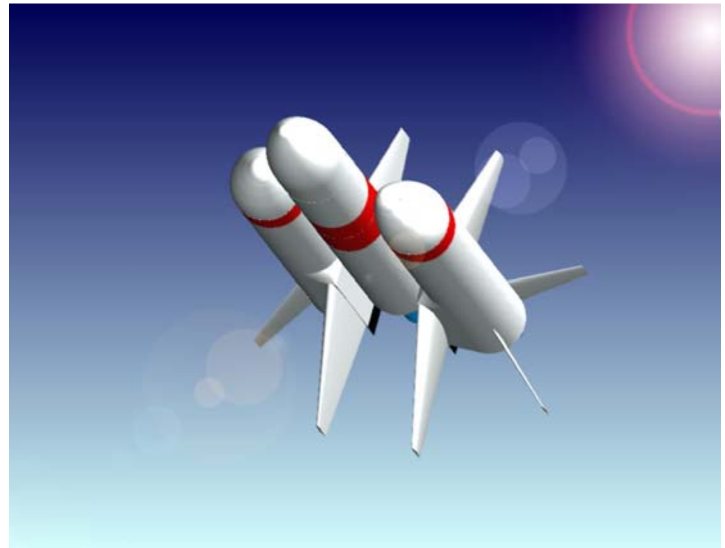
Motivation and Background

LOX/hydrocarbon: promising propellant combination for

- high power booster engine (LFBB, RLV)
- upper stage



advantages

- low costs
- easy ground operation
- high performance (I_{sp} lower than H_2, thrust/weight ratio higher than H_2)
- low toxic potential (green propellant)

HC candidates for booster engines: kerosene, methane

trade-off between kerosene and CH_4

- **I_{sp}=thrust/mass of propellant**
- **thrust/weight**
- **tank masses**
- **chamber cooling:**
  - cooling capability
  - pressure drop
  - coking behavior
- **combustion:**
  - soot formation
  - combustion stability

trade-off under discussion

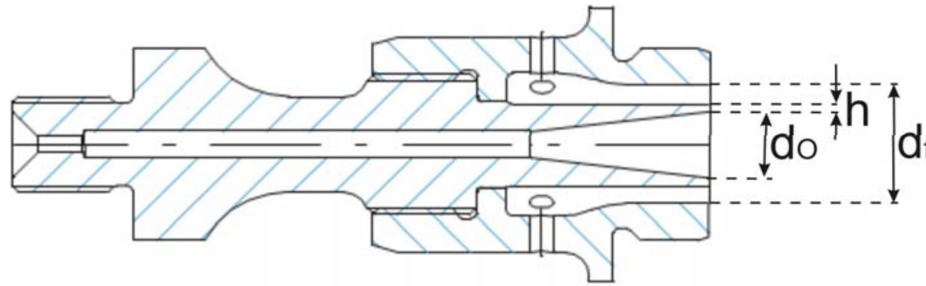
CH_4 for basic investigations of LOX/HC-combustion

- **simple kinetics**
- **well defined composition**

as compared to kerosene

Why to compare LOX/H_2 with LOX/CH_4?

- lot of data on LOX/H_2 spray combustion available
- LOX/CH_4 and LOX/H_2 use coaxial injectors
  - CH_4 injected at typ. 280K
  - LOX injected at typ. 120K
  - $v_{CH4} >> v_{LOX}$



propellant injectors are key components

- combustion efficiency
- combustion stability
- thermal and chemical load on combustor walls

Rahman S.A., Santoro R.J., "A Review of coaxial gas/liquid spray experiments and correlations", AIAA 94-2772, 1994

Vingert L., Gicquel P., Lourme D., Ménoret L, "Coaxial injector atomization", in AIAA Progress in Astronautics and Aeronautics, Vol. 169, 1995

relevant thermo-physical properties of O_2, CH_4, H_2

	O_2	CH_4	H_2	
critical temperature	154.6	190.5	32.9	[K]
critical pressure	5.04	4.60	1.28	[MPa]
reduced pressure P/P_{crit} [1]	1.19	1.30	4.69	
reduced pressure T/T_{crit} [1]	0.65	1.47	3.65	
density [1]		47.3	11.7	[kg/m³]
viscosity [1]		12.0	4.94	[μPa·s]
specific heat [1]		43.89	32.3	[J/mol·K]
thermal conductivity [1]		0.038	0.11	[W/m·K]
laminar flame velocity [1]		3.93	10.7	[m/s]
ignitability limits		5.1-61	4-94	[Vol %]

[1]at injector exit conditions: $P_C = 6$ MPa, $T_{H2} = 120$ K, $T_{CH4} = 280$ K

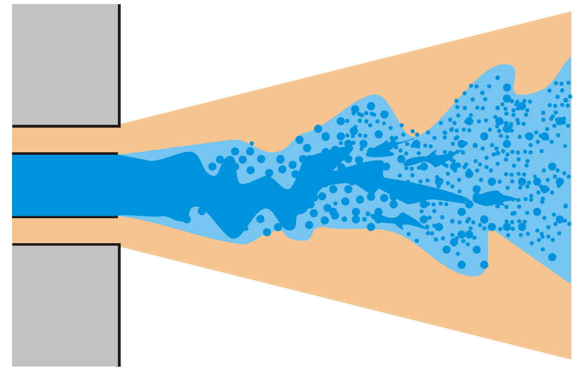
Atomization

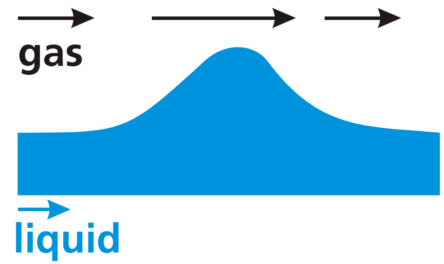
complex interaction of several forces

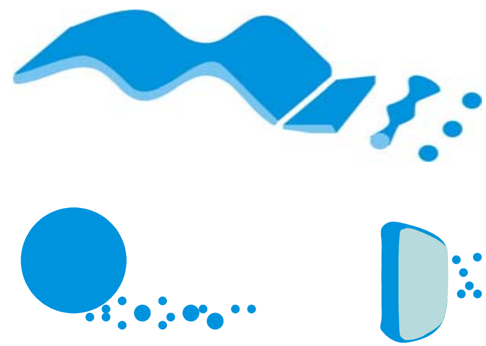
- aerodynamic forces
- surface tension
- viscosity
- turbulence level of liquid jet and gas flow
- sudden change of boundary conditions at injector exit

- basic mechanisms leading to atomization neither completely identified nor well modeled

Ledoux M., Caré I., Micci M, Glogowski M., Vingert L., Gicquel P., Atomization of Coaxial Injectors, 2nd Int. Symp. on LRP, Chatillon, 1995







Injector scaling

scaling

- injector geometry $d_O, d_f, h, \ldots$
- flow conditions at injector exit $v_o, v_f, \rho_o, \rho_f, \mu_o \ldots$
- groups of non-dimensional numbers

Weber number $$We = \frac{\rho_{fuel}(v_{fuel} - v_{ox})^2 d_{ox}}{\sigma}$$

momentum flux ratio $$J = \frac{\left(\rho v^2\right)_{fuel}}{\left(\rho v^2\right)_{ox}}$$

liquid Reynolds number $$Re_l = \frac{\rho_{ox} v_{ox} d_{ox}}{\mu_{ox}}$$

velocity ratio $$R_V = \frac{v_{fuel}}{v_{ox}}$$

Ohnesorge number $$Oh = \frac{\sqrt{We}}{Re}$$

Injector scaling: examples

atomization regime
(Farago, Chigier):

$We < 25$ **Rayleigh breakup**

$25 < We < 100$ **membrane-type breakup**

$100 < We < 500$ **fibre-type breakup**

droplet size
(Rahman, Santoro)

$$D \propto d_o{}^a \sigma^b \qquad 0 \leq a \leq 2.9 \qquad -0.2 \leq b \leq 0.3$$

intact core length
(Villermaux)

$$x \approx \frac{6}{\sqrt{J}}$$

problem: correlations derived under non-representative conditions for rocket propulsion

- **H_2O as substitute for LOX**
- **cold flow**
- **data for LOX/H_2 only for specific configurations**

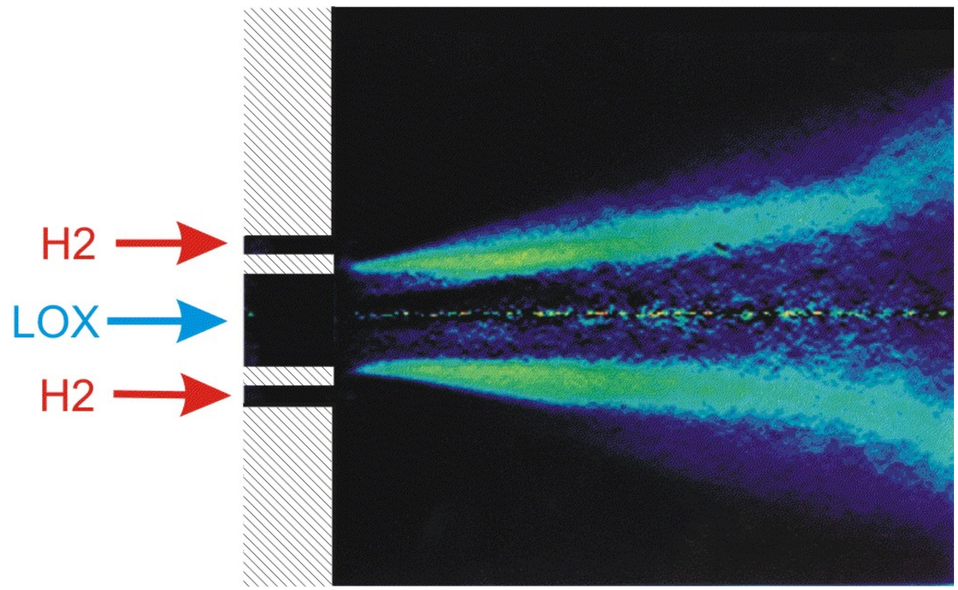
H_2O as substitute in cold flow tests

property		H_2O 1 bar	LOX 1 bar	LOX 10 bar	LOX 30 bar	LOX 100 bar
surface tension σ	[mN/m]	73	15	7	3	supercritical state
viscosity μ	[μPa·s]	1000	195	99	59	30

- difficult to adjust non-dimensional numbers including σ and μ with H_2O
- We, Re_{liq} can be more than an order of magnitude different from representative conditions

Atomization in hot fire conditions

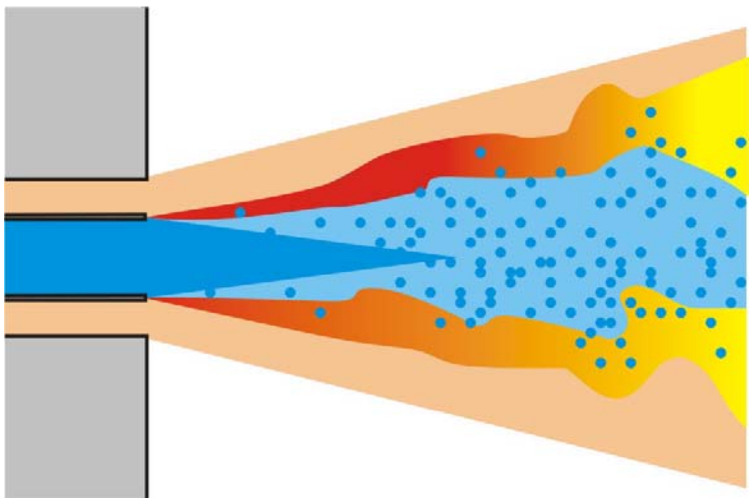
- flame between LOX-jet and annular fuel-flow
- influence of heat release and mixing layer of reactants/products on LOX-jet disintegration
- fluid properties at injector exit (We, J, Re_l, ...) sufficient to characterize atomization in hot fire tests?



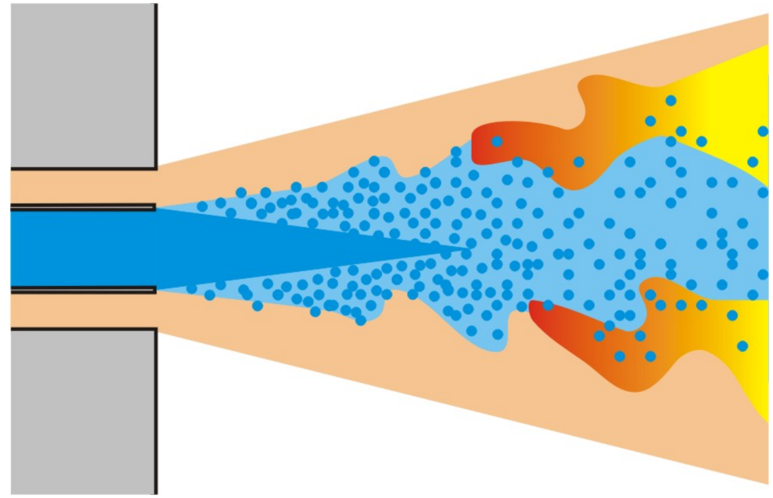
OH-imaging of flame at $P_C = 8$ MPa at P8 test facility

flame stabilization mechanisms

flame anchored at LOX-post



lifted flame

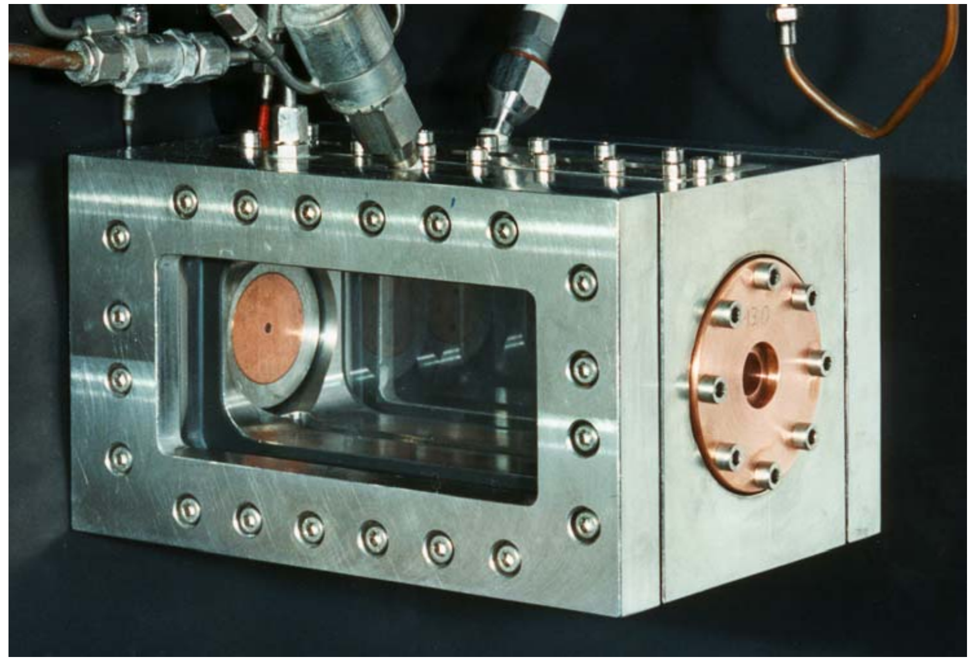


- influence of kinetic and thermo-physical properties of propellants on flame stabilization mechanism?
- influence of stabilization mechanism on atomization?

DLR

M3 test facility, micro combustor

- **propellants at representative conditions**
  - LOX, H_2 @ 88K
  - CH_4 @ 280K
- **L=14cm, A=6x6cm²**
- **single coaxial injector**
- **max. P_C=1.5 MPa**
- **max. run time 3s**
- **full optical access**
- **pressure representative for ignition transients**
- **hot fire tests!**



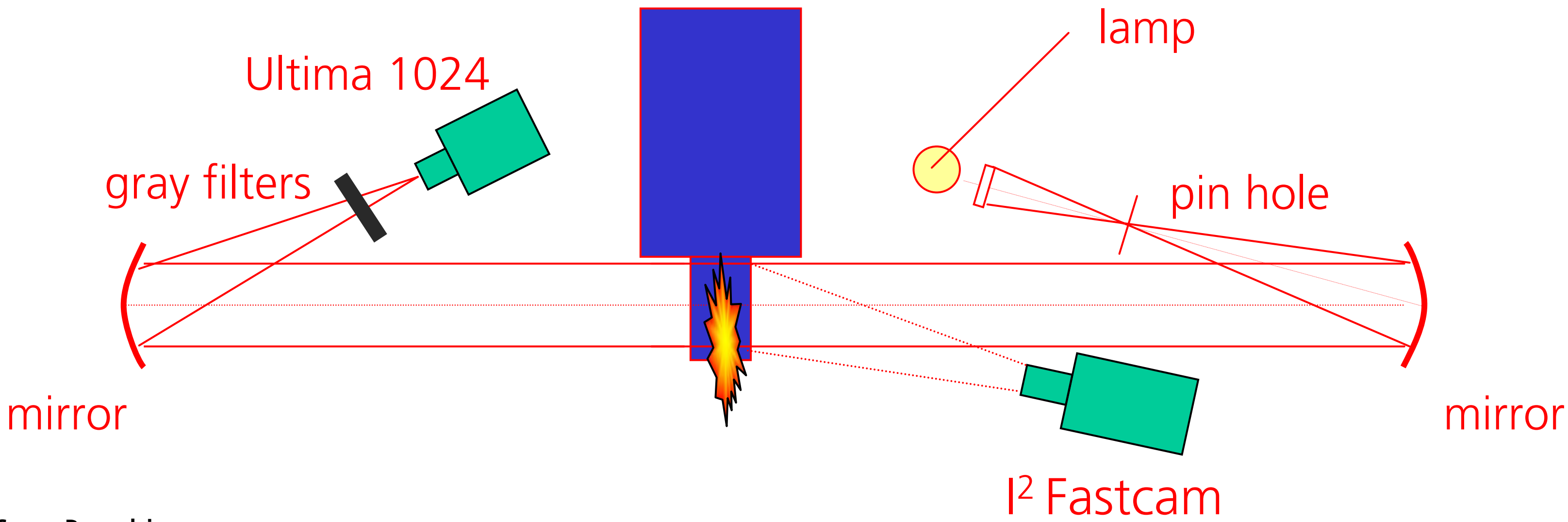
optical diagnostics

flame visualization

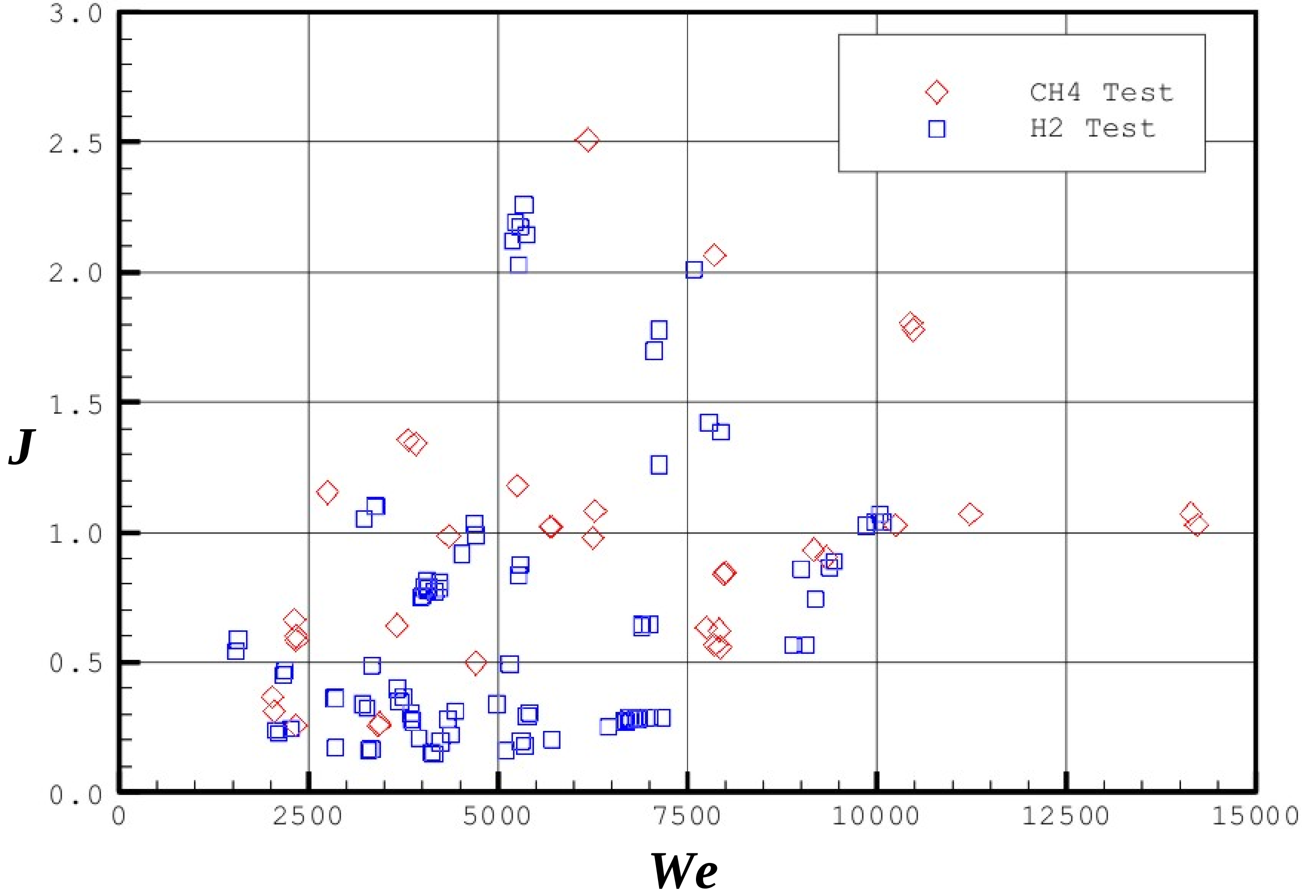
- high speed OH-imaging (≈310nm)
- ULTIMA I^2 ICCD
- up to 27 kfps

flow visualization / liquid phase

- Schlieren photography
- Kodak Flowmaster

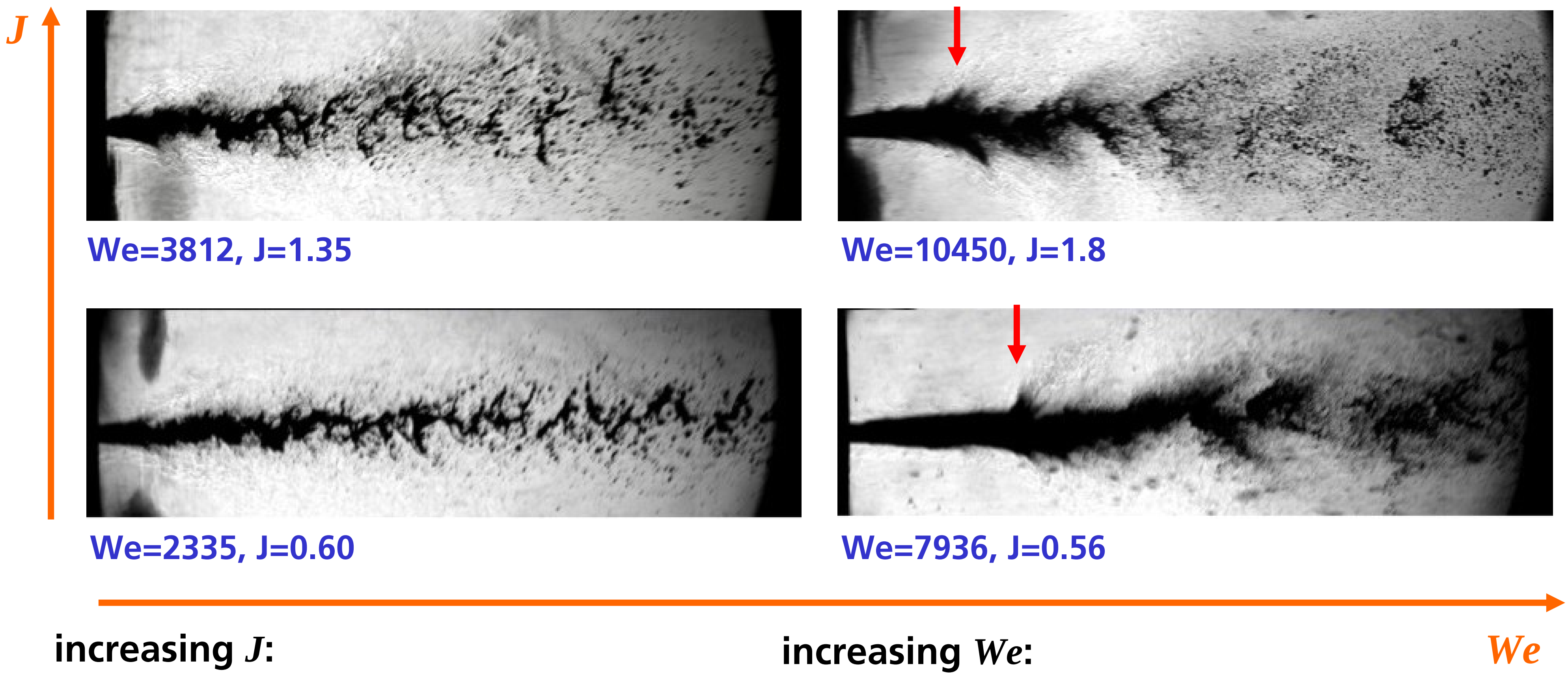


Test conditions



- independent variation of Weber-number We and momentum flux ratio J

LOX spray pattern for CH_4/LOX spray flames (P_C=1.5bar)



increasing *J*:

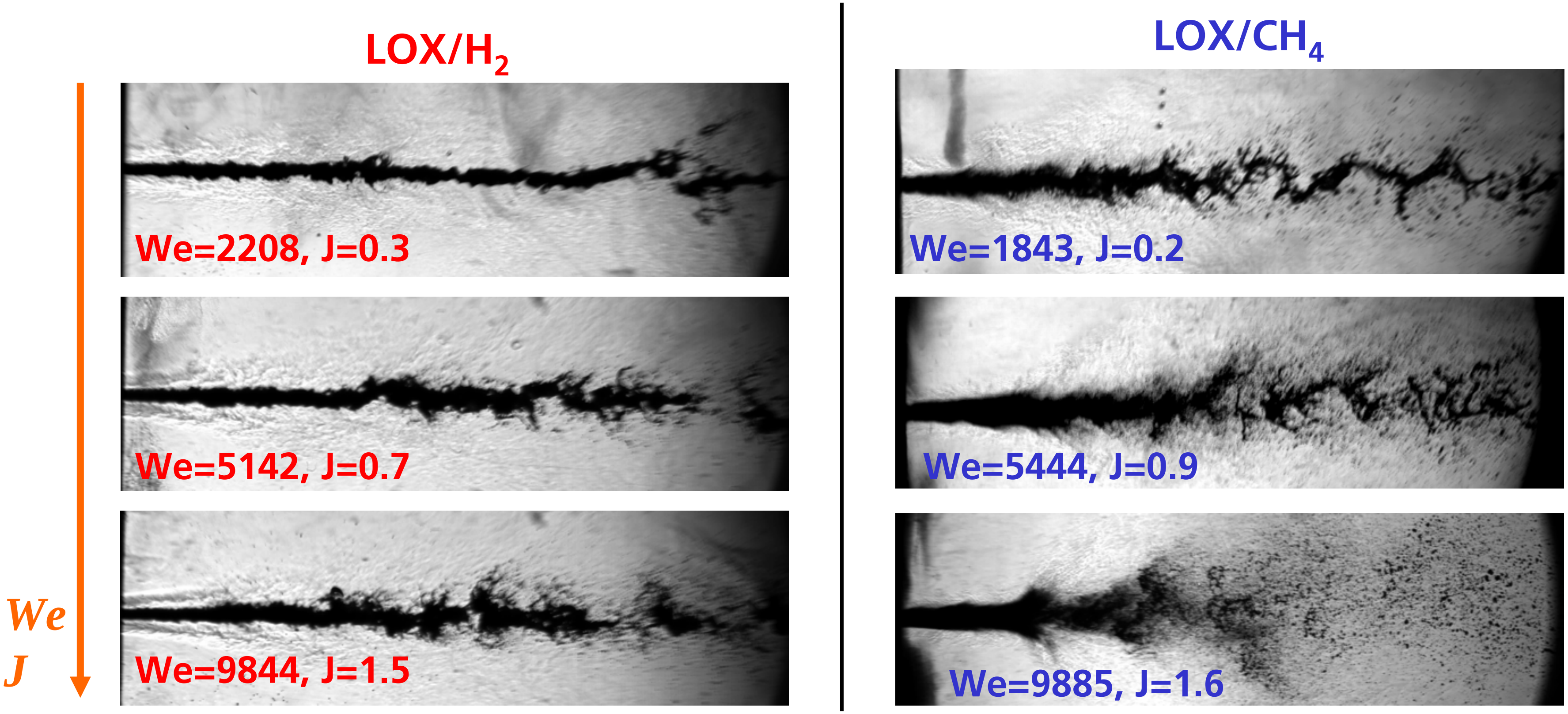
- higher dispersion of liquid phase
- decreasing visible intact core length

increasing *We*:

- smaller droplets
- sudden change of atomization behaviour

DLR

LOX-spray pattern for LOX/H_2 and LOX/CH_4-spray flames



- similar trends for variation of We and J for both propellants
- atomization significantly more efficient for CH_4
- visible breakup length much larger for H_2 than for CH_4

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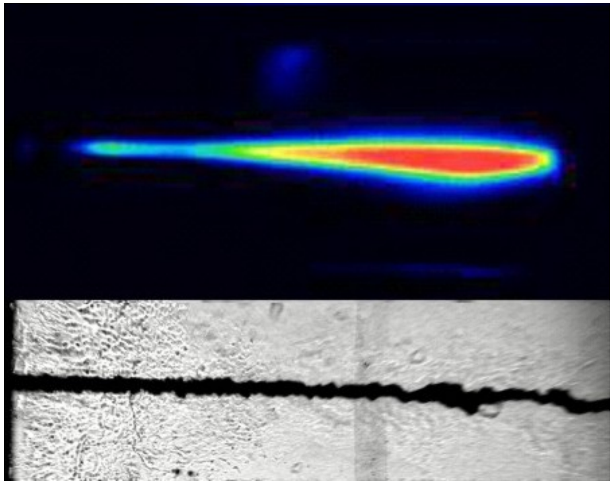
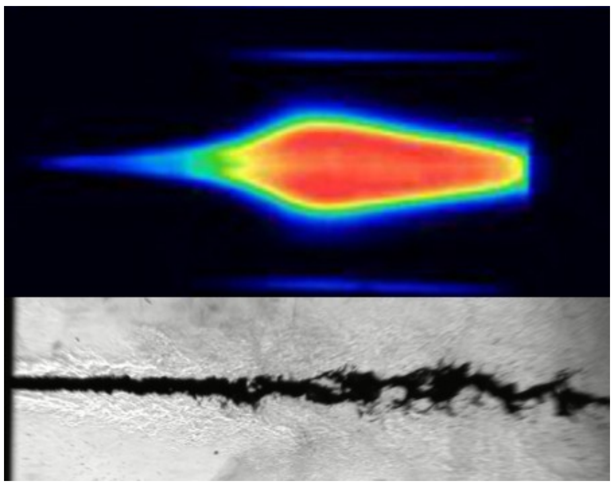
Flame and LOX-spray pattern for LOX/H_2 and LOX/CH_4

LOX/H_2

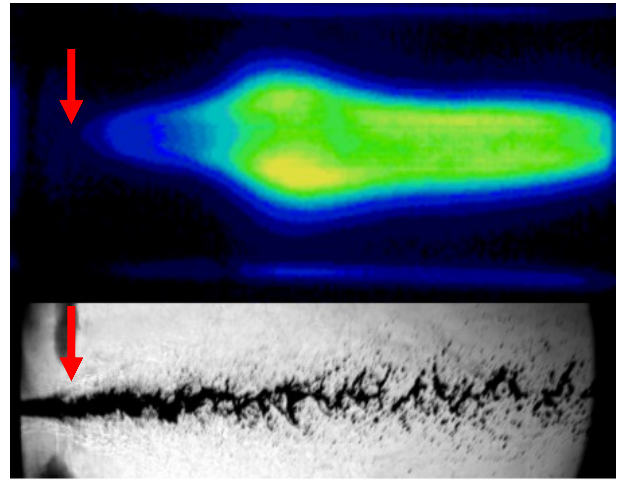


We=2192
J=0.47

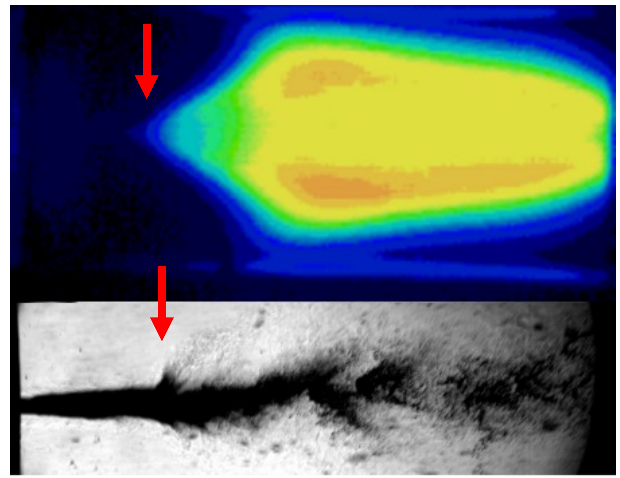


We=7007
J=0.65

LOX/CH_4



We=2335
J=0.60



We=7936
J=0.56

- significantly larger flame spreading angle for CH_4
- anchored flames for H_2, lifted flames for CH_4

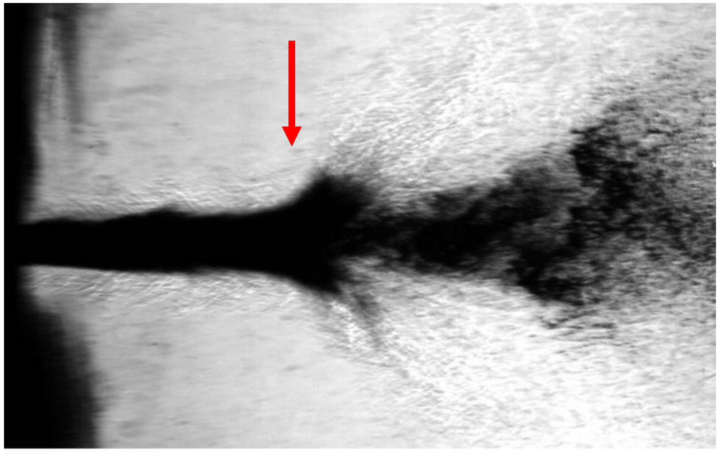
Stabilization of lifted flame in LOX/CH_4 spray

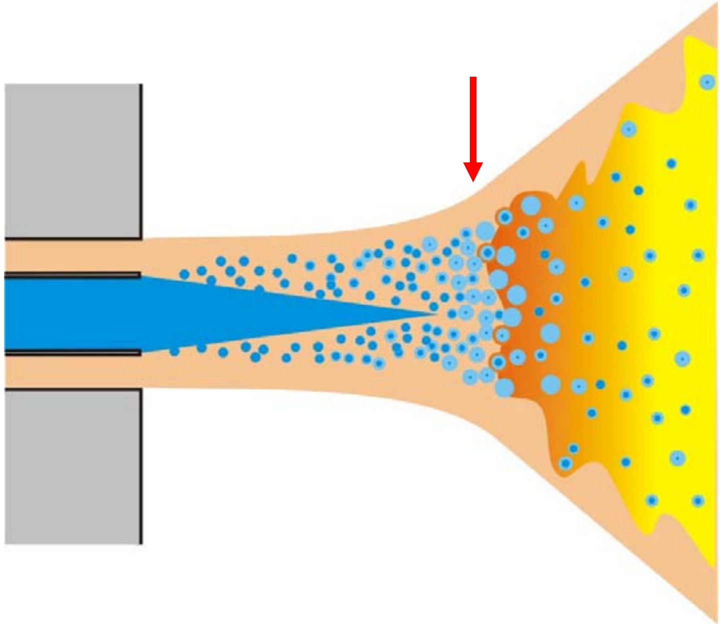
upstream the stabilization point:

- atomization
- droplet evaporation
- mixing of CH_4 and GO_2
- increasing R_{OF} due to LOX evaporation

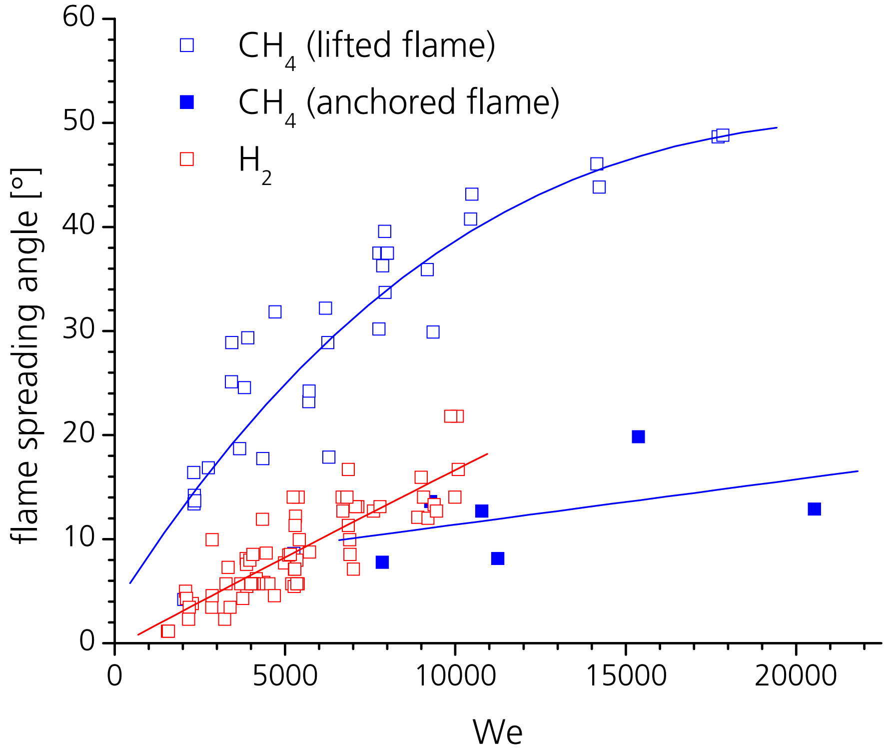
downstream the stabilization point:

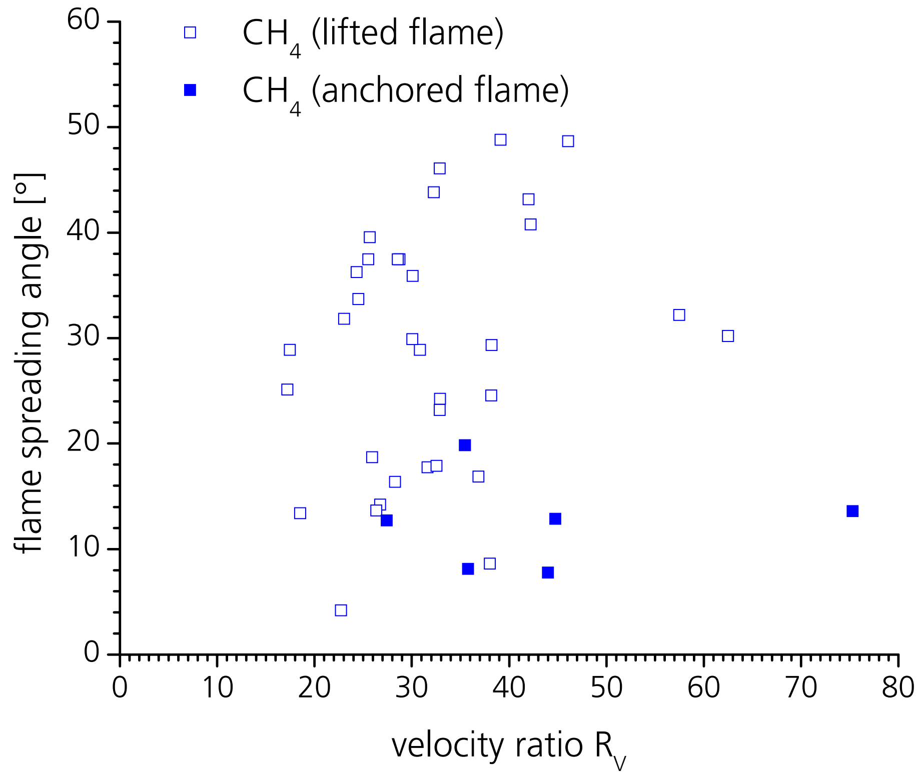
- distributed reaction
- heat release, production of reactants
- flame position depends on amount of GO_2 / local mixture ratio





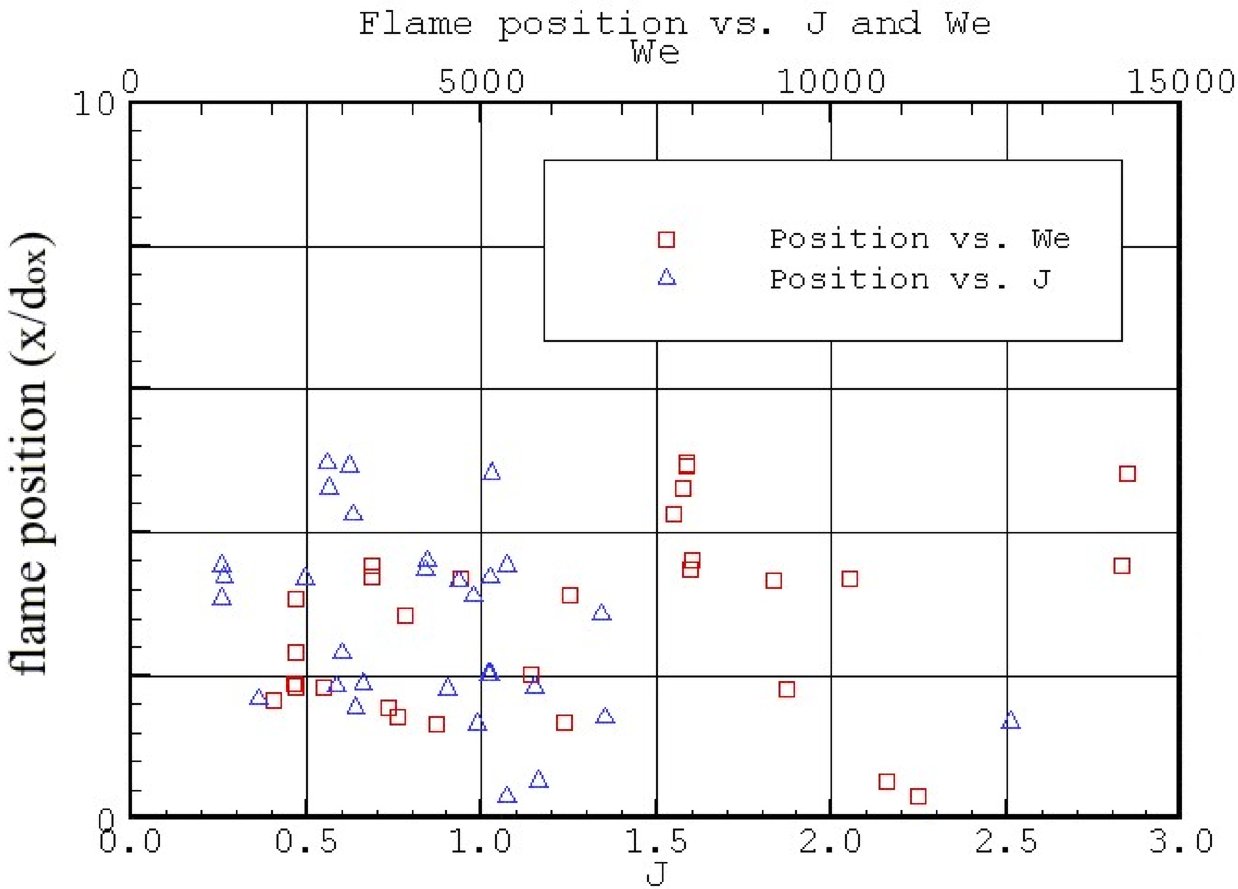
Flame spreading angle for LOX/CH_4- and LOX/H_2-spray flames





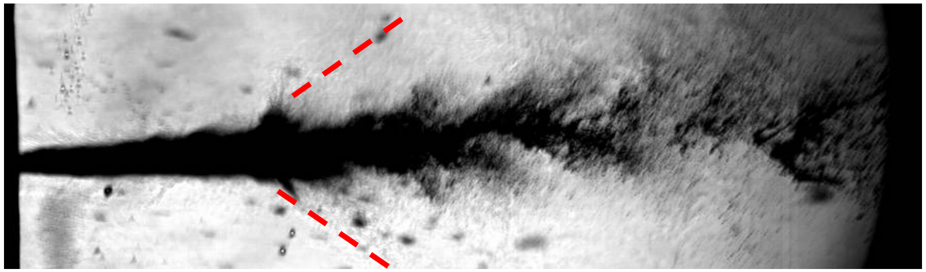
- **best correlation with *We***
- **no correlation with *J*, *Oh*, R_V, Re_{liq}**
- **large spreading angles for lifted flames**

Lift-off distance as function of *We* and *J*

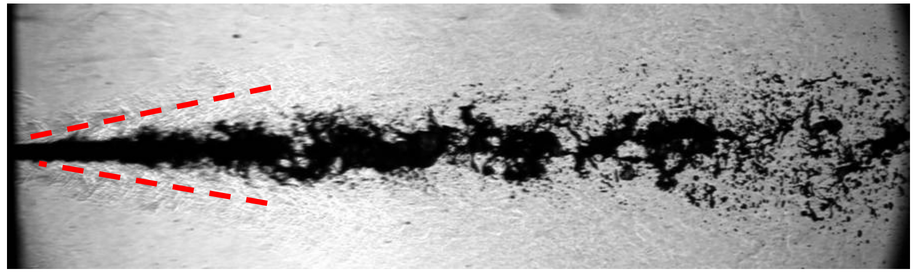


- no correlation of flame lift-off distance with any of the non-dimensional numbers J, Oh, R_V, Re_{liq}, We found

Effect of combustion chamber pressure on atomization and flame pattern for LOX/CH_4-spray flame



P_C=1.5bar
We=7260, *J*=0.5



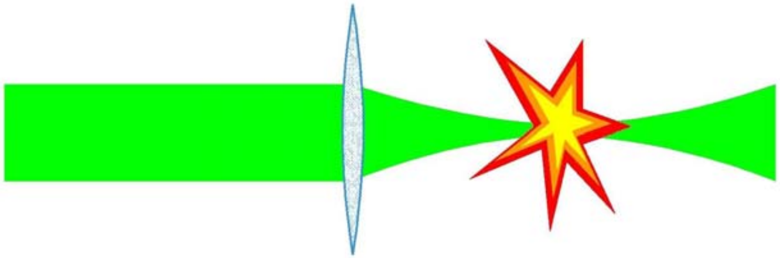
P_C=3.0bar
We=8417, *J*=0.5

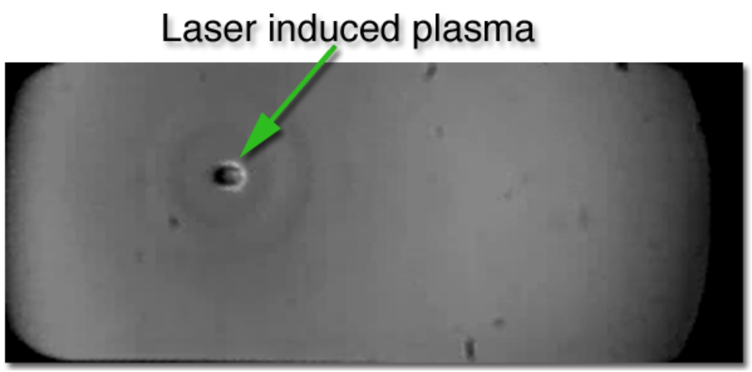
- lifted flames at pressures above 3bar
- for lifted flames significantly more violent atomization process downstream the flame anchoring position

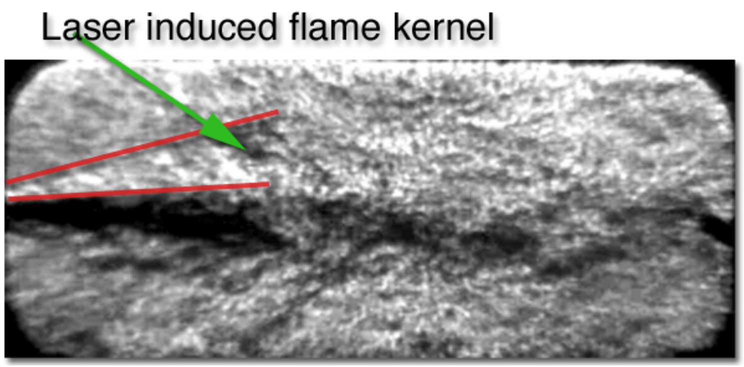
Ignition transient

ignition by laser induced gas break down

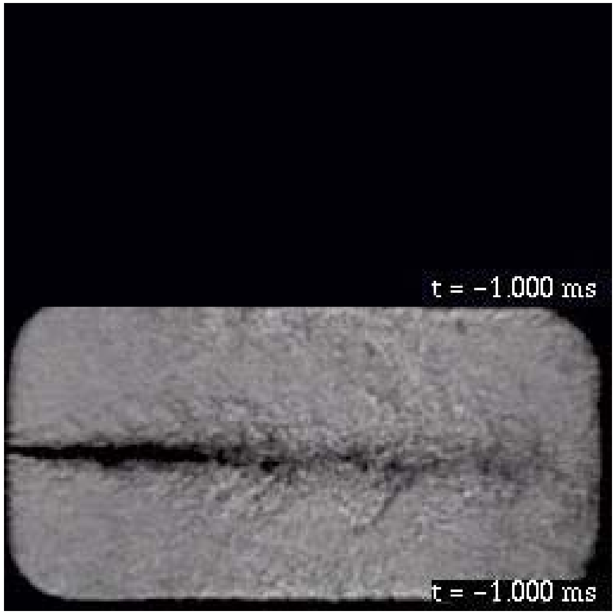
- **full control of time and location of ignition**
- **no distortion of the flow due to ignition equipment**
- **energy deposition**
  - Nd:YAG-laser, 532nm , 195 mJ/pulse, 10ns : ~10GW/cm² in the laser focus
  - focus-position:
    - z = 36 mm downstream injector
    - r=2.5mm off-axis
  - results independent on laser pulse energy (80-195mJ/pulse)

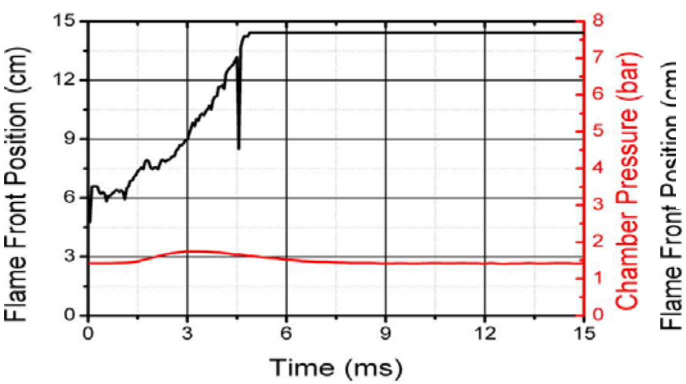


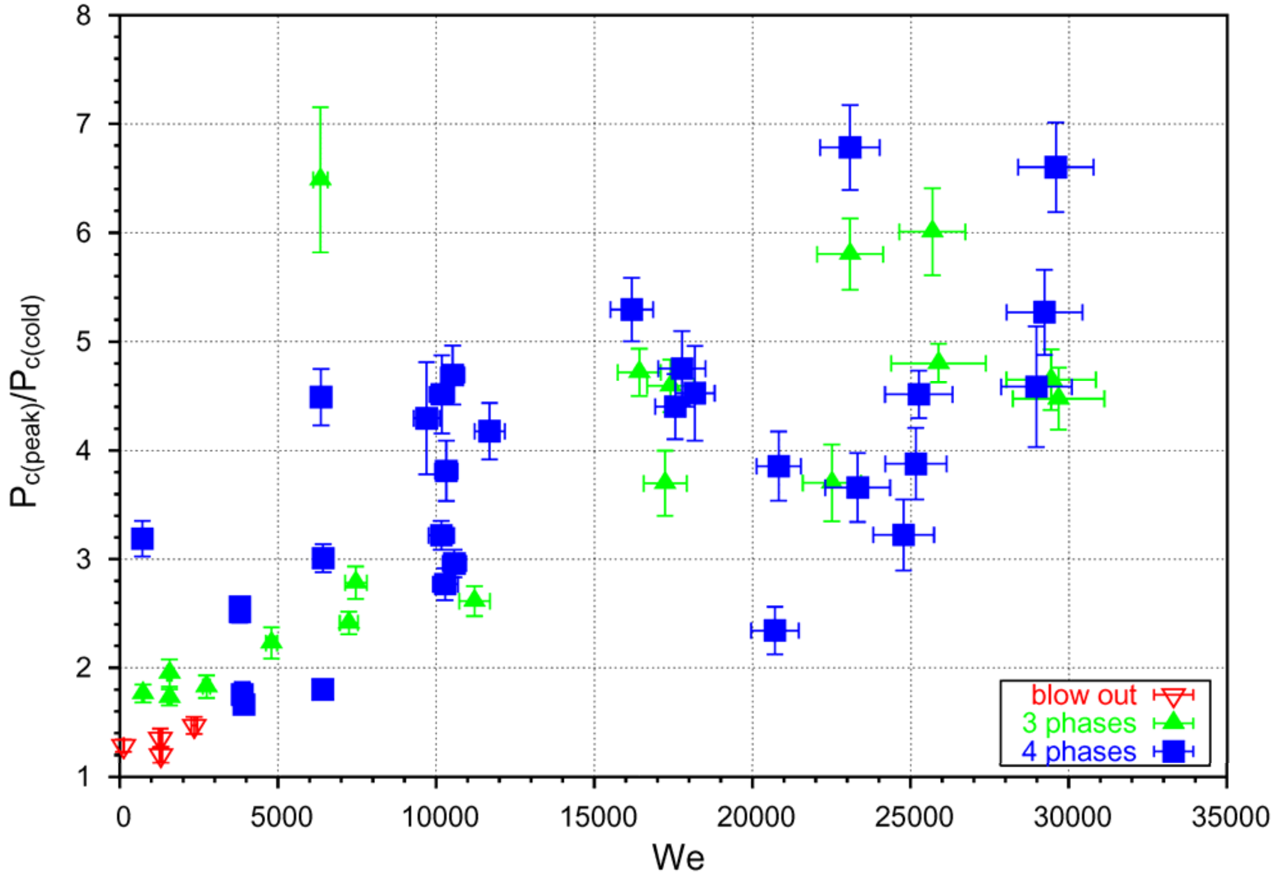




flame evolution for the 3 types of ignition scenarii (LOX/H_2):

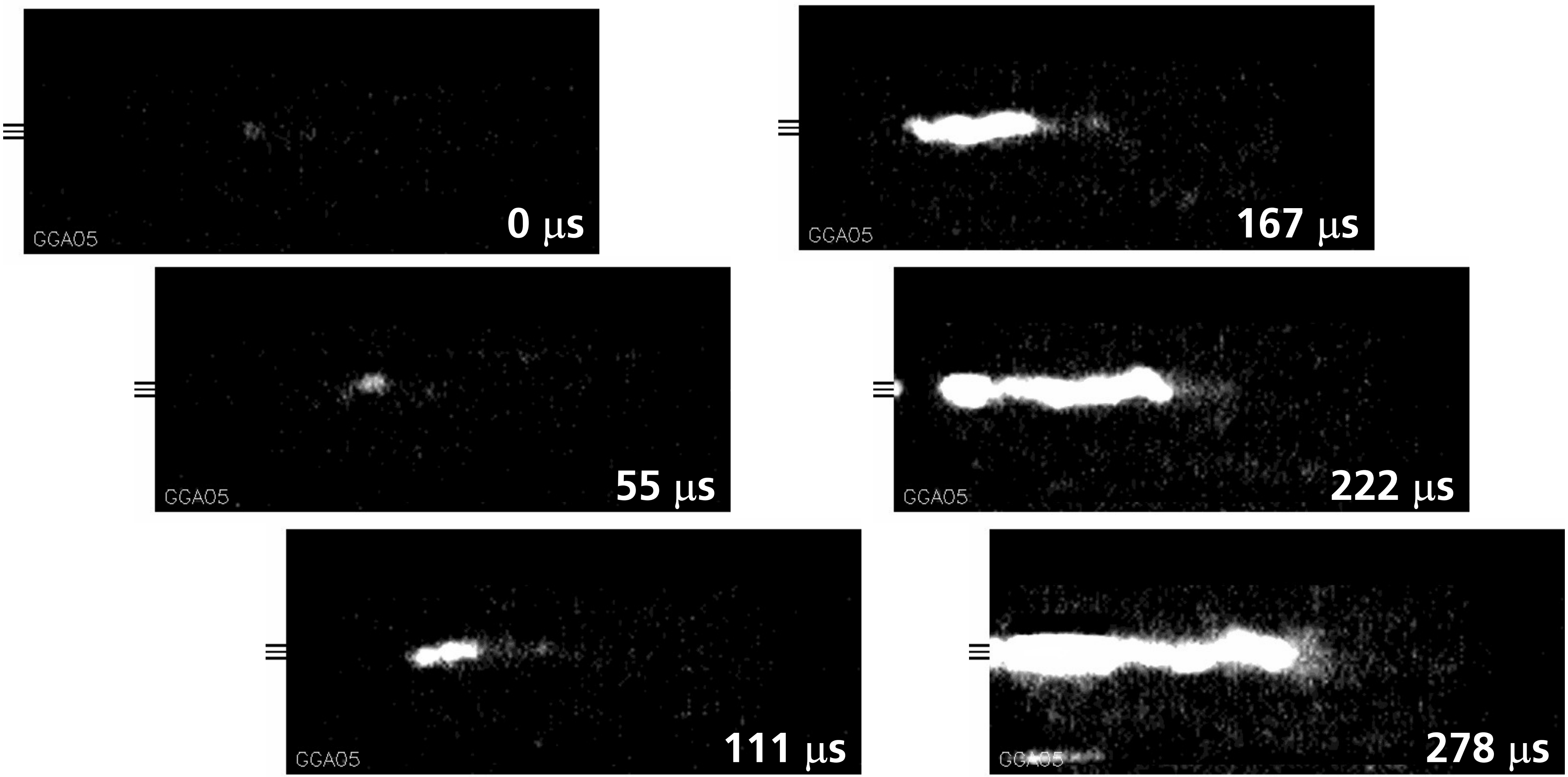




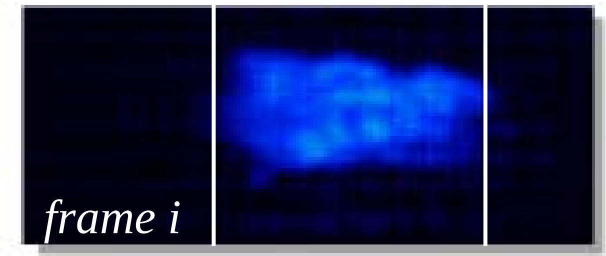


- ignition pressure peak well correlated with *We*
- flame blow-out clearly correlated with H_2-momentum flow $I_{H2}=\rho v^2 A$: blow-out for $I_{H2}<0.8\text{kg}\cdot\text{m/s}^2$

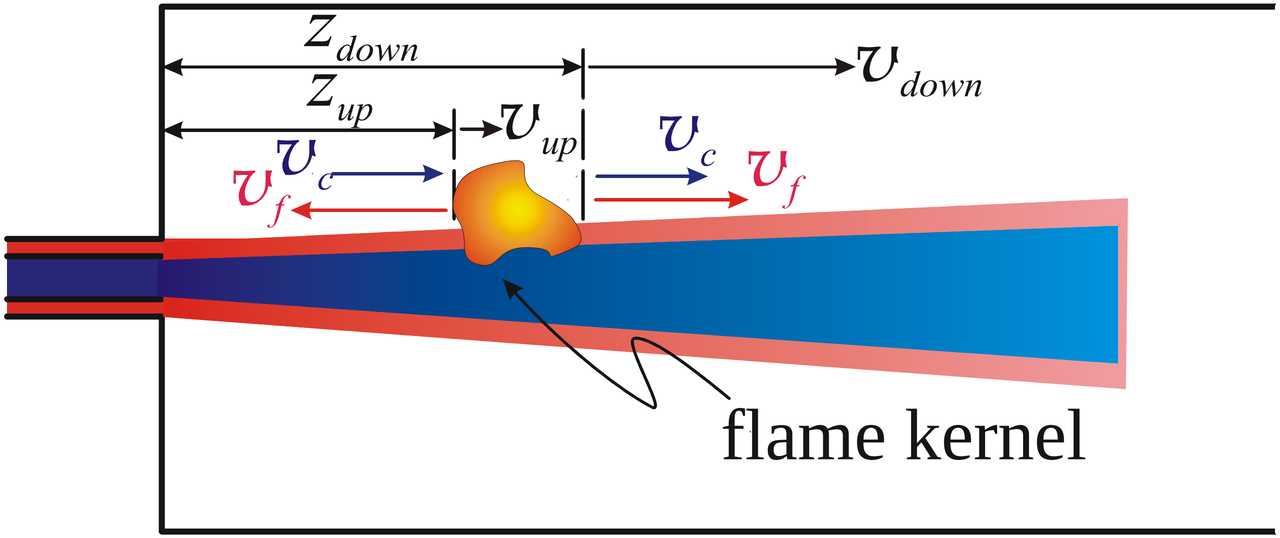
flame kernel evolution



data reduction



$z_U(t_i)$ $z_D(t_i)$



flame front velocities

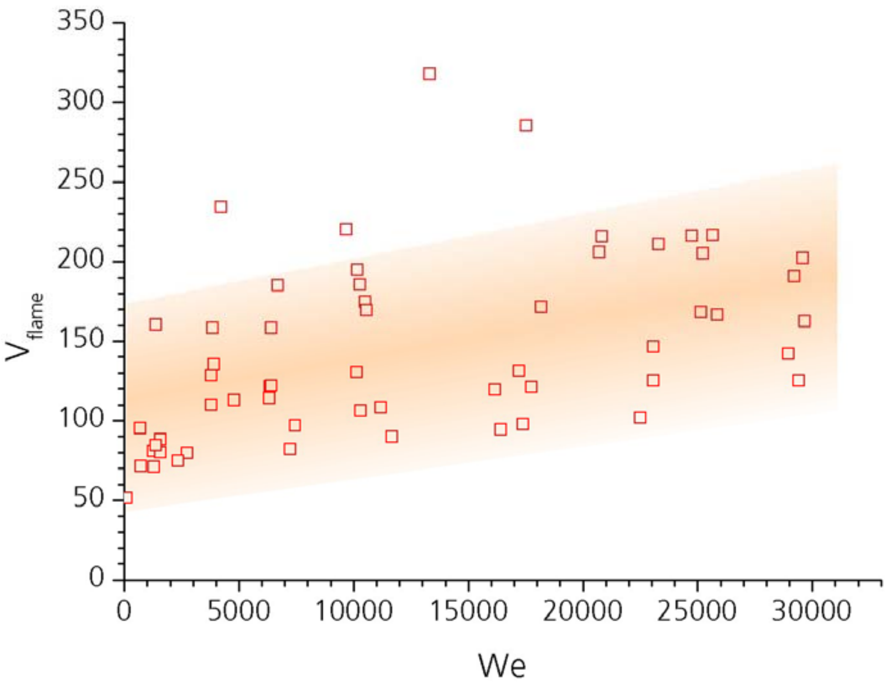
- determination of upstream- and downstream flame front positions: $z_U(t_i)\,,\quad z_D(t_i)$
- determination of upstream- and downstream flame front velocities: $\upsilon_U = \dfrac{z_U(t_{i+1}) - z_U(t_i)}{\Delta t}$

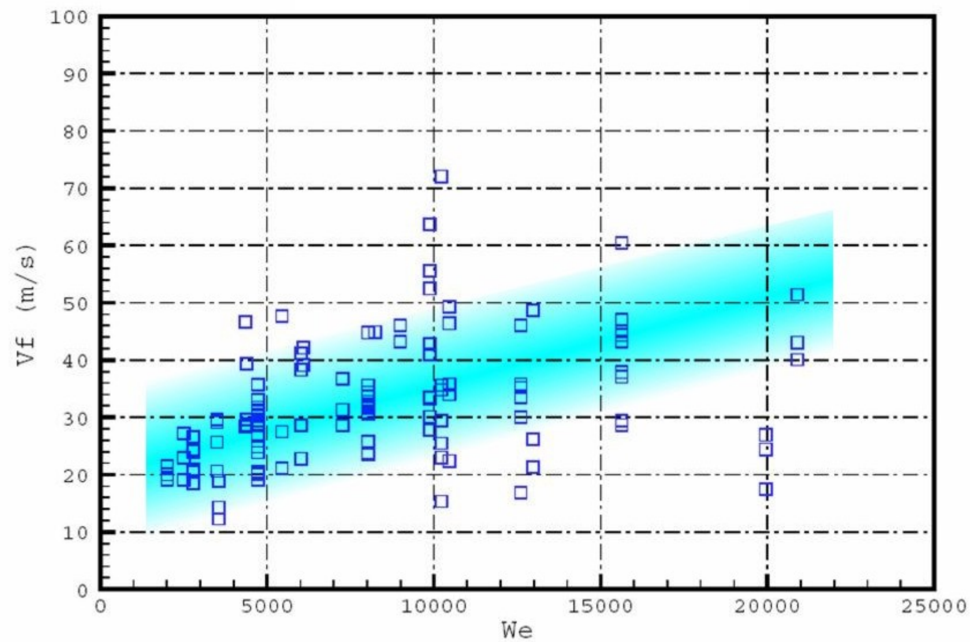
$$\upsilon_D(z_D) = \upsilon_C(z_D) + \upsilon_F(z_D) \qquad \upsilon_U(z_U) = \upsilon_C(z_U) - \upsilon_F(z_U)$$

- determination of flame front- and convection velocities: $\upsilon_C = \dfrac{\upsilon_D + \upsilon_U}{2}$ $\quad \upsilon_F = \dfrac{\upsilon_D - \upsilon_U}{2}$

flame front velocities

LOX/H_2 **LOX/CH_4**



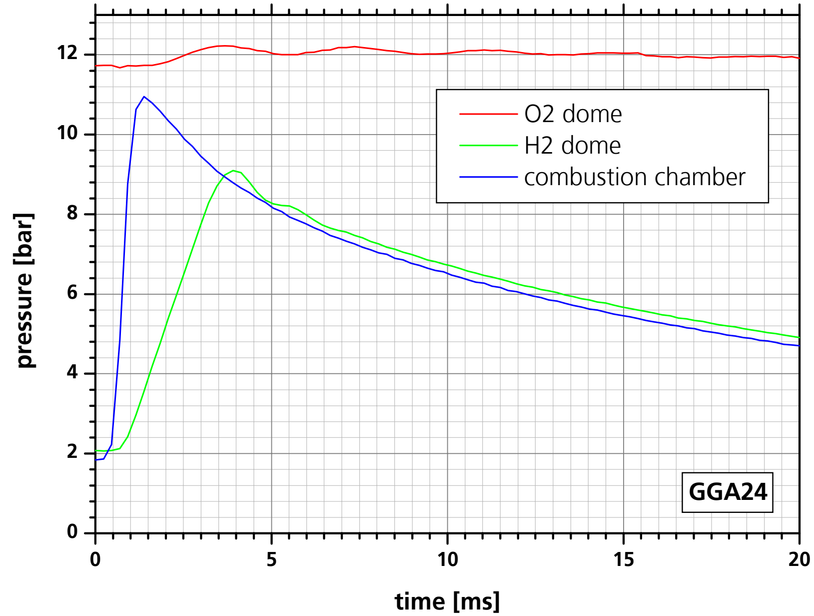


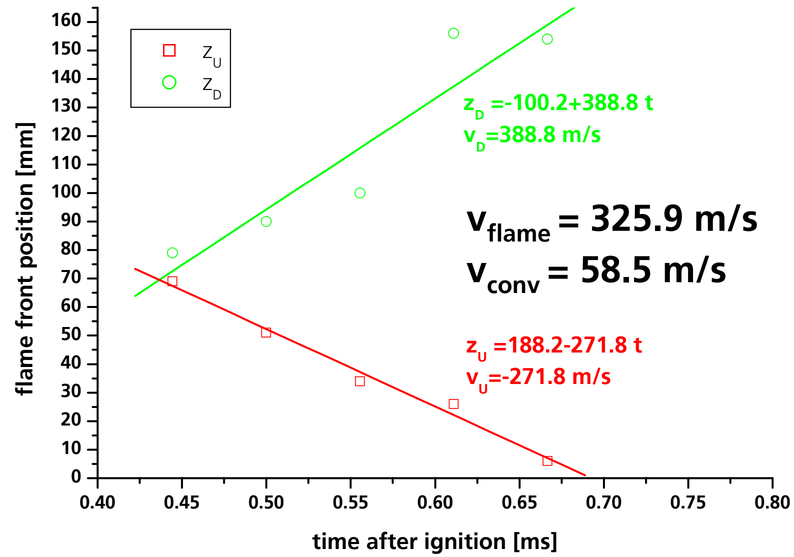
- **flame front velocity >> laminar burning velocity**
- **week correlation with We, no strong correlation with J, Oh, R_V, Re_{liq}**
- **$(v_{flame})_{H2} / (v_{flame})_{CH4} \approx 3 - 5$; ratio of laminar buring velocities 2.7**

ignition tests for code validation

- **injection of GO_2/GH_2 to reduce complexity**
- **determination of**
  - pressure evolution during ignition transient
  - convective velocity of flame kernel
  - flame front velocity of expanding flame kernel

- **data used for code validation by**
  - ONERA Châtillon
  - SNECMA Vernon
  - CERFACS Toulouse
  - DLR Lampoldshausen





Coaxial injection at supercritical pressure

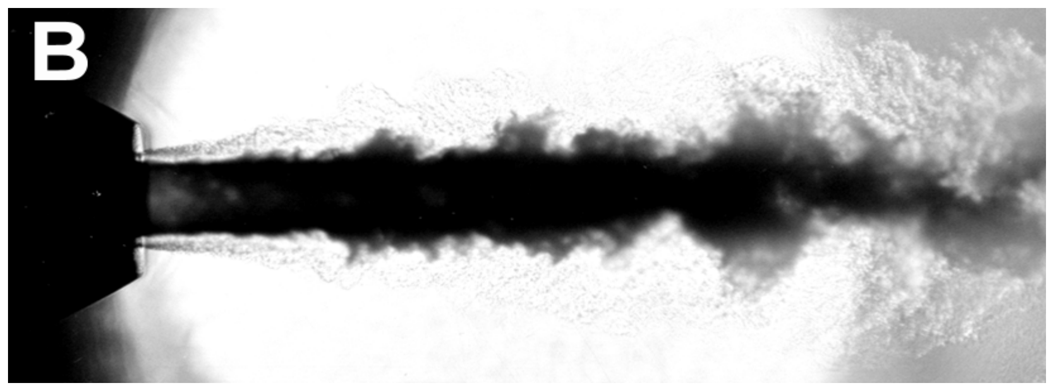
Binary liquid N_2/gaseous He system

d_{LN2} = 1.9 mm, v_{LN2} = 5 m/s, v_{He} = 100 m/s, T_{LN2} = 97 K, T_{He} = 280 K.

A: P_C=1.0 MPa, subcritical N_2

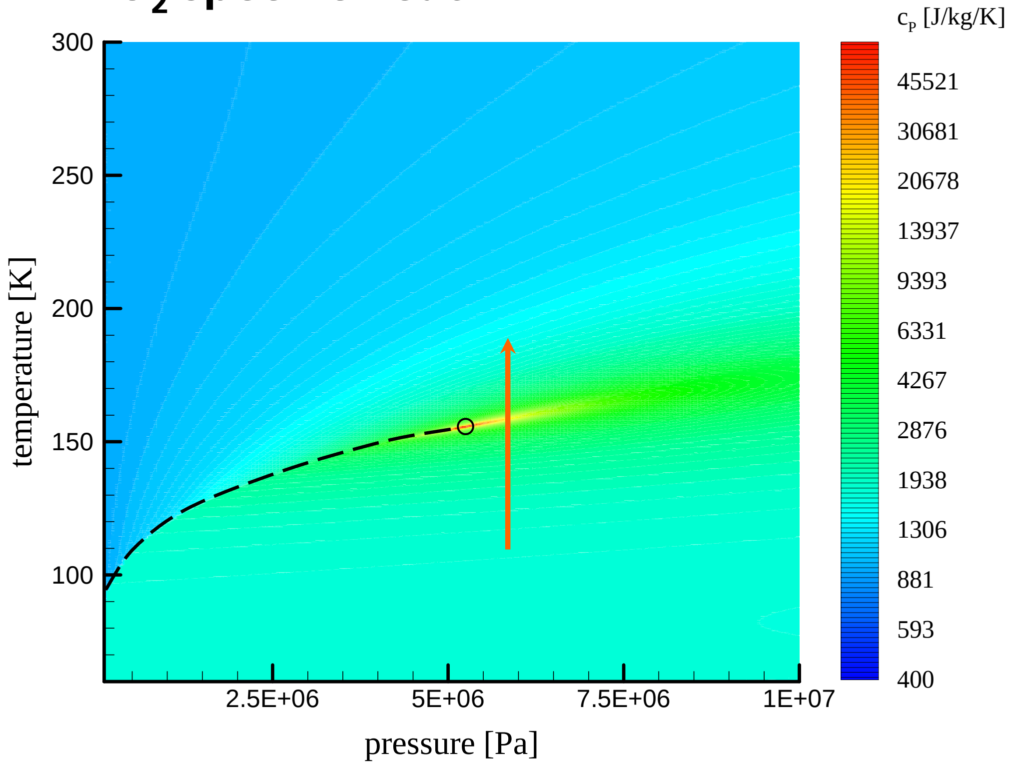
B: P_C=6.0 MPa, transcritical N_2

- **spray formation at subcritical pressure**
- **reduced surface tension approaching the critical point**
- **turbulent mixing of dense and light fluid components at at supercritical pressure**

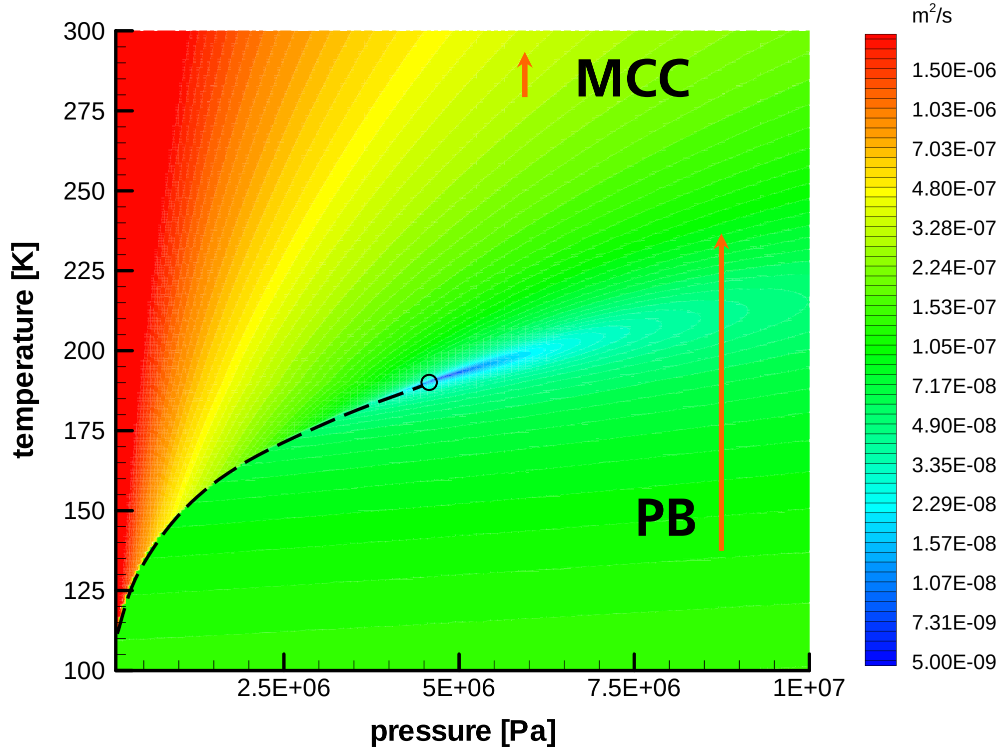


Thermo-physical properties in the near critical region

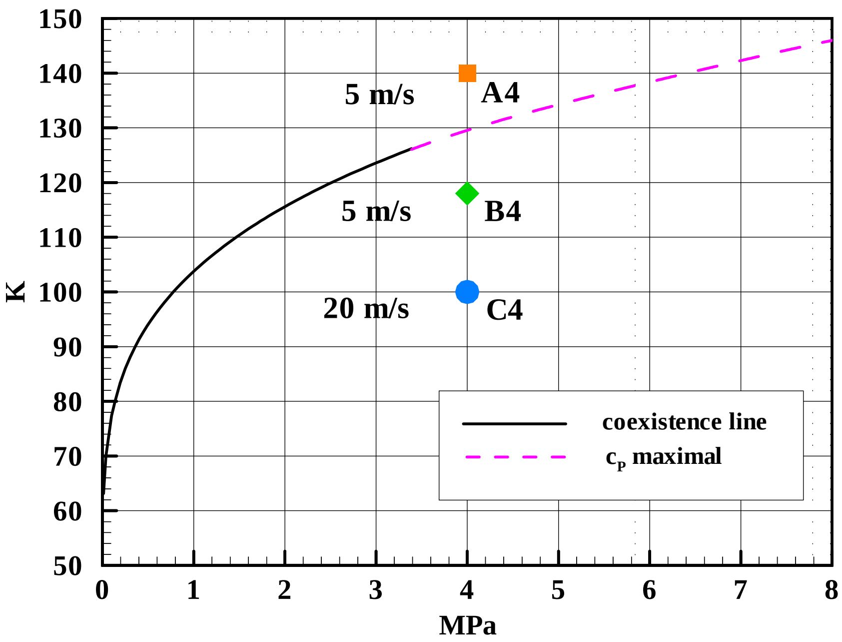
O_2 specific heat



CH_4 thermal diffusivity



LN_2 free jet-decay, Raman scattering

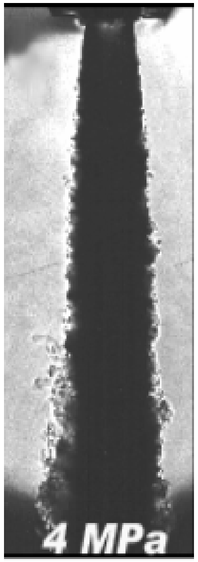


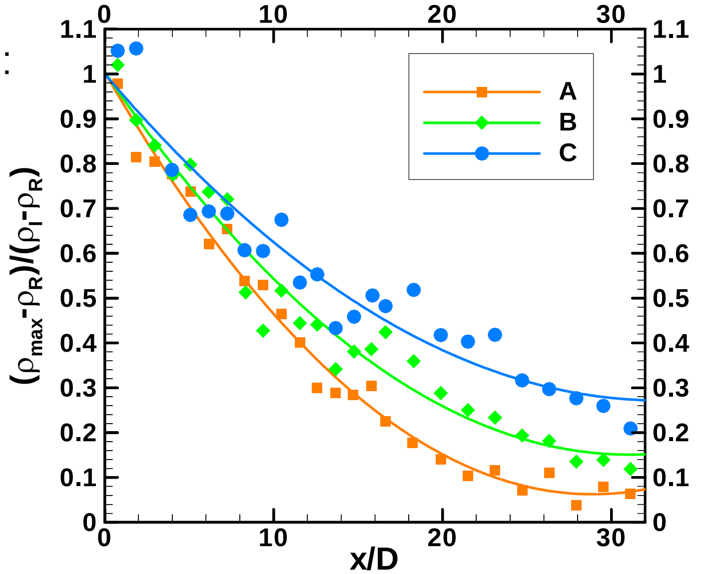
Injection temperatures:

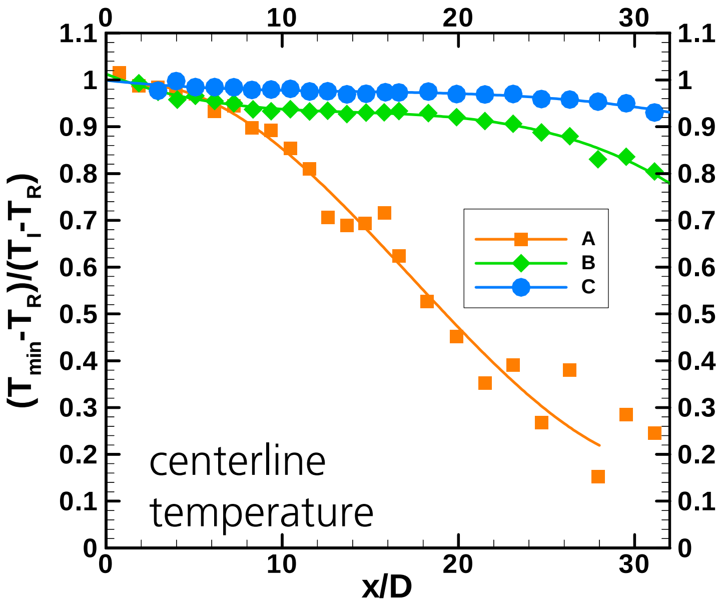
A4: 140K

B4: 118K

C4: 100K







- An appropriate equation of state is used to calculate temperature
- The colder the initial temperature, the slower the growth and development of the jet
- For $T_{initial} < T^*$ (cases B4 & C4) the heat exchange does not affect the centerline temperature due to specific heat behavior in the near critical region

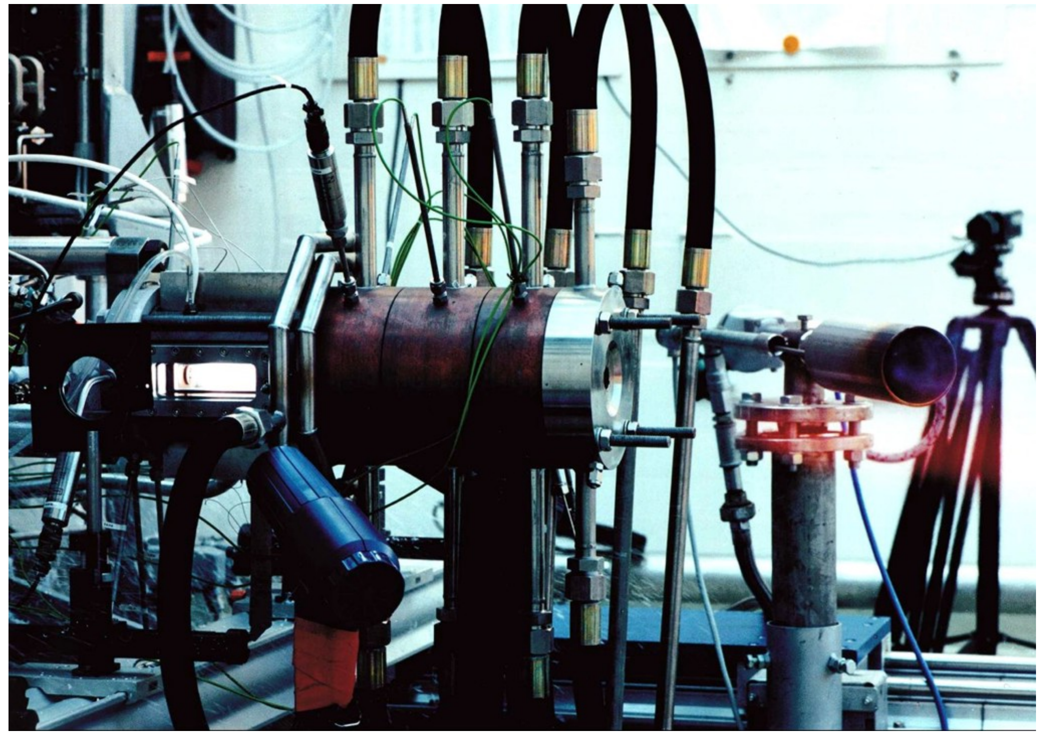
Combustion at representative pressure conditions

P8 test facility

- **GH_2, LH_2 supply**
- **CH_4 supply in preparation**

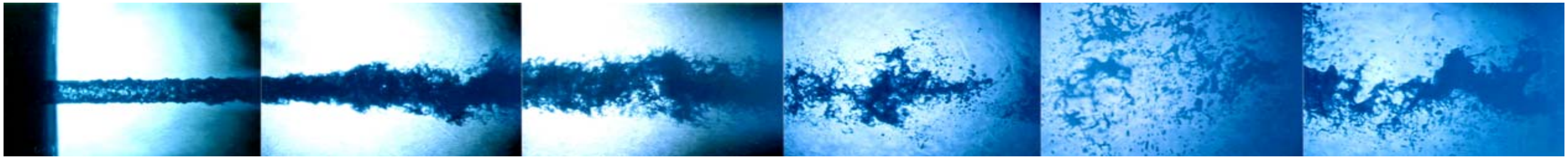
DLR combustion chamber "C"

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

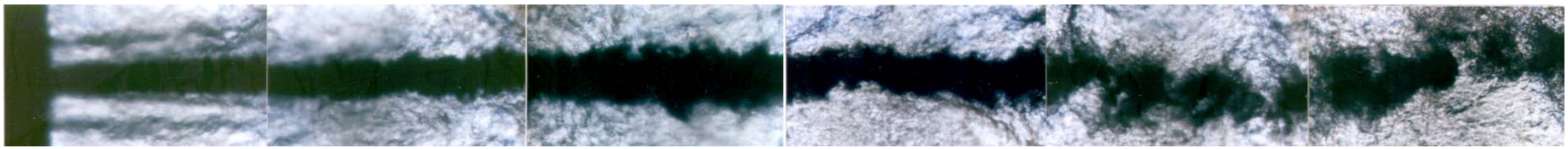


Combustion Studies LOX/H_2 at super critical pressure

LOX-jet disintegration:



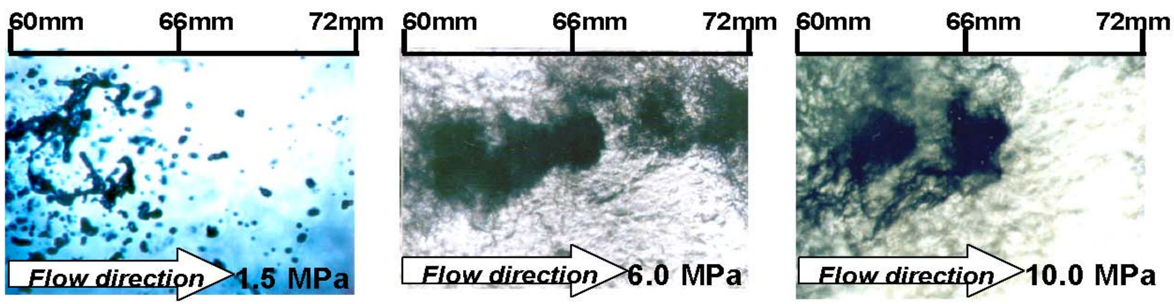
(a) Subcritical Pressure, 1.5 MPa Combustion



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

Conclusions

- **injector scaling for reactive sprays**
  - non-dimensional parameters characterising cold flow conditions at injector exit not sufficient
  - flame stabilization mechanism has significant influence on atomization process and droplet distribution in the flow
  - coupling between atomization and combustion
  - scaling has to take care for kinetics and transport properties

    $\psi=\delta/h$ δ: laminar flame thickness, h: LOX-post thickness
    (Juniper M., Candel S., Journal of Propulsion and Power, Vol. 19, No. 5, p. 332)

tests conditions should be as near as possible to representative conditions (propellants, pressure, ...) to get insight into relevant flame/spray interaction processes!

Perspectives

- **influence of LOX-post wall thickness on lift-off behaviour**
- **GO_2/GCH_4-ignition**
- **investigation of LOX/CH_4 spray combustion at supercritical pressure at P8 test facility** (starting in July this year)