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Multiscale analysis of primary atomization in cryogenic liquid rocket engines

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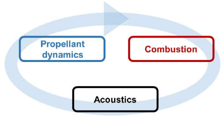
CONTEXT

Liquid rocket propulsion and combustion instabilities

Ariane 6 launcher (ArianeGroup).

- The **performance and stability** of liquid rocket engines depend strongly on the atomization of the cryogenic propellants inside the combustion chamber.
- Under **subcritical conditions**, the oxidizer is injected in liquid phase, while the fuel is injected in gaseous phase.
- In a **coaxial assisted injection configuration**, the liquid jet is destabilized by the faster gaseous annular flow.
- **Primary atomization** describes this destabilization of the liquid flow and the subsequent formation of **liquid ligaments** that will detach from the liquid core and later produce droplets.

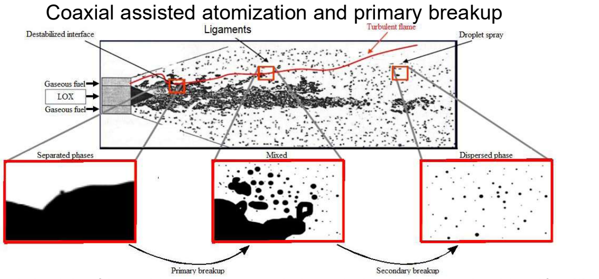


Mechanisms involved in the triggering of combustion instabilities.

Propellant dynamics { Injection, **Primary breakup**, Secondary breakup, Evaporation

- Primary breakup is a driving mechanism in the triggering of **combustion instabilities** under subcritical conditions.

Coaxial assisted atomization and primary breakup



Schematic description of the coaxial assisted primary atomization mechanism in subcritical regime. Adapted from [1].

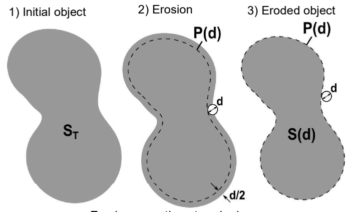
- Focus on the **size, morphology, and dynamics of the intact liquid core**.
- The morphology of the liquid core can be described by:
  - A **structural** part describing the overall shape and size of the liquid core;
  - A **textural** part describing the wrinkling of the liquid-gas interface.

OBJECTIVE

Development of a multiscale image analysis technique to measure the size of atomizing liquid structures in rocket engines. These measurements are then used to predict characteristics of the droplet spray produced by these liquid structures during the atomization process, as a function of the engine operating conditions.

MULTISCALE ANALYSIS

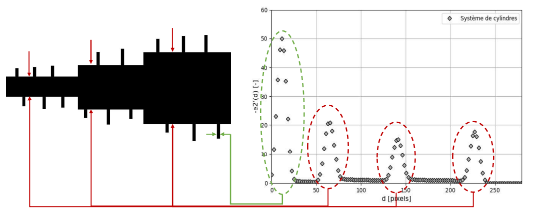
- Image analysis method based on a **scale distribution,** $e_2(d)$ [2], measured with the help of successive **erosions** of the liquid system.
- Allows to characterize the morphology and size of liquid structures [3].
- Small scales are linked to the texture of the interface, and large scales are linked to the structure of the liquid core.
- Peaks of $e_2'(d)$ represent **characteristic scales** of the object.
- The measurement of a series of images from an atomization process allows to obtain **the scale distribution of the liquid ligaments**. These can then be used to characterize the droplets produced by these ligaments.



Erosion operation at scale d.

$$e_2(d) = [E_2(d)]_{,d} = [S_T - S(d)]_{,d} = P(d)/2$$

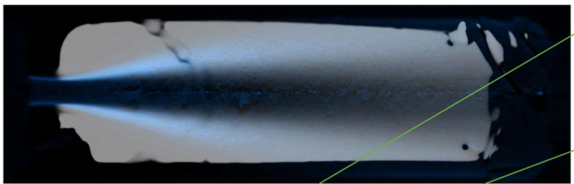
$$e_2'(d) = [e_2(d)]_{,d}$$



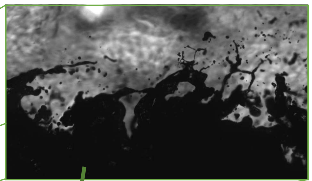
Derivative of the scale distribution of a synthetic object showing textural and structural elements.

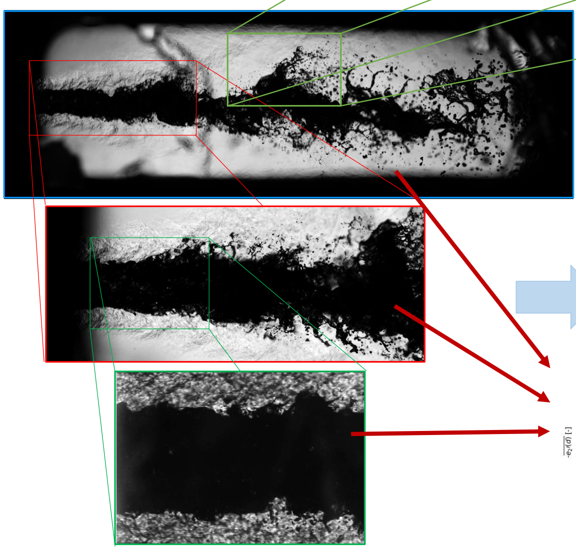
EXPERIMENTAL REACTIVE CONDITIONS: LOX - GCH_4

- Experimental images [4] from the MASCOTTE test-bench [5] at ONERA. **Different operating conditions** representative of liquid rocket engine combustion chambers during transient or low-thrust operation.

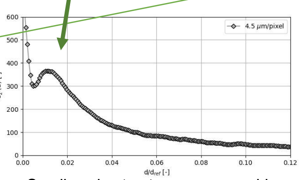


Abel-transformed OH emission image superimposed with an average backlighting image.*

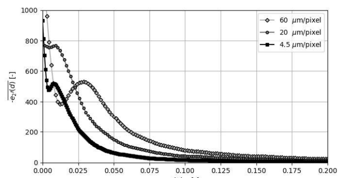




Instantaneous backlighting images (60, 20 and 4.5 µm/pixel).



Small-scale structures measured in different spatial positions.

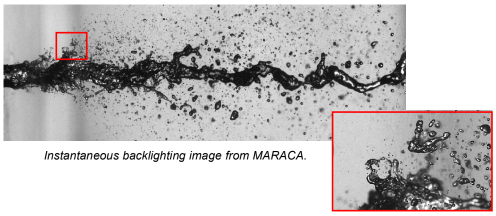


Effect of optical resolution on the measurement of small-scale structures

$e_2'(d)$ (Scale distribution of liquid ligaments) → **Droplet spray characteristics**

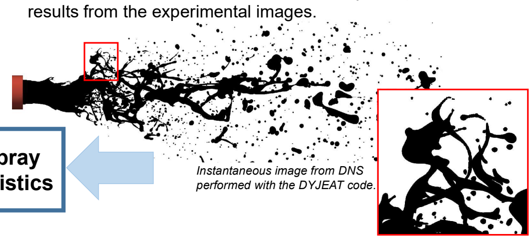
NON-REACTIVE CONDITIONS: Air - water

- Experimental images from the MARACA test-bench at CORIA.
- Very high optical resolution to allow the measurement of the small liquid structures highlighted below.



Instantaneous backlighting image from MARACA.

- Direct Numerical Simulation results showing the same phenomenon.
- Validation of the numerical simulations by comparison with results from the experimental images.



Instantaneous image from DNS performed with the DYJEAT code.

CONCLUSIONS

- Increasing numerical resolution enhances the accuracy of the measurement of the smallest scales.
- Increasing the optical resolution allows to capture smaller scales.
- The method allows to compare results from different operating conditions.
- The scale distribution of the liquid ligaments can be used to predict characteristics of the resulting droplet spray, which is important for the design and validation of numerical simulations.

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