Atomization and Combustion in LOX/H₂- and LOX/CH₄-Spray Flames Spray

M. Oschwald¹, F. Cuoco², B. Yang³, M. De Rosa¹

¹German Aerospace Center (DLR), Lampoldshausen, Germany
²Avio S.p.A., Italy
³Northwestern Polytechnical University, China

International Symposium on Heat and Mass Transfer in Spray Systems
Antalya, Turkey, June 5-10, 2005
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\text{sp} lower than H\text{2}, thrust/weight ratio higher than H\text{2})
- low toxic potential (green propellant)
HC candidates for booster engines: kerosene, methane

trade-off between kerosene and CH₄

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

CH₄ for basic investigations of LOX/HC-combustion

- simple kinetics
- well defined composition as compared to kerosene

trade-off under discussion
Why to compare LOX/H₂ with LOX/CH₄?

- lot of data on LOX/H₂ spray combustion available
- LOX/CH₄ and LOX/H₂ use coaxial injectors
  - CH₄ injected at typ. 280K
  - LOX injected at typ. 120K
  - \( v_{\text{CH}_4} \gg v_{\text{LOX}} \)


### relevant thermo-physical properties of $O_2$, $CH_4$, $H_2$

<table>
<thead>
<tr>
<th></th>
<th>$O_2$</th>
<th>$CH_4$</th>
<th>$H_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>critical temperature</td>
<td>154.6</td>
<td>190.5</td>
<td>32.9</td>
</tr>
<tr>
<td>critical pressure</td>
<td>5.04</td>
<td>4.60</td>
<td>1.28</td>
</tr>
<tr>
<td>reduced pressure $P/P_{crit}$</td>
<td>1.19</td>
<td>1.30</td>
<td>4.69</td>
</tr>
<tr>
<td>reduced pressure $T/T_{crit}$</td>
<td>0.65</td>
<td>1.47</td>
<td>3.65</td>
</tr>
<tr>
<td>density $^1$</td>
<td>47.3</td>
<td>11.7</td>
<td></td>
</tr>
<tr>
<td>viscosity $^1$</td>
<td>12.0</td>
<td>4.94</td>
<td></td>
</tr>
<tr>
<td>specific heat $^1$</td>
<td>43.89</td>
<td>32.3</td>
<td></td>
</tr>
<tr>
<td>thermal conductivity $^1$</td>
<td>0.038</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>laminar flame velocity $^1$</td>
<td>3.93</td>
<td>10.7</td>
<td></td>
</tr>
<tr>
<td>ignitability limits</td>
<td>5.1-61</td>
<td>4-94</td>
<td></td>
</tr>
</tbody>
</table>

$^1$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

Injector scaling

scaling

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

Weber number

\[
We = \frac{\rho_{\text{fuel}} (v_{\text{fuel}} - v_{\text{ox}})^2}{d_{\text{ox}}} \frac{d_{\text{ox}}}{\sigma}
\]

momentum flux ratio

\[
J = \frac{(\rho v^2)_{\text{fuel}}}{(\rho v^2)_{\text{ox}}}
\]

liquid Reynolds number

\[
Re_l = \frac{\rho_{\text{ox}} v_{\text{ox}} d_{\text{ox}}}{\mu_{\text{ox}}}
\]

velocity ratio

\[
R_v = \frac{v_{\text{fuel}}}{v_{\text{ox}}}
\]

Ohnesorge number

\[
Oh = \frac{\sqrt{We}}{Re}
\]
Injector scaling: examples

**Atomization regime**

(Farago, Chigier):

- $W_e < 25$: Rayleigh breakup
- $25 < W_e < 100$: membrane-type breakup
- $100 < W_e < 500$: fibre-type breakup

**Droplet size**

(Rahman, Santoro)

$$D \propto d_o^a \sigma^b$$

$$0 \leq a \leq 2.9$$

$$-0.2 \leq b \leq 0.3$$

**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
H₂O as substitute in cold flow tests

<table>
<thead>
<tr>
<th>property</th>
<th>H₂O 1 bar</th>
<th>LOX 1 bar</th>
<th>LOX 10 bar</th>
<th>LOX 30 bar</th>
<th>LOX 100 bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>surface tension σ</td>
<td>73 mN/m</td>
<td>15 mN/m</td>
<td>7 mN/m</td>
<td>3 mN/m</td>
<td>supercritical state</td>
</tr>
<tr>
<td>viscosity μ</td>
<td>1000 µPa·s</td>
<td>195 µPa·s</td>
<td>99 µPa·s</td>
<td>59 µPa·s</td>
<td>30 µPa·s</td>
</tr>
</tbody>
</table>

- difficult to adjust non-dimensional numbers including $\sigma$ and $\mu$ with H₂O
- $We, Re_{liq}$ 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 ($We, J, Re_\mu$ ...) 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?
M3 test facility, micro combustor

- propellants at representative conditions
  - LOX, H$_2$ @ 88K
  - CH$_4$ @ 280K
- L=14cm, A=6x6cm$^2$
- 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 ($\approx 310 \text{nm}$)
- ULTIMA $I^2$ ICCD
- up to 27 kfps

flow visualization / liquid phase
- Schlieren photography
- Kodak Flowmaster

Ultima 1024
gray filters
mirror
lamp
pin hole
mirror
$I^2$ Fastcam
Test conditions

- independent variation of Weber-number $We$ and momentum flux ratio $J$
LOX spray pattern for CH$_4$/LOX spray flames ($P_C=1.5$bar)

- **Increasing $J$:**
  - Higher dispersion of liquid phase
  - Decreasing visible intact core length

- **Decreasing $J$:**
  - Smaller droplets
  - Sudden change of atomization behaviour

$W_e = 3812$, $J=1.35$

$W_e = 10450$, $J=1.8$

$W_e = 2335$, $J=0.60$

$W_e = 7936$, $J=0.56$
LOX-spray pattern for LOX/H₂ and LOX/CH₄-spray flames

- similar trends for variation of $We$ and $J$ for both propellants
- atomization significantly more efficient for CH₄
- visible breakup length much larger for H₂ than for CH₄
Flame and LOX-spray pattern for LOX/H₂ and LOX/CH₄

- LOX/H₂
  - We=2192
  - J=0.47
- LOX/CH₄
  - We=2335
  - J=0.60
  - We=7936
  - J=0.56

- significantly larger flame spreading angle for CH₄
- anchored flames for H₂, lifted flames for CH₄
Stabilization of lifted flame in LOX/CH\textsubscript{4} spray

upstream the stabilization point:

- atomization
- droplet evaporation
- mixing of CH\textsubscript{4} and GO\textsubscript{2}
- increasing R\textsubscript{OF} due to LOX evaporation

downstream the stabilization point:

- distributed reaction
- heat release, production of reactants
- flame position depends on amount of GO\textsubscript{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

Institute of Space Propulsion
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

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

$P_c=1.5$ bar

$W_e=7260$, $J=0.5$

$P_c=3.0$ bar

$W_e=8417$, $J=0.5$
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/H₂):

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

flame front velocities

- determination of upstream- and downstream flame front positions: \( z_U(t_i), z_D(t_i) \)

- determination of upstream- and downstream flame front velocities:
  \[
  u_U = \frac{z_U(t_{i+1}) - z_U(t_i)}{\Delta t}
  \]

\[
\begin{align*}
  \nu_D(z_D) &= \nu_C(z_D) + \nu_F(z_D) \\
  \nu_U(z_U) &= \nu_C(z_U) - \nu_F(z_U)
\end{align*}
\]

- determination of flame front- and convection velocities:
  \[
  \nu_C = \frac{\nu_D + \nu_U}{2}, \quad \nu_F = \frac{\nu_D - \nu_U}{2}
  \]
flame front velocities

LOX/H₂

LOX/CH₄

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

\[ z_U = 188.2 - 271.8 \, t \]
\[ v_{\text{U}} = -271.8 \, \text{m/s} \]
\[ z_D = -100.2 + 388.8 \, t \]
\[ v_{\text{D}} = 388.8 \, \text{m/s} \]

\[ v_{\text{flame}} = 325.9 \, \text{m/s} \]
\[ v_{\text{conv}} = 58.5 \, \text{m/s} \]
Coaxial injection at supercritical pressure

Binary liquid N\textsubscript{2}/gaseous He system

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

A: \( P_C = 1.0 \text{ MPa}, \) subcritical N\textsubscript{2}

B: \( P_C = 6.0 \text{ MPa}, \) transcritical N\textsubscript{2}

\begin{itemize}
    \item spray formation at subcritical pressure
    \item reduced surface tension approaching the critical point
    \item turbulent mixing of dense and light fluid components at at supercritical pressure
\end{itemize}
Thermo-physical properties in the near critical region

O₂ specific heat

CH₄ thermal diffusivity
LN$_2$ free jet-decay, Raman scattering

- 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 $T_{\text{initial}} < T^*$ (cases B4 & C4) the heat exchange does not affect the centerline temperature due to specific heat behavior in the near critical region

Injection temperatures:
A4: 140K
B4: 118K
C4: 100K
Combustion at representative pressure conditions

P8 test facility
- GH₂, LH₂ supply
- CH₄ supply in preparation

DLR combustion chamber “C”
- single injector head
- P_c up to 10 MPa, combustion at supercritical O₂- and CH₄-pressures
- optical access
  - shadowgraphy
  - OH-imaging
  - CARS
Combustion Studies LOX/H₂ 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 O₂-clumps of larger size than typical liquid entities in subcritical case

Visualization of O₂-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
    \[ \psi = \frac{\delta}{h} \]
    \( \delta \): laminar flame thickness, \( h \): LOX-post thickness
  

*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
- $\text{GO}_2$/GCH$_4$-ignition
- investigation of LOX/CH$_4$ spray combustion at supercritical pressure at P8 test facility (starting in July this year)