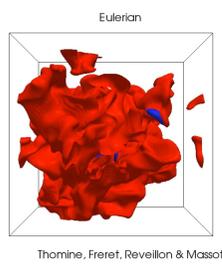
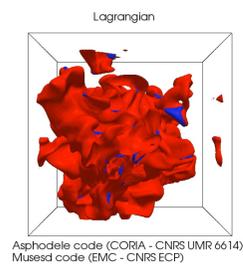
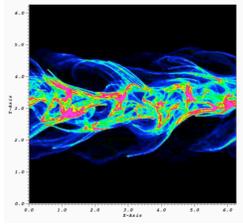
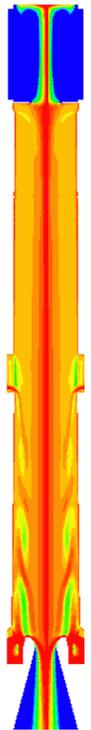
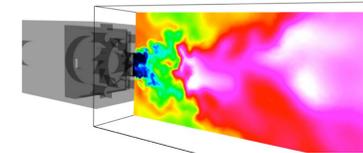


## Quelques exemples de milieux réactifs multi-échelles



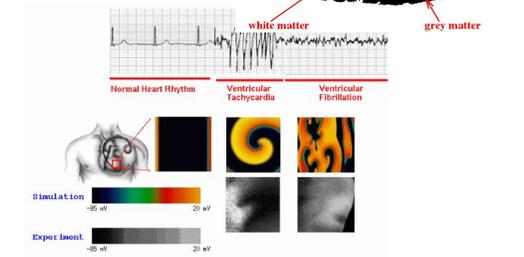
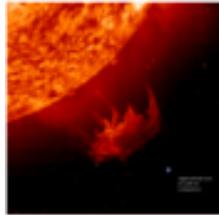
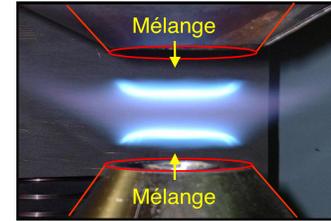
Marc Massot, Laurent Séries  
Centre de Mathématiques Appliquées  
Ecole Polytechnique - Paris



Conseiller Scientifique ONERA – Palaiseau - DMPE

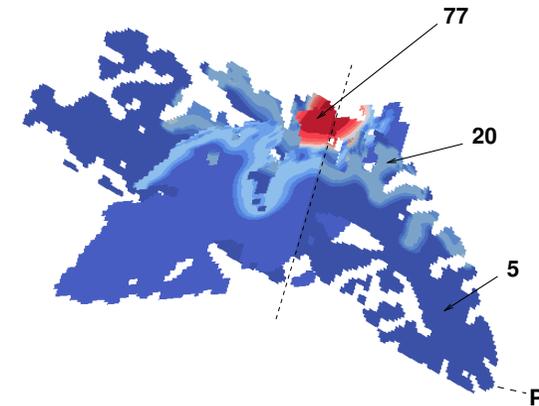
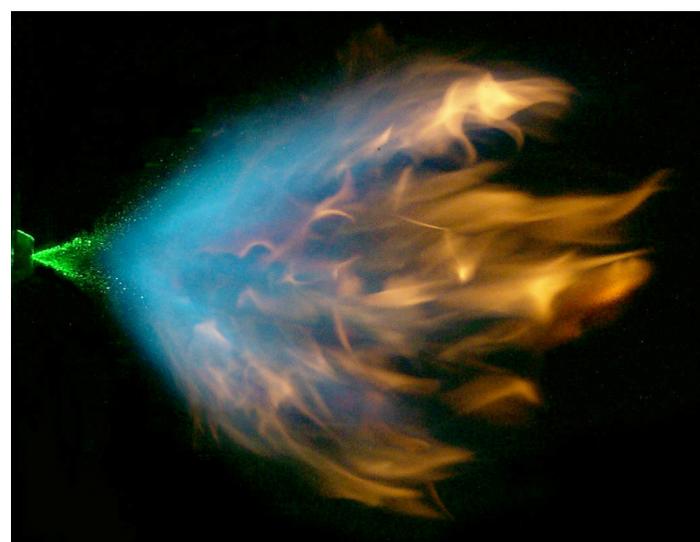
## ➤ Fields of applications :

- Flame Dynamics, homogeneous and two-phase **combustion**
- Multi-scale reaction fronts in **Nonlinear chemical dynamics and biomedical engineering** (spiral and scroll waves, strokes, ...)
- **Atmospheric pressure discharges** (Streamers) for flame stabilization and out of thermal and chemical equilibrium weakly ionized plasma flows for **atmospheric re-entry and solar physics**
- Separated and disperse two-phase flows, polydisperse spray flows for **combustion chambers in automotive, aeronautic and solid propulsion applications.**



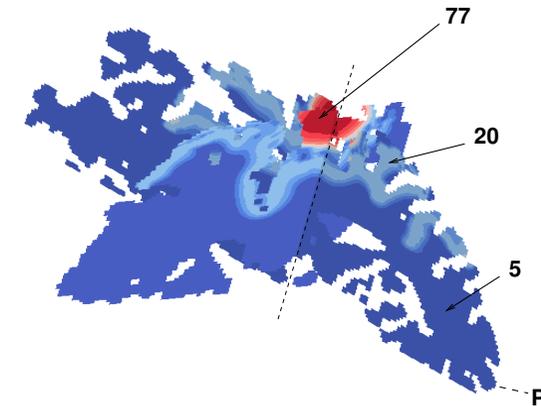
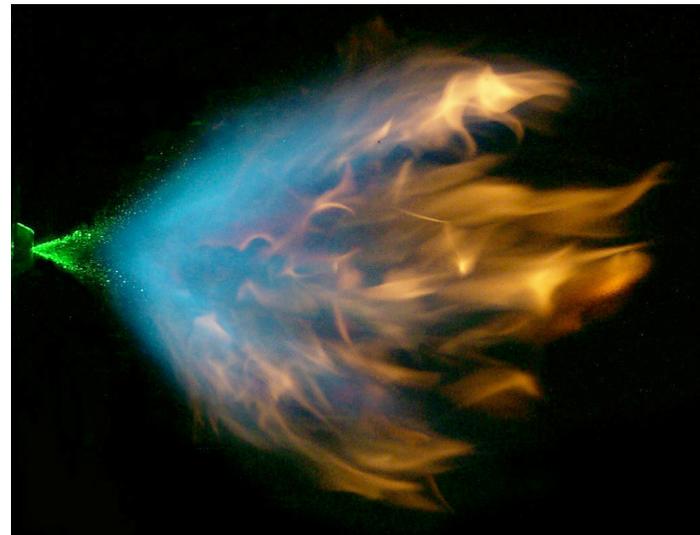
## Qu'est ce qu'un milieu réactif multi-échelle? – quelques exemples

- Ecoulements diphasique dans une chambre de combustion (Ingénierie)
- Etage d'Accélération à Poudre des fusée / moteur Vulcain d'Ariane (Ing.)
- Atmosphère du Soleil (Physique des plasmas)
- Cerveau Humain (Génie Biomédical) – Motifs des coquillages / animaux



## Qu'est ce qu'un milieu réactif multi-échelle? – quelques exemples

- **Complexité** : multiplicité de phénomènes et d'échelles de temps et d'espace
- **Réactifs** : existence de plusieurs « composants » qui « réagissent entre eux » comme dans le cadre de la chimie – exemple typique COMBUSTION

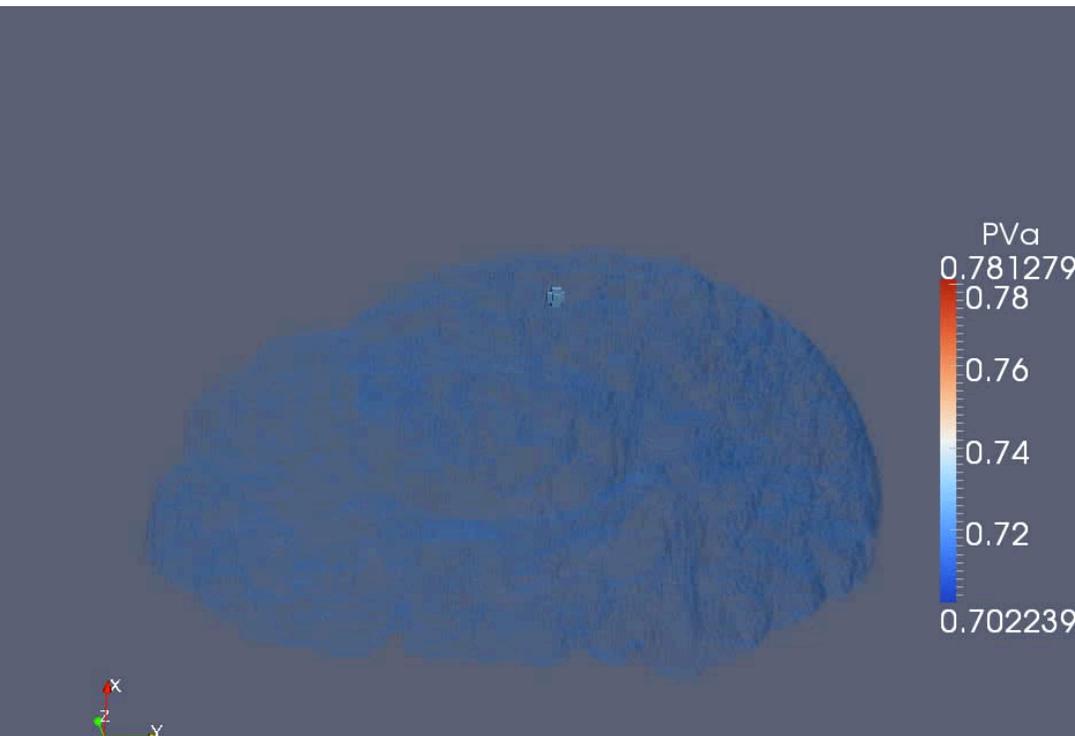


## Qu'est ce qu'un milieu complexe et réactifs – quelques exemples

- **Complexité** : multiplicité de phénomènes et d'échelles de temps et d'espace
- **Réactifs** : existence de plusieurs « composants » qui « réagissent entre eux » comme dans le cadre de la chimie – exemple typique COMBUSTION

Accident vasculaire cérébral ischémique  
(2h – onde de dépolarisation)

-- Ondes Spirale en dynamique  
Chimie non-linéaire – BZ



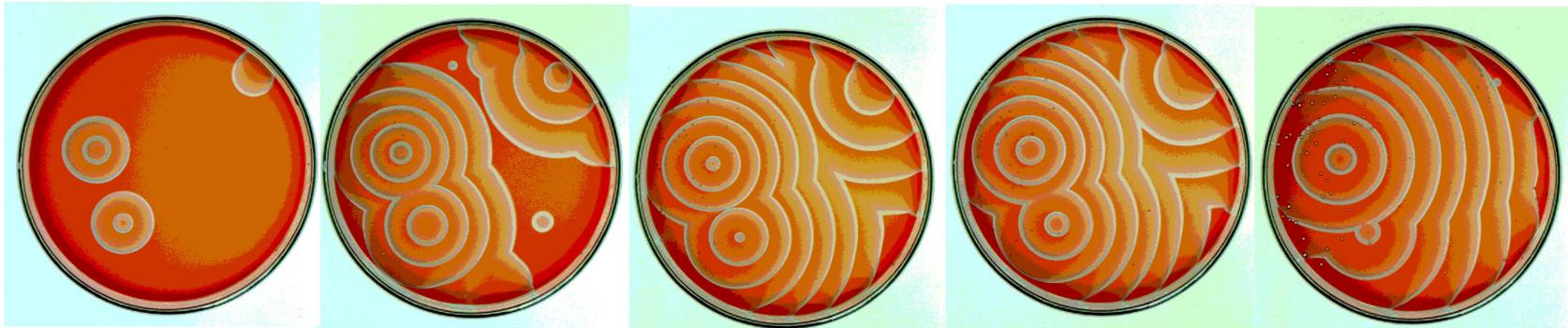
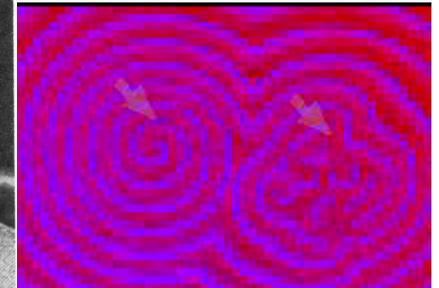
# Waves in the Belousov-Zhabotinsky reaction



**Boris P. Belousov**  
(Soviet Union, 1951, left)



**Anatol M. Zhabotinsky**  
(Soviet Union, 1961, right)



**Chemical reactions can be oscillatory (periodic)!**

## Qu'est ce qu'un milieu complexe et réactifs – quelques exemples

- **Complexité** : multiplicité de phénomènes et d'échelles de temps et d'espace
- **Réactifs** : existence de plusieurs « composants » qui « réagissent entre eux » comme dans le cadre de la chimie – exemple typique COMBUSTION

### Turing Patterns in Chemistry and Biology



## Reaction-diffusion equations

- ▶ Let  $U(x,t)$  and  $V(x,t)$  be the density functions of two chemicals or species which interact or react

$$U_t = D_U \Delta U + f(U, V),$$

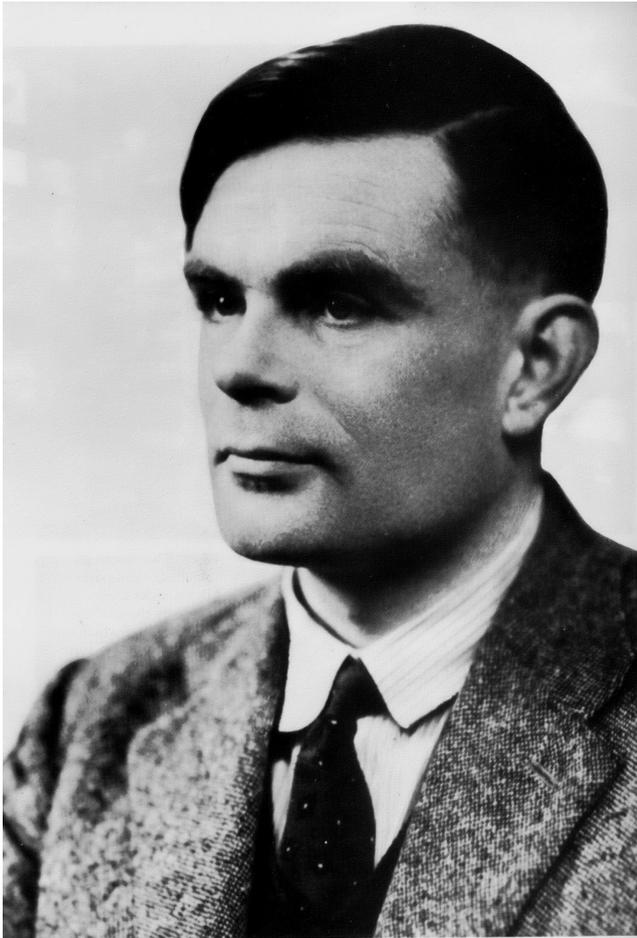
$$V_t = D_V \Delta V + g(U, V).$$

Alan Turing (1952 *Phil. Trans. Roy. Soc.* )

“The Chemical Basis of Morphogenesis”

**Morphogenesis** (from the Greek *morphê* shape and *genesis* creation) is one of three fundamental aspects of developmental biology along with the control of cell growth and cellular differentiation. Morphogenesis is concerned with the shapes of tissues, organs and entire organisms and the positions of the various specialized cell types.

# Alan Turing (1912-1954)



- One of greatest scientists in 20<sup>th</sup> century
- Designer of Turing machine (a theoretical computer) in 1930's
- Breaking of U-boat Enigma, saving battle of the Atlantic
- Initiate nonlinear theory of biological growth

<http://www.turing.org.uk/>



# Spotted body and striped tail or legs



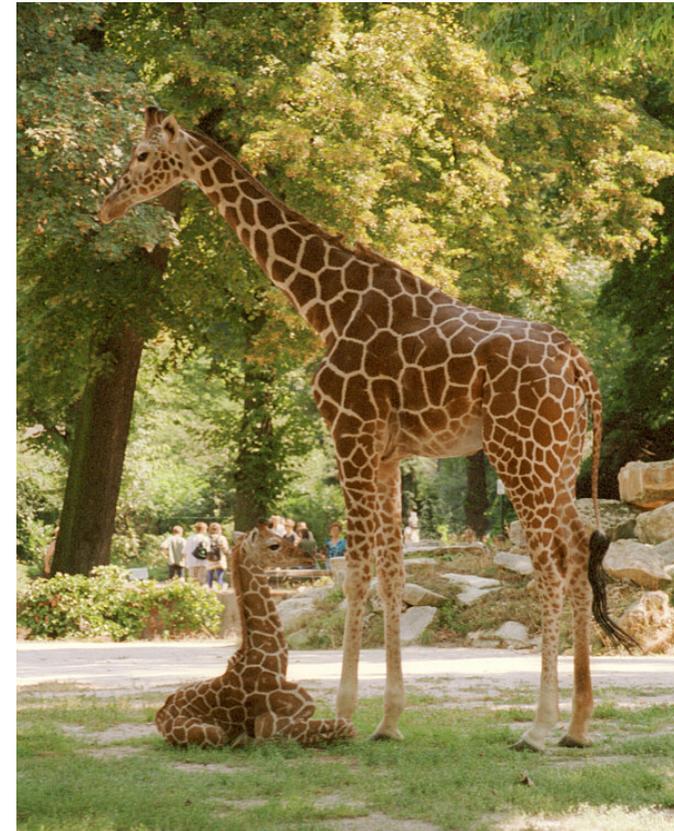
Cheetah (upper), Okapi (lower)



Tiger (upper), Leopard (lower)



# Spotted body and striped tail



**Genet (left), Giraffe (right)**

See H. Meinhardt “The algorithmic beauty of sea shells”



Patterns of sea shells

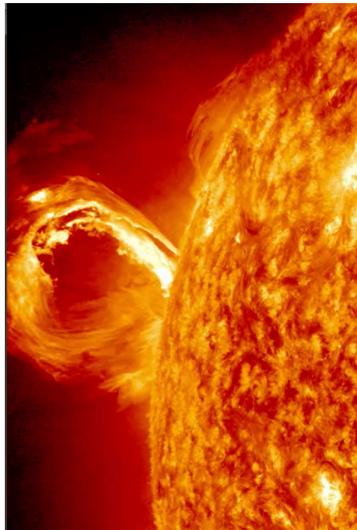


Patterns of tropical fishes

## Qu'est ce qu'un milieu complexe et réactifs – quelques exemples

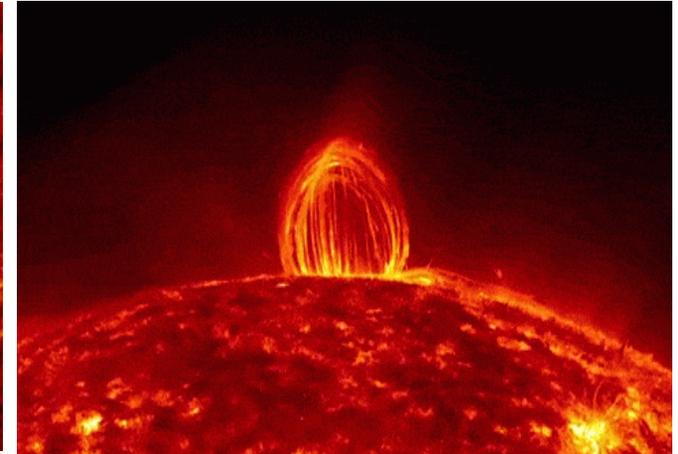
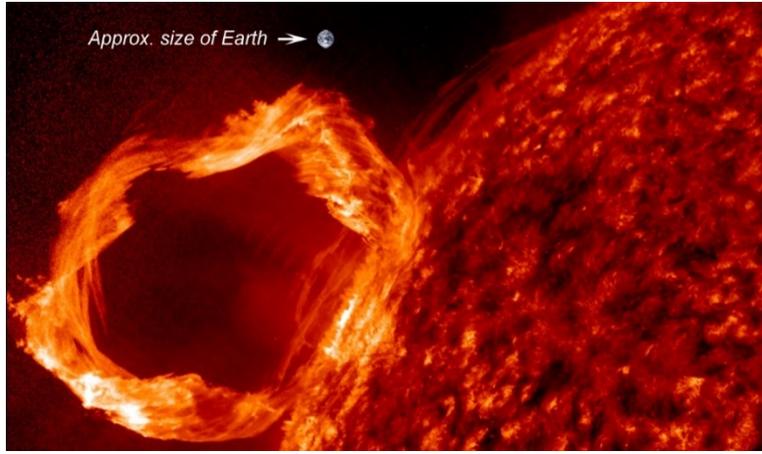
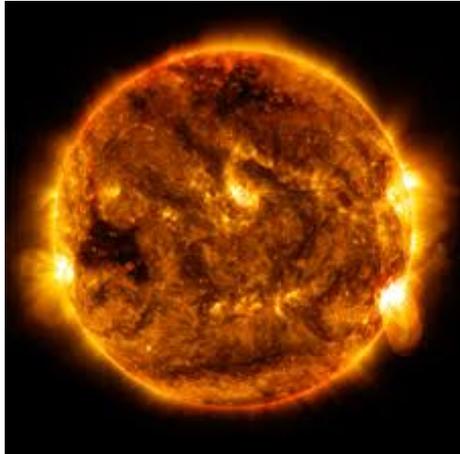
- **Complexité** : multiplicité de phénomènes et d'échelles de temps et d'espace
- **Réactifs** : existence de plusieurs « composants » qui « réagissent entre eux » comme dans le cadre de la chimie – exemple typique COMBUSTION

Eruptions Solaires  
(prédire le temps solaire!)



Moteurs fusée – EAP (Booster)  
Discovery – Ariane (Vulcain)





**Quentin WARGNIER**  
**June 2017 – SMAI**

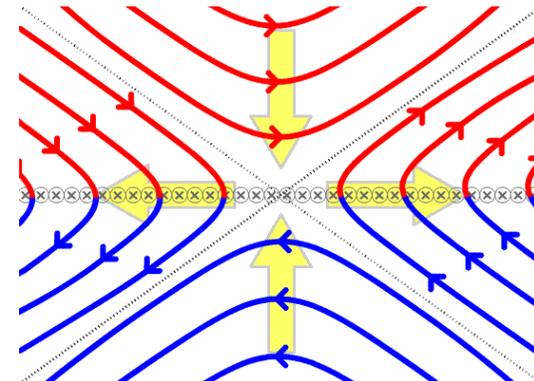
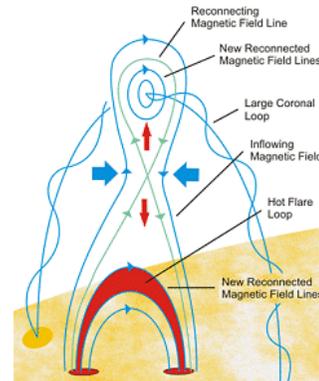
CMAP Ecole Polytechnique

Laboratoire de Mathématiques d'Orsay, NASA Ames Research Center – Heliophysics group

von Karman Institute for Fluid dynamics

► Collisional model for the sun atmosphere (photosphere to chromosphere)

- The solar flares mechanism
- Space weather
- Understanding the corona heating
  - Magnetic reconnection process
  - Dissipation effect ? Resistivity ? Transport properties



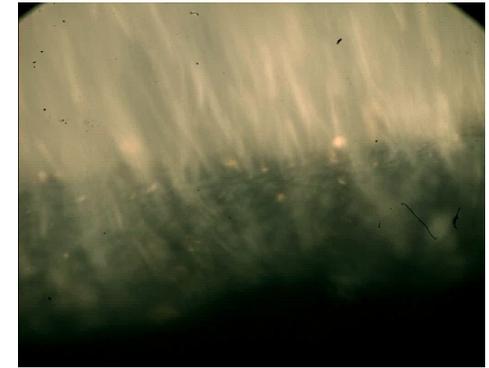
**Challenge:**  
**A model which can represent the magnetic reconnection process in sun chromosphere condition**

# Solid propulsion for rocket boosters



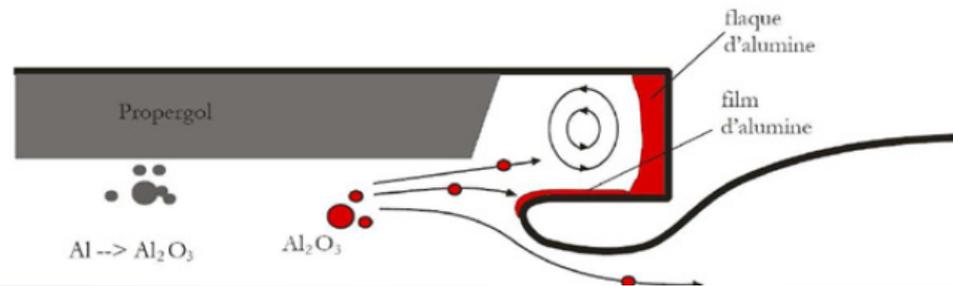
Solid Rocket Motor (boosters, missiles...) :

- Aluminum  $\Rightarrow$  higher specific impulse
- Combustion  $\Rightarrow$  liquid aluminum oxide ( $\text{Al}_2\text{O}_3$ )
- **Polydisperse droplets** (below  $200\mu\text{m}$ )
- Interaction with flow  $\Rightarrow$  performance deterioration



Issues :

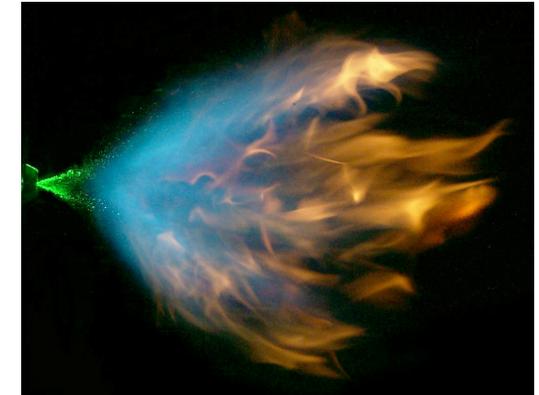
- Influence on chamber **instabilities**
- Specific impulse loss in the nozzle
- Aluminum oxide slag accumulation
- Insulation erosion
- Jet signature



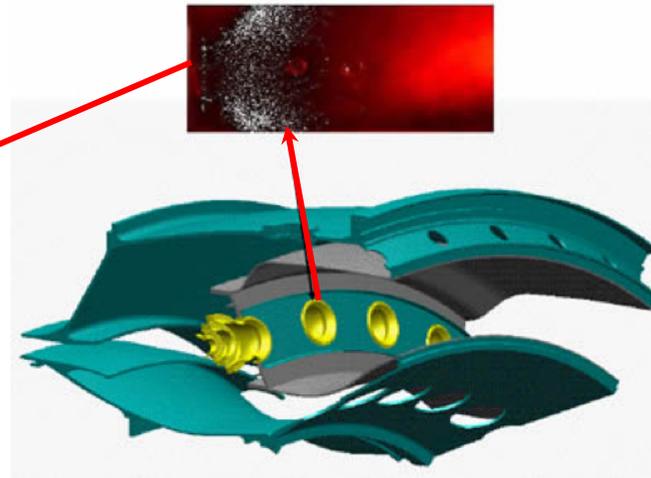
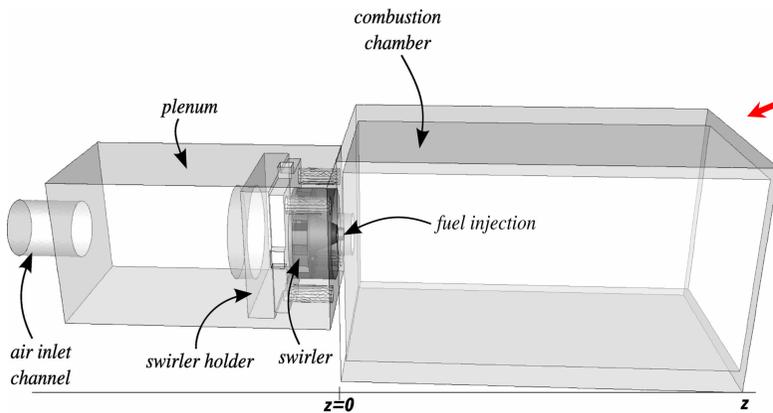
## Injection of fuel in Aeronautical Engines (Source ONERA).

Annular Combustion chamber

one sector reproduced in the MERCATO Experiment



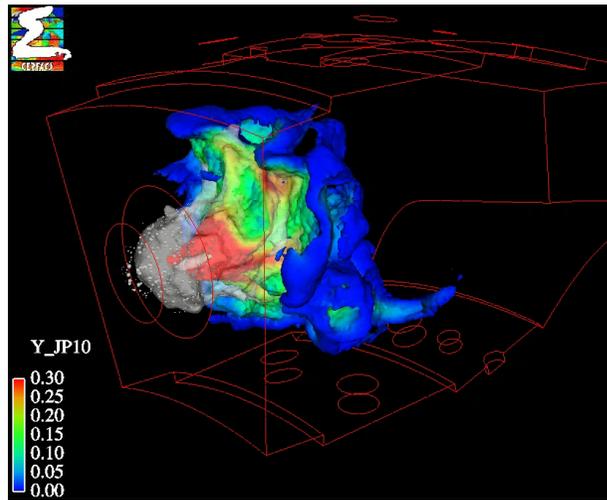
(Source Prof. Bowman, Stanford)



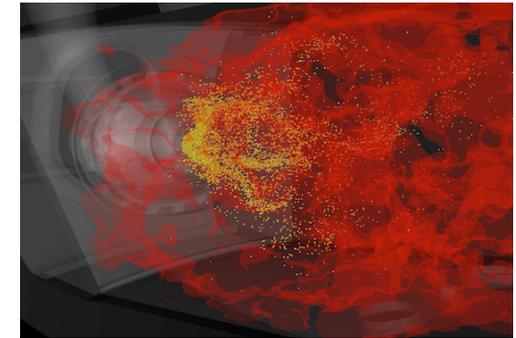
### Various phenomena

- Injection
- Primary atomization
- Secondary break-up
- Turbulent dispersion
- Droplet/droplet interaction
- Droplet/wall interaction
- Evaporation
- Combustion

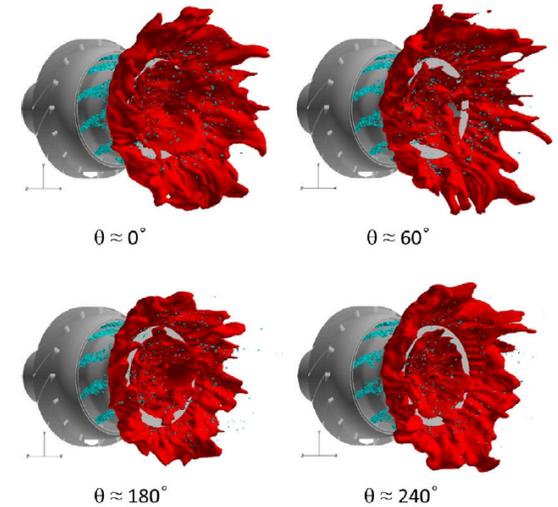
# LES of Two-phase flows



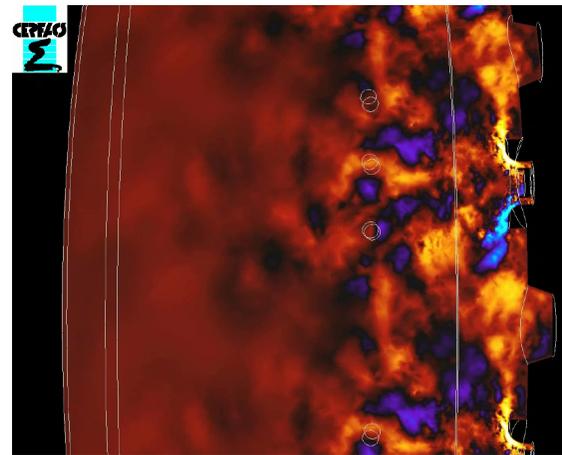
Two-phase flow LES of the steady regime of one sector of an annular aeronautical combustor, 2005, S. Pascaud, CERFACS and Turbomeca (SAFRAN group)



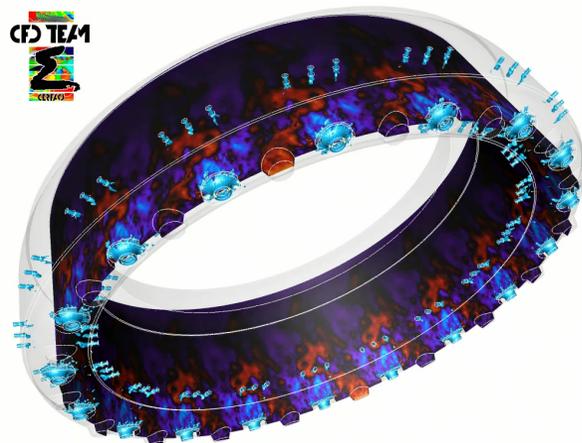
Cascade technology, Pratt & Whitney gas turbine



Tachibana et al, C&F 2015 - Time evolution of three-dimensional iso-thermal surfaces at 1500 K (in red) and main fuel droplet distributions (in light blue) – JAXA – Kyoto Univ.

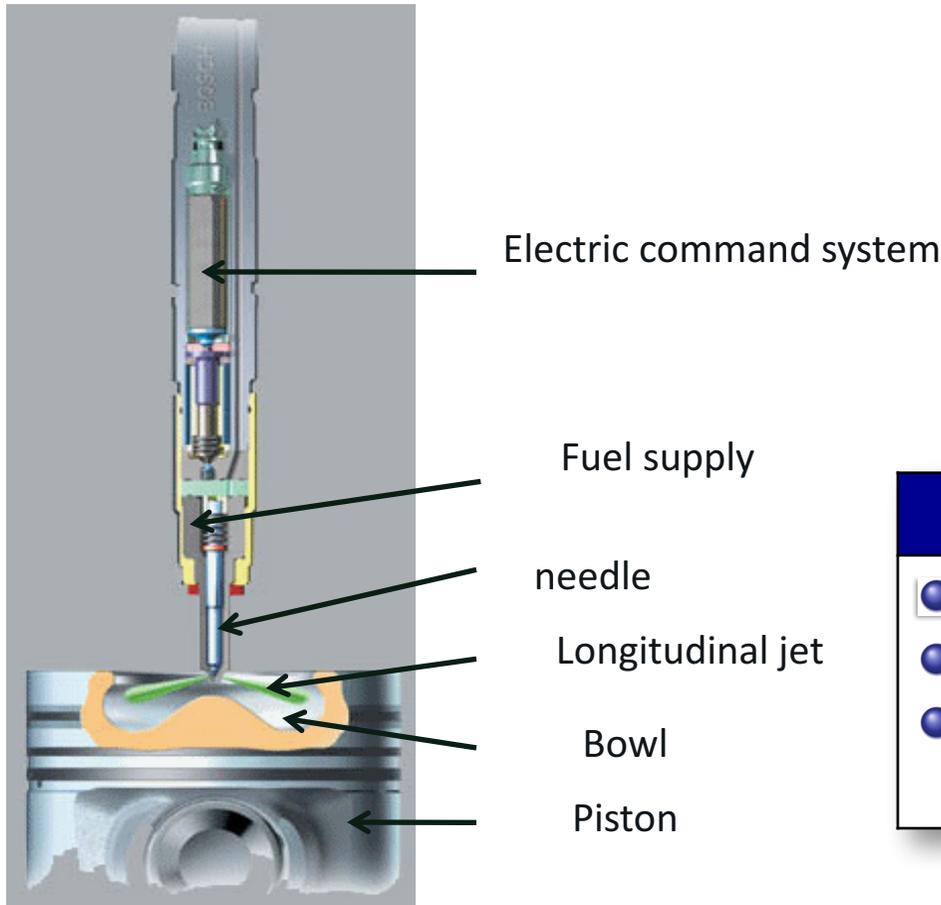


Flame front propagation in the LES of the ignition of a full helicopter combustor, 2007, M. Boileau, CERFACS and Turbomeca (SAFRAN group)



Flame front propagation in the LES of the ignition of a full helicopter combustor, 2007, M. Boileau, G. Staffelbach, CERFACS and Turbomeca (SAFRAN group)

# Fuel injection



Multiphase flow involved



Fig: Dumouchel, Coria

## Injection parameters

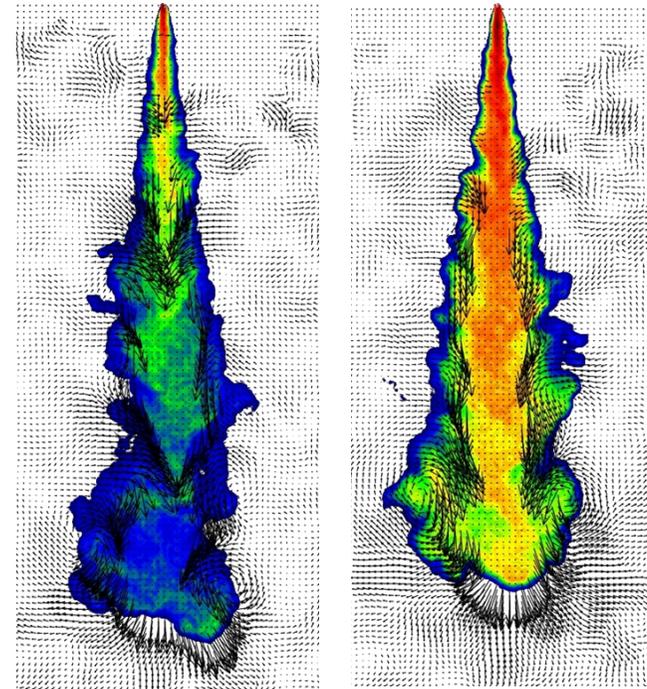
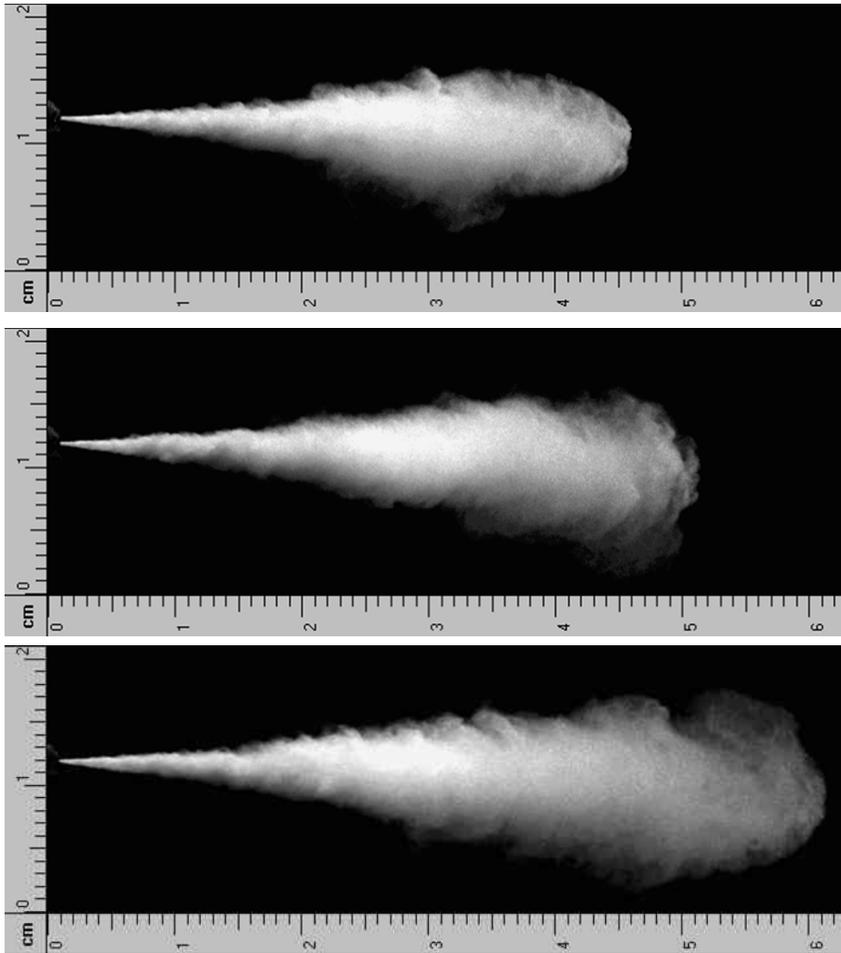
- Injection pressure: 2000 bar
- Injection velocity:  $600 \text{ m.s}^{-1}$
- Injection time : 2ms

## Experimental visualizations



Source : Sandia National Labs

## Experimental visualizations (Back light – PIV/LIEF)



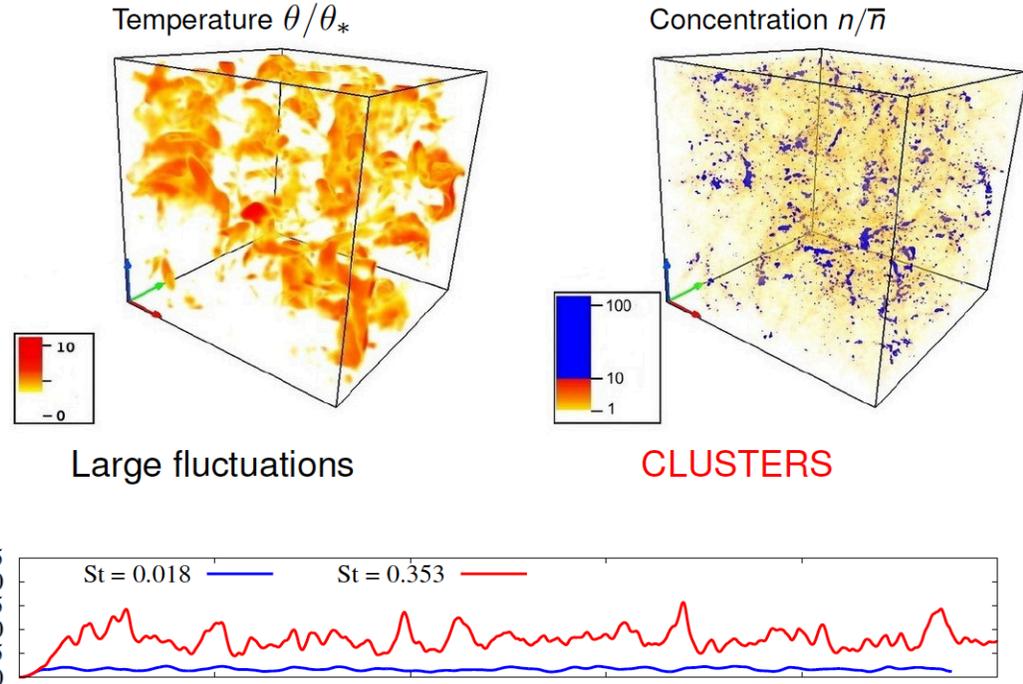
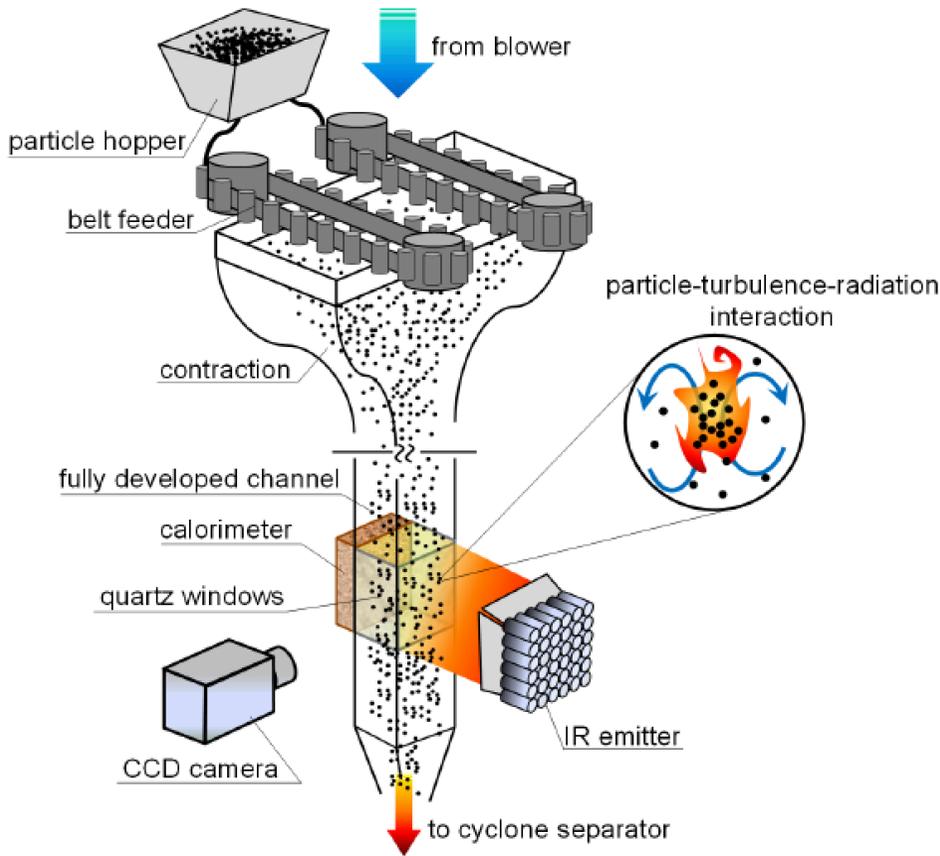
Source : IFP Energies nouvelles, France

# Coupling of radiative heating / spray dynamics / turbulence

## PSAAP2 project CTR Stanford – Solar Harvesting

Zamansky, Coletti, Massot, Mani, PoF 2014

Zamansky, Coletti, Massot, Mani, JFM 2016

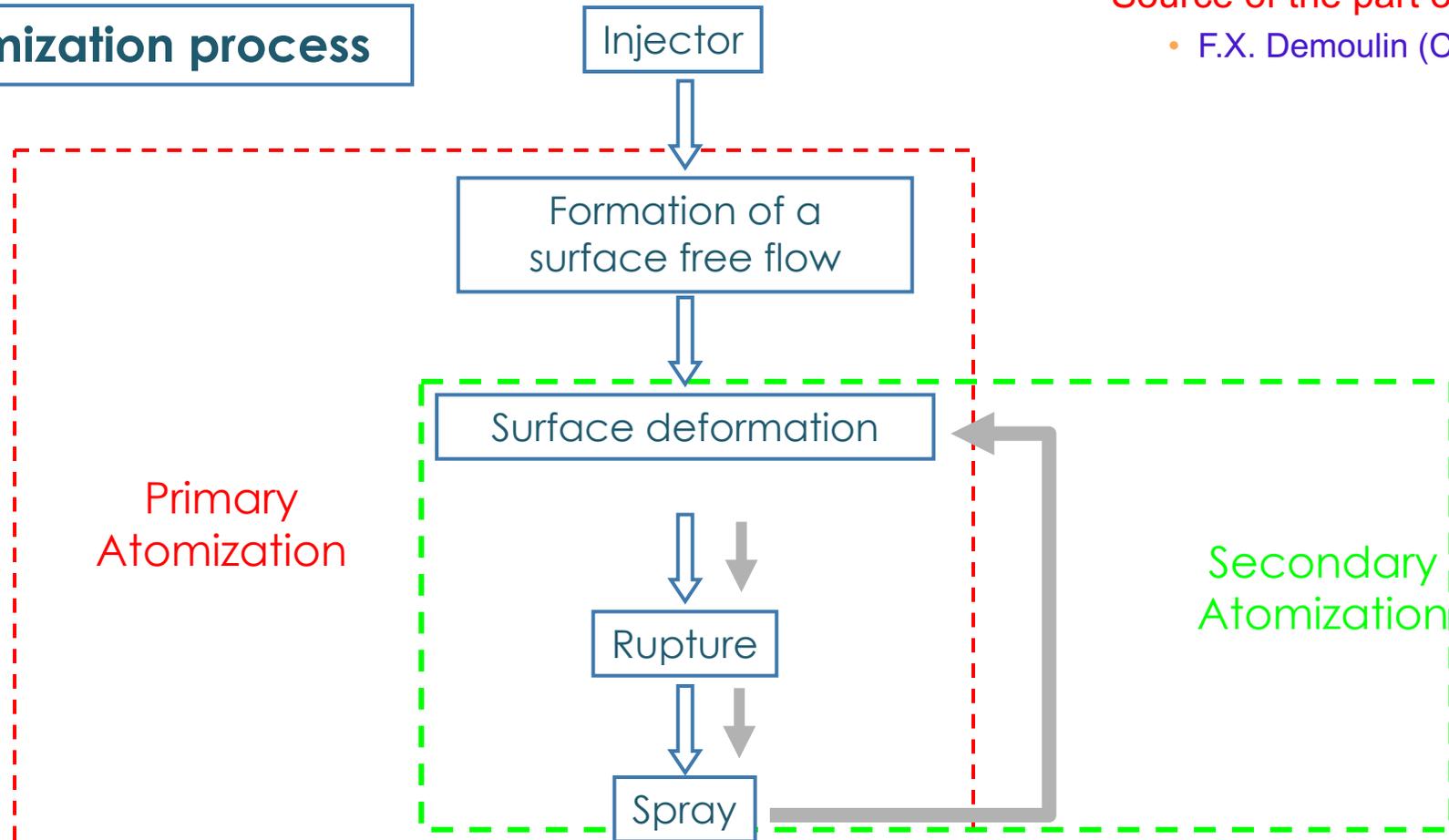


# Fundamental of atomization process

## Atomization process

Source of the part on atomization

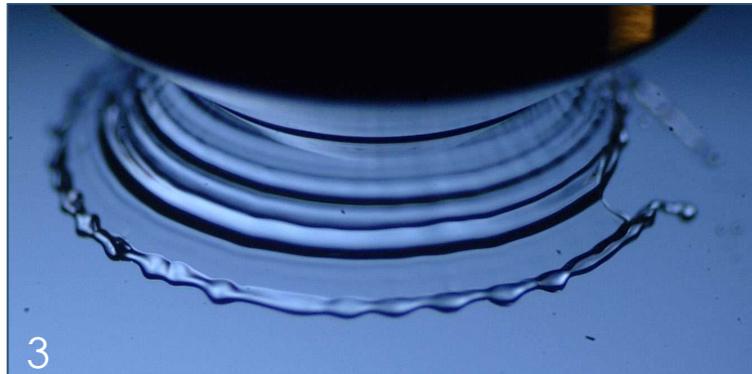
- F.X. Demoulin (CORIA- Rouen)



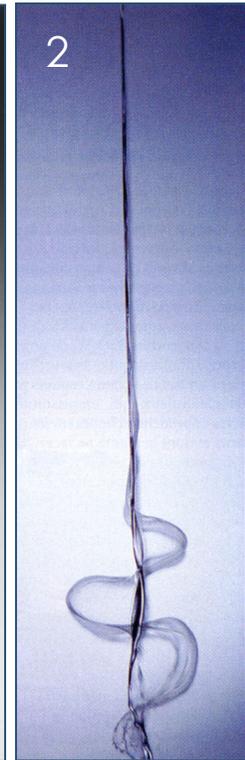
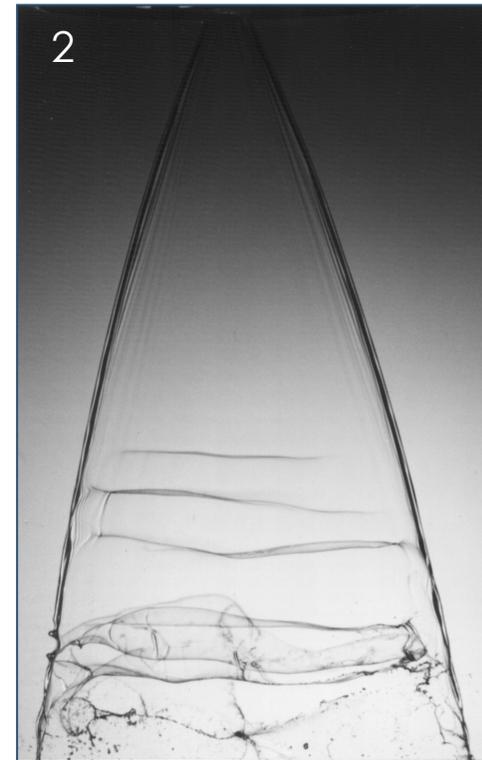
## Influence of the geometry



1 – Cylindrical jet : capillary instability  
Rayleigh-Plateau



2 – Liquid sheet  
Kelvin-Helmholtz instability



3 – Annular sheet  
Kelvin-Helmholtz instability

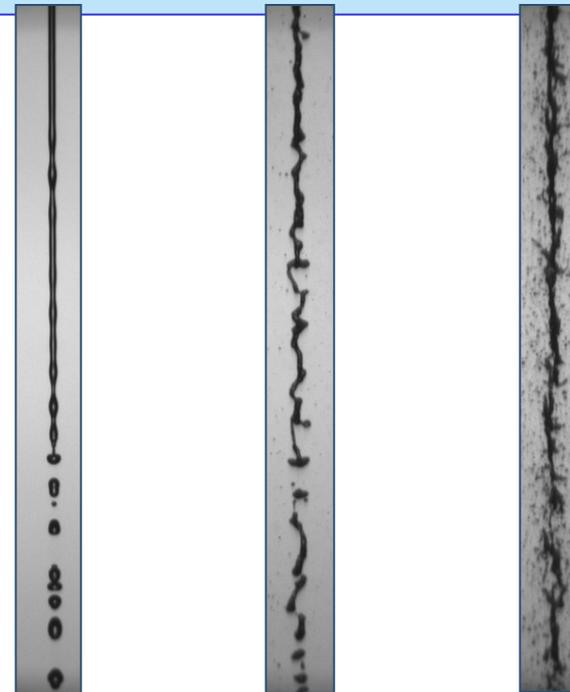
## Influence of mean liquid velocity

- $d = 600 \mu\text{m}$
- Eau/air

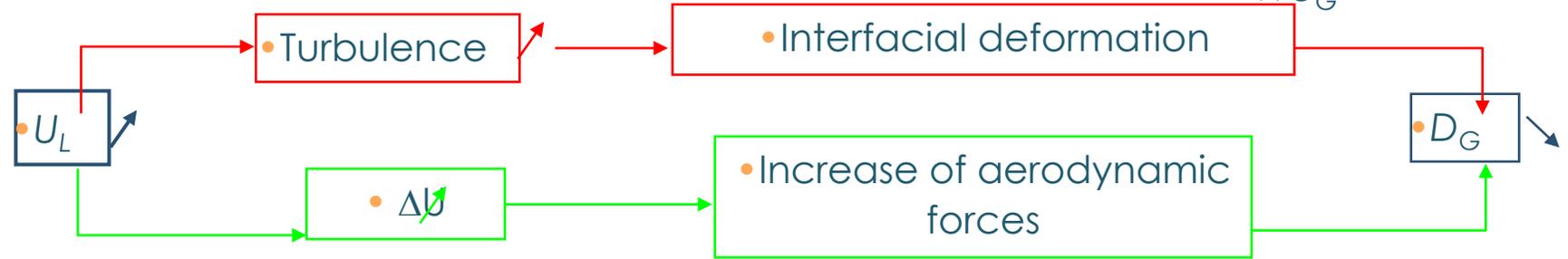
$$\text{Re} = \frac{\rho_L U_L d}{\mu_L}$$

$$\text{We}_G = \frac{\rho_G (U_G - U_L)^2 d}{\sigma}$$

Photos CORIA

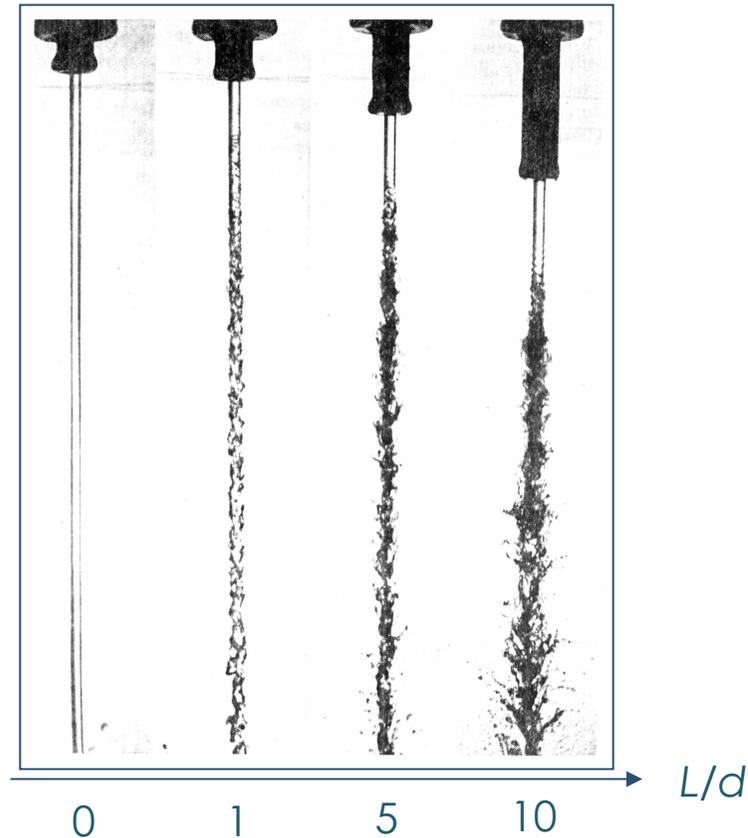


1.4 m/s      24 m/s      47 m/s →  $U_L$   
 0.02      6      24 →  $We_G$



## Influence of inlet velocity profile

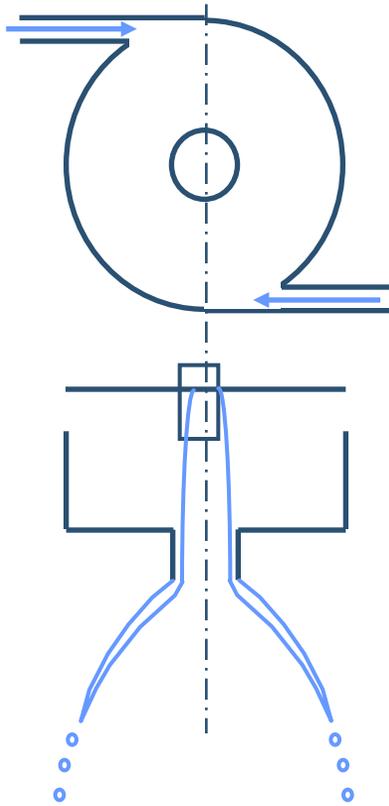
- $d = 2.54 \text{ mm}$
- Glycerol-eau/air
- $U_L = 20 \text{ m/s}$
- $We_G = 15$
- Photos : Mc Carthy et Molloy, 1973



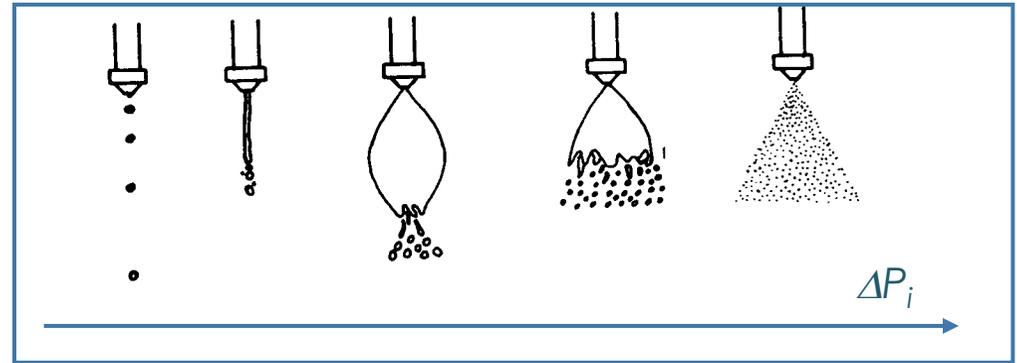
- The relaxation of the velocity profile may generate instabilities that promote the atomization process

## Influence of velocity profile at the inlet

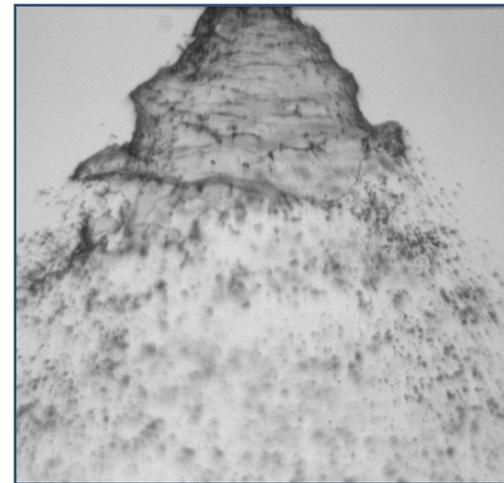
• Schematic

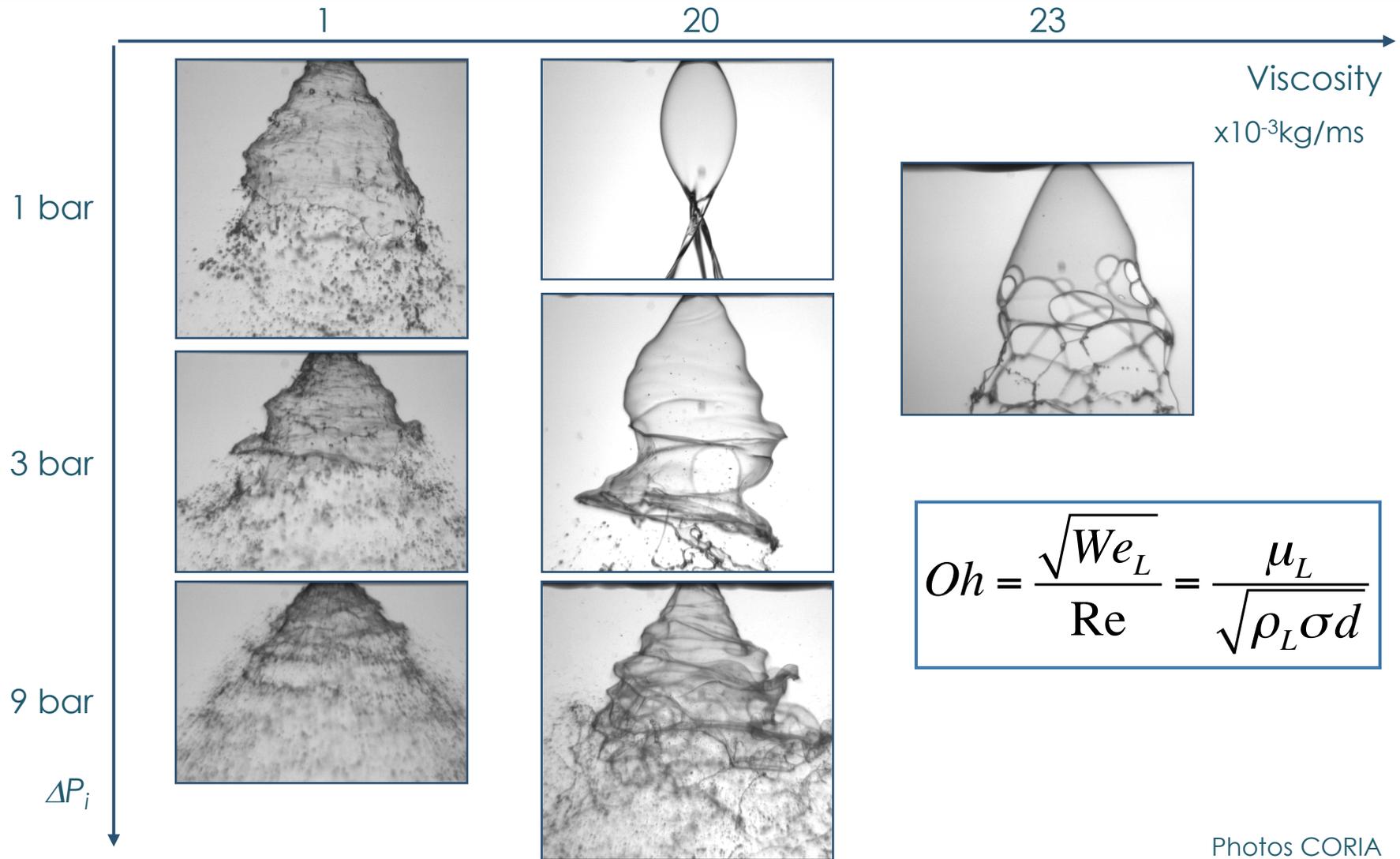


• Swirl injector

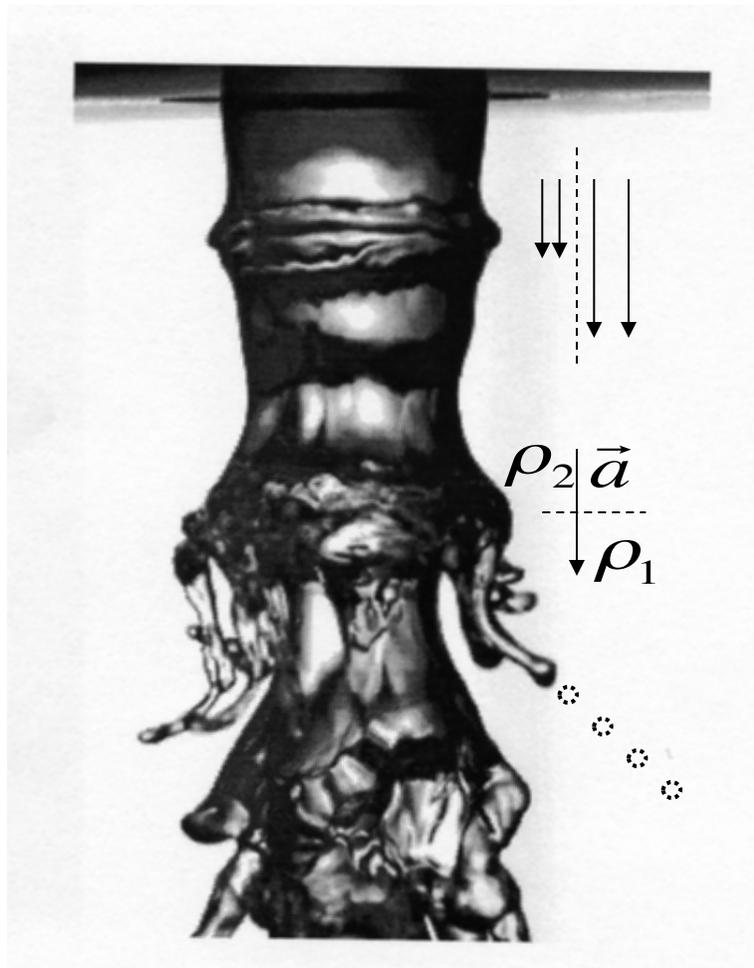


• Example





Various physical phenomena and instabilities



Kelvin-Helmholtz

Rayleigh-Taylor

Rayleigh-Plateau

- *Lasheras, Villermaux, Hopfinger, JFM (1998)*
- *Lasheras, Hopfinger, Annual Review of Fluid Mechanics (2000)*

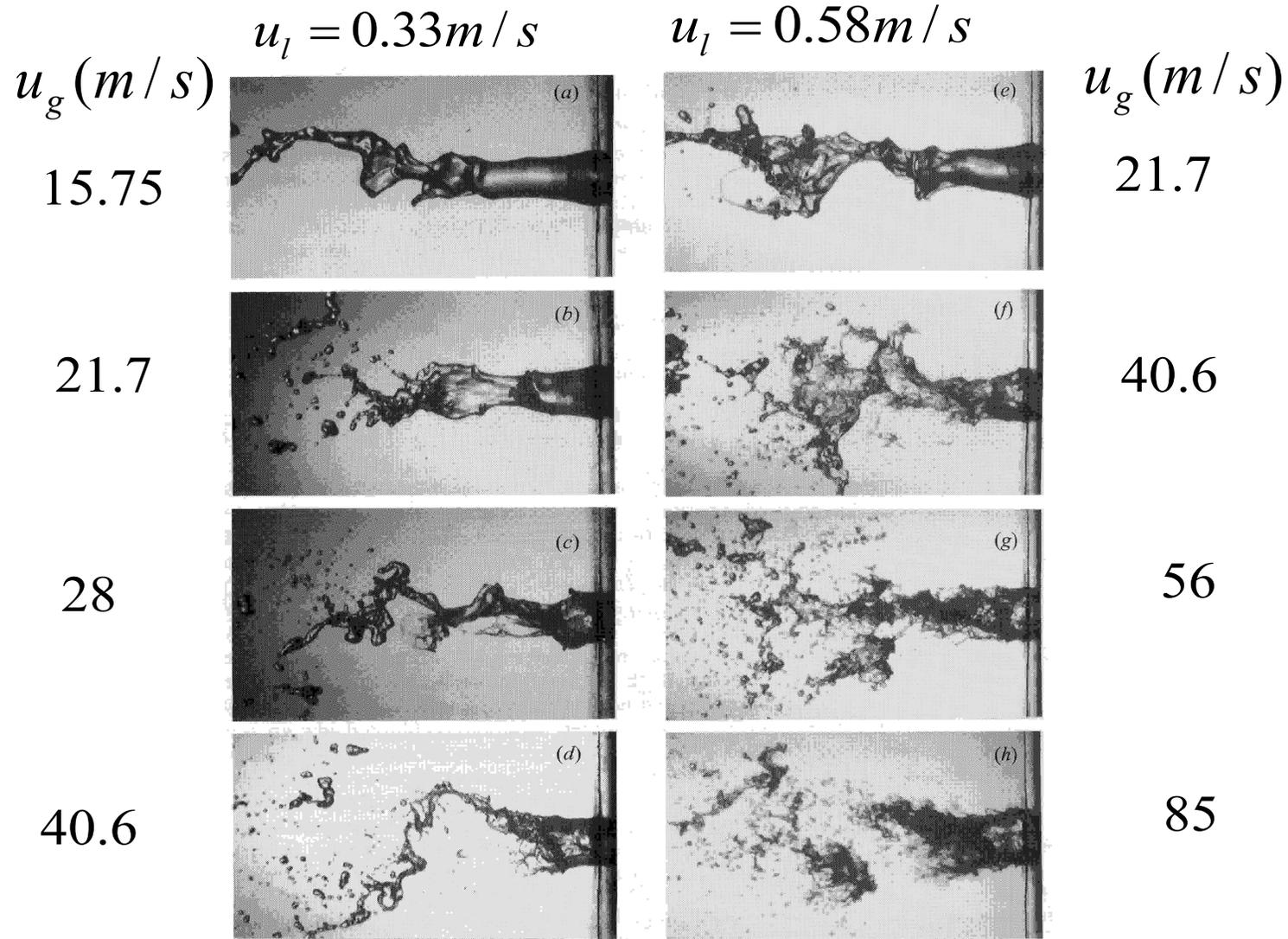


FIGURE 2. Instantaneous flow visualization of the break-up of the liquid jet by the annular air jet. (a)  $U_g = 15.75 \text{ m s}^{-1}$ ,  $M = 3.8$ ,  $We_0 = 16$ ,  $Re_i = 830$ ; (b)  $U_g = 21.7 \text{ m s}^{-1}$ ,  $M = 7.35$ ,  $We_0 = 31$ ,  $Re_i = 1120$ ; (c)  $U_g = 28 \text{ m s}^{-1}$ ,  $M = 12.2$ ,  $We_0 = 52$ ,  $Re_i = 1450$ ; (d)  $U_g = 40.6 \text{ m s}^{-1}$ ,  $M = 25$ ,  $We_0 = 110$ ,  $Re_i = 2100$ ; (e)  $U_g = 21.7 \text{ m s}^{-1}$ ,  $M = 2.05$ ,  $We_0 = 31$ ,  $Re_i = 1120$ ; (f)  $U_g = 40.6 \text{ m s}^{-1}$ ,  $M = 7.0$ ,  $We_0 = 110$ ,  $Re_i = 2100$ ; (g)  $U_g = 56 \text{ m s}^{-1}$ ,  $M = 13$ ,  $We_0 = 210$ ,  $Re_i = 2900$ ; (h)  $U_g = 85.4 \text{ m s}^{-1}$ ,  $M = 31$ ,  $We_0 = 489$ ,  $Re_i = 4420$ .

## Air assisted Atomization

$$J = \frac{\rho_G U_G^2}{\rho_L U_L^2}$$

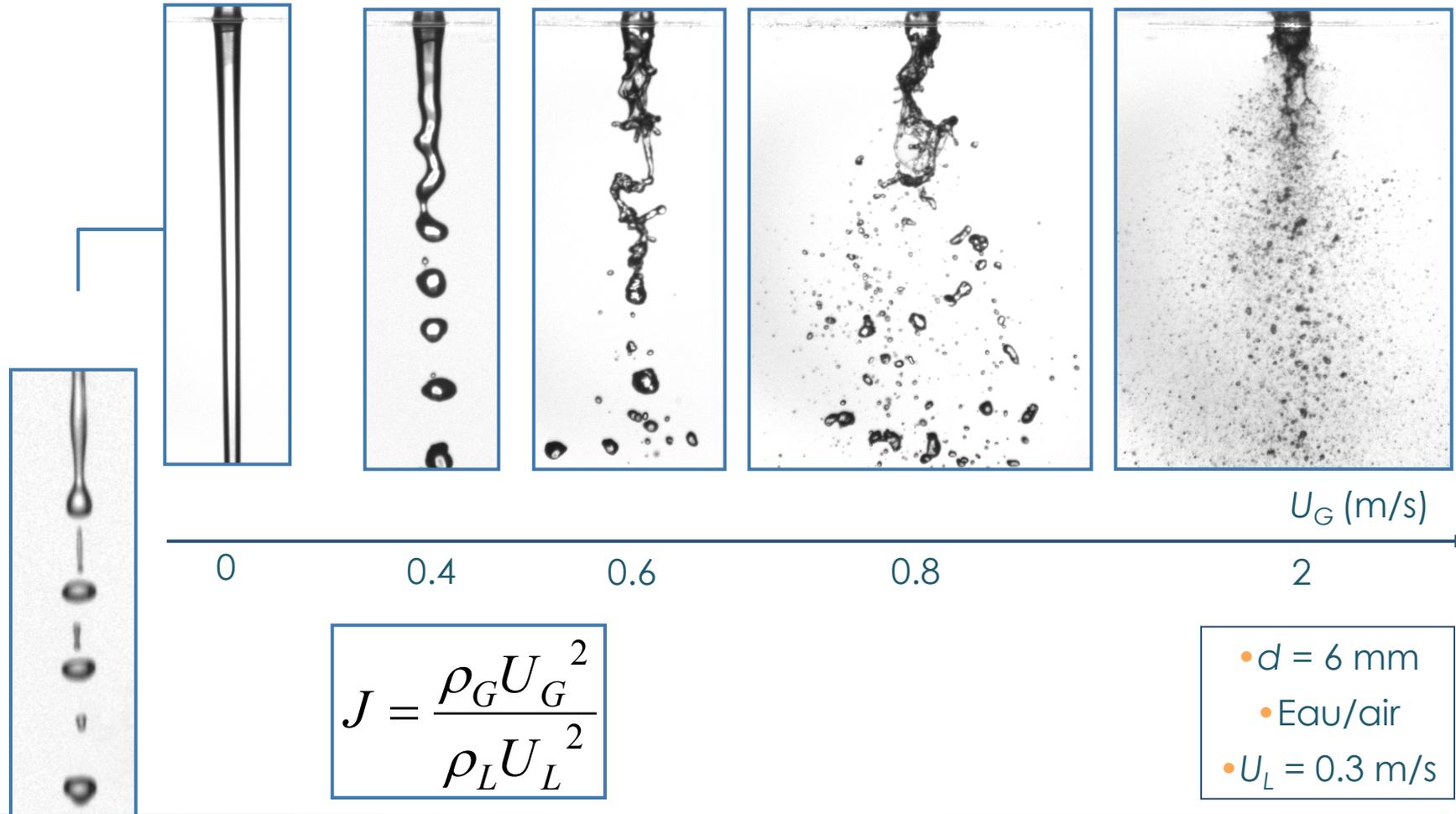
Photos : Carvalho, Heitor and Santos (1998)

- Liquid thickness :  $e = 0.7 \text{ mm}$
- $L/e = 114$
- $e_G : 7 \text{ mm}$
- Water/air

$U_G \text{ (m/s)}$



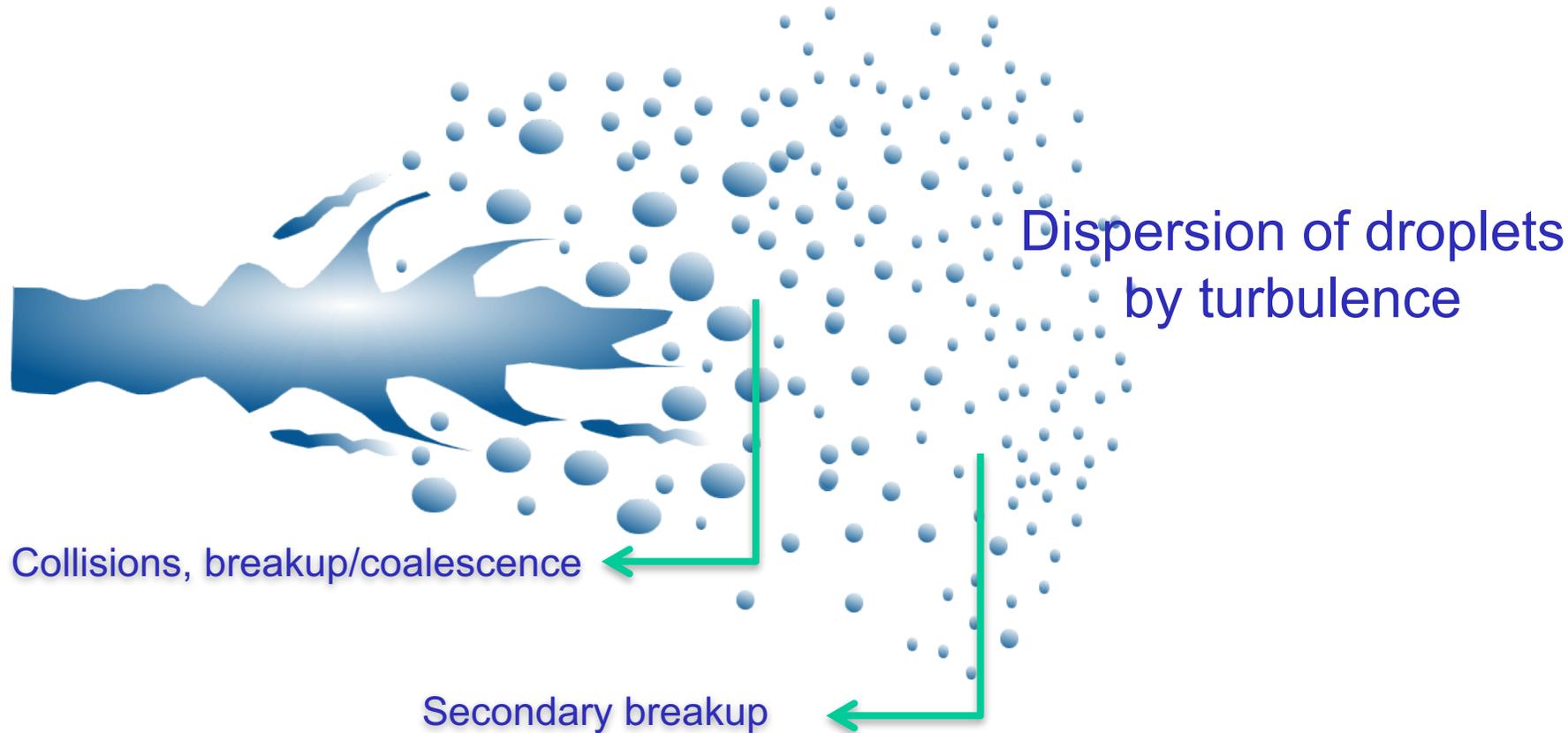
## Air assisted atomization (Co-axial jets)



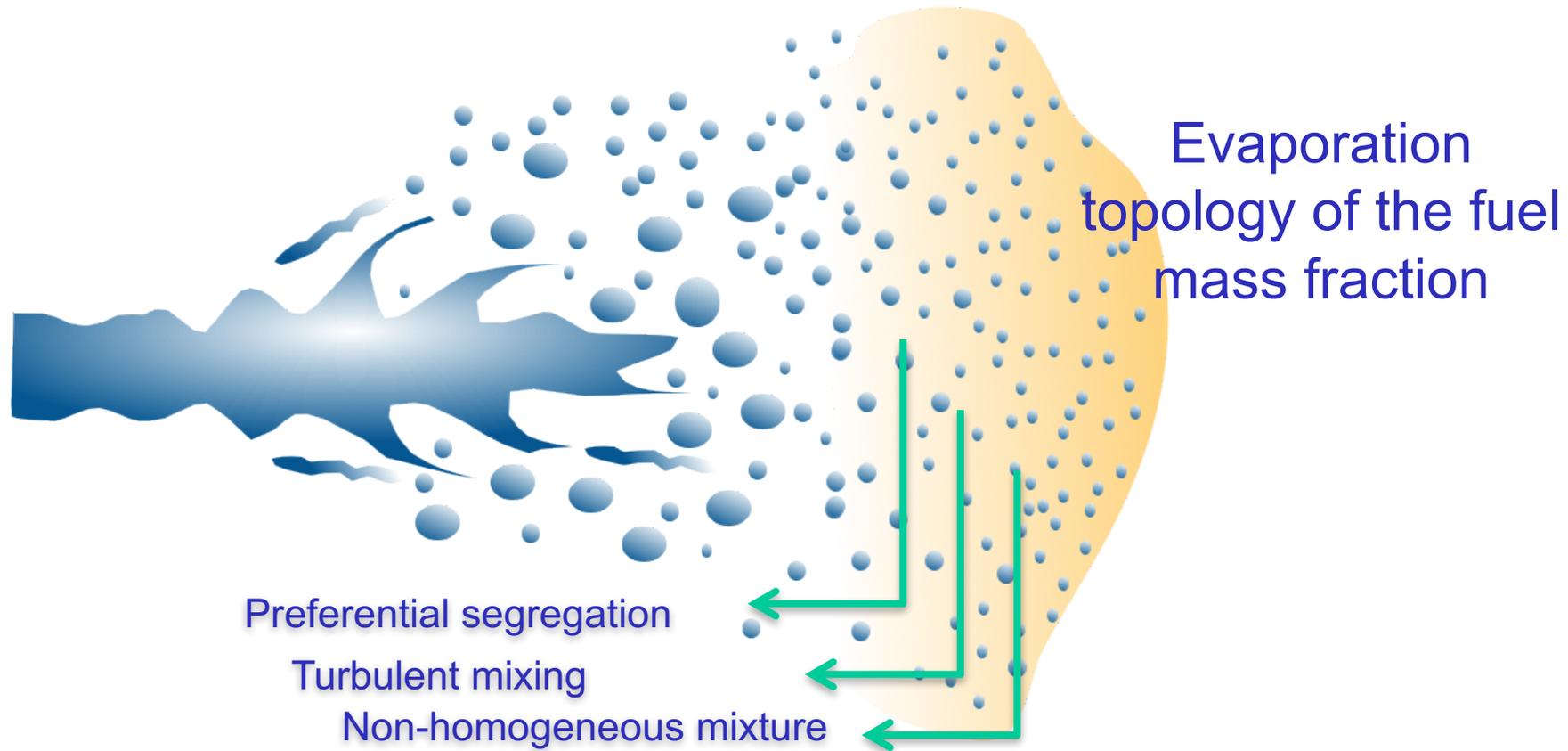
Source

• J. Reveillon  
(CORIA- Rouen France)

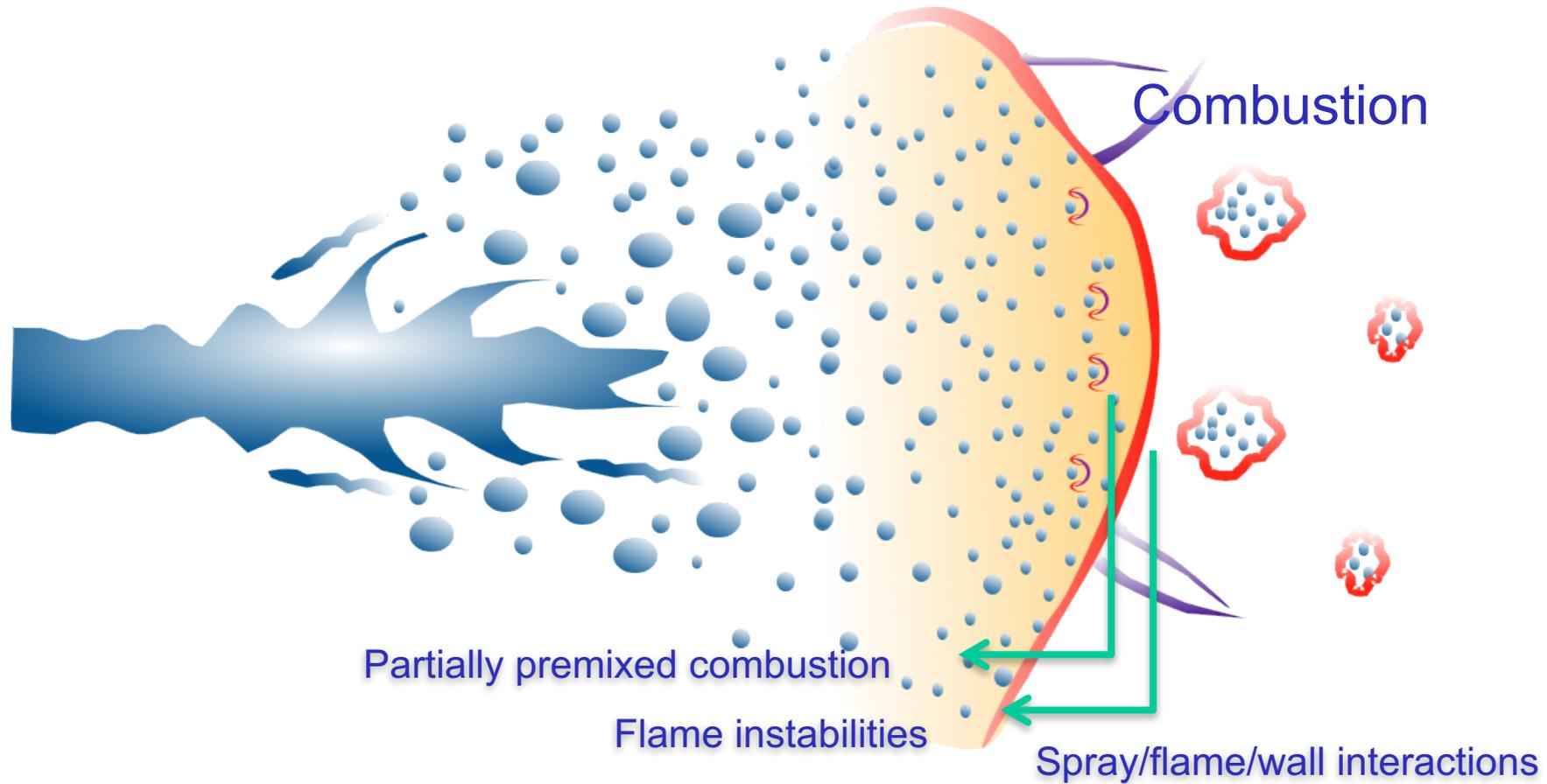
## Combustion chamber



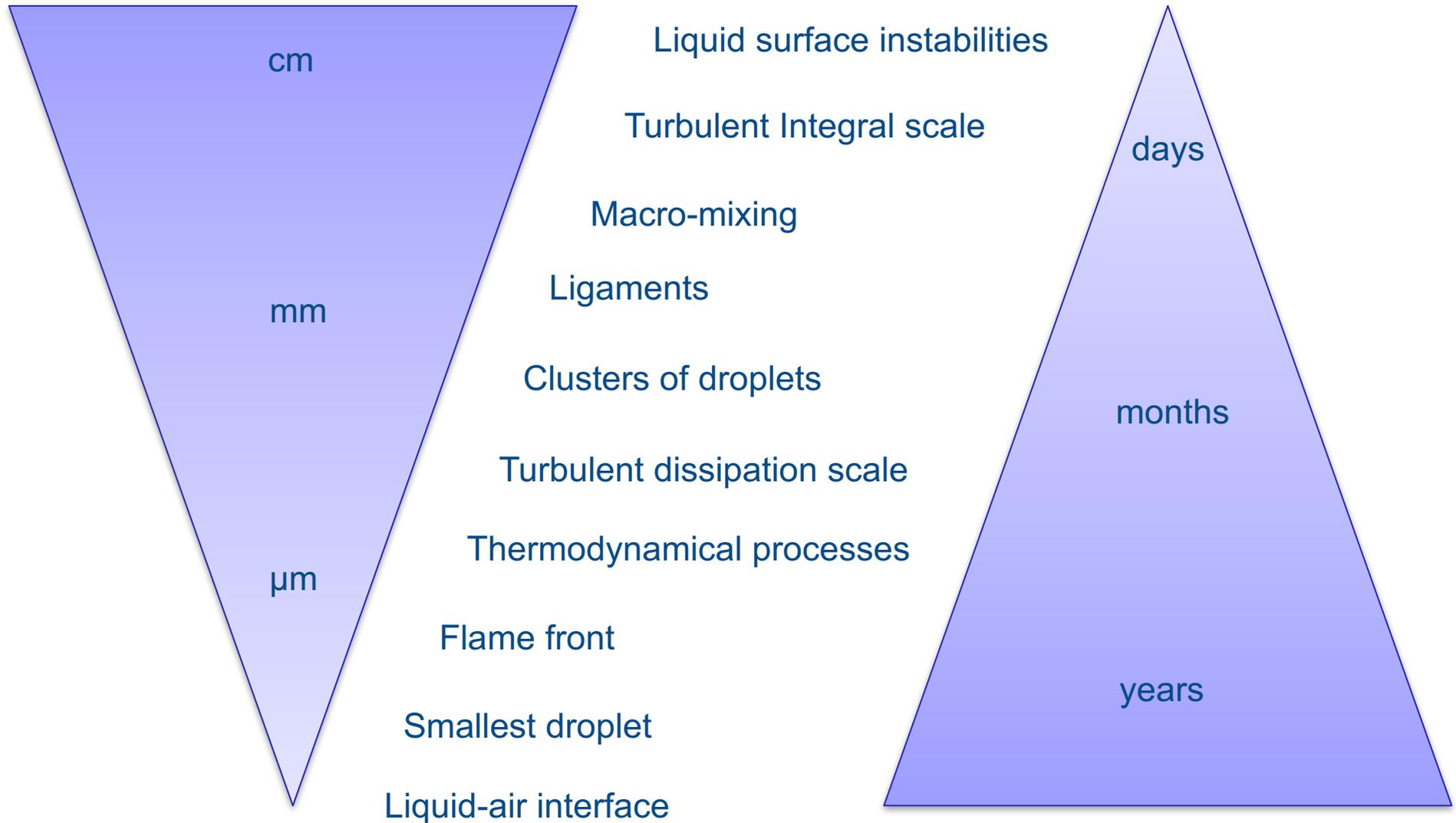
## Combustion chamber



# Combustion chamber



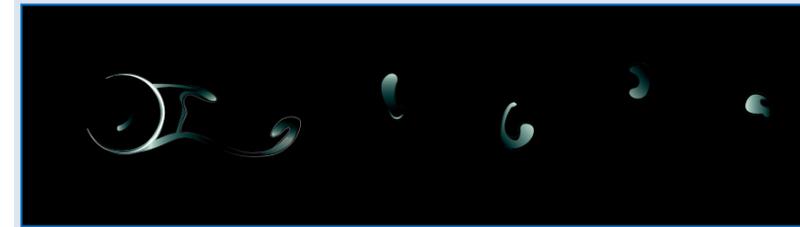
## A wide range of scales





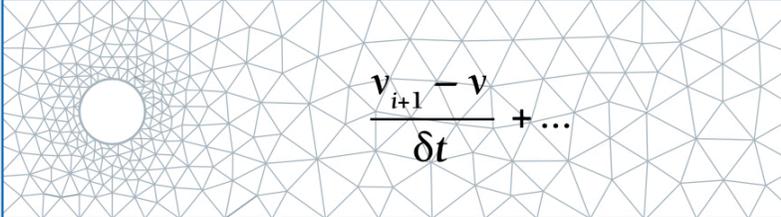
## Quelles mathématiques et quelles contributions pour ces applications ?

- Partir d'un phénomène physique
- Formuler une hiérarchie de modèles math. (Equations déterministes / aléatoires)
- Analyser mathématiquement ces modèles (bien posés – comportement qualitatif)
- Discrétiser ces équations / Convergence (schémas numériques adaptés)
- Simuler sur un ordinateur (calcul scientifique – calcul intensif)
- Reproduire / comprendre / prédire

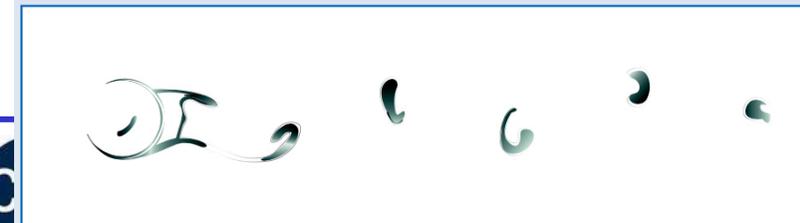




$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = - \nabla p + \nu \nabla^2 \mathbf{v}$$



$$\frac{\mathbf{v}_{i+1} - \mathbf{v}}{\delta t} + \dots$$



## Quelles mathématiques pour contribuer dans ces applications ?

- Formuler les modèles mathématiques
- Analyser mathématiquement ces modèles – comportement qualitatif
- Discrétiser ces équations / Analyse numérique et Convergence
- Simuler sur un ordinateur – nouvelles architectures de calcul - calcul intensif

Entry #: 102337



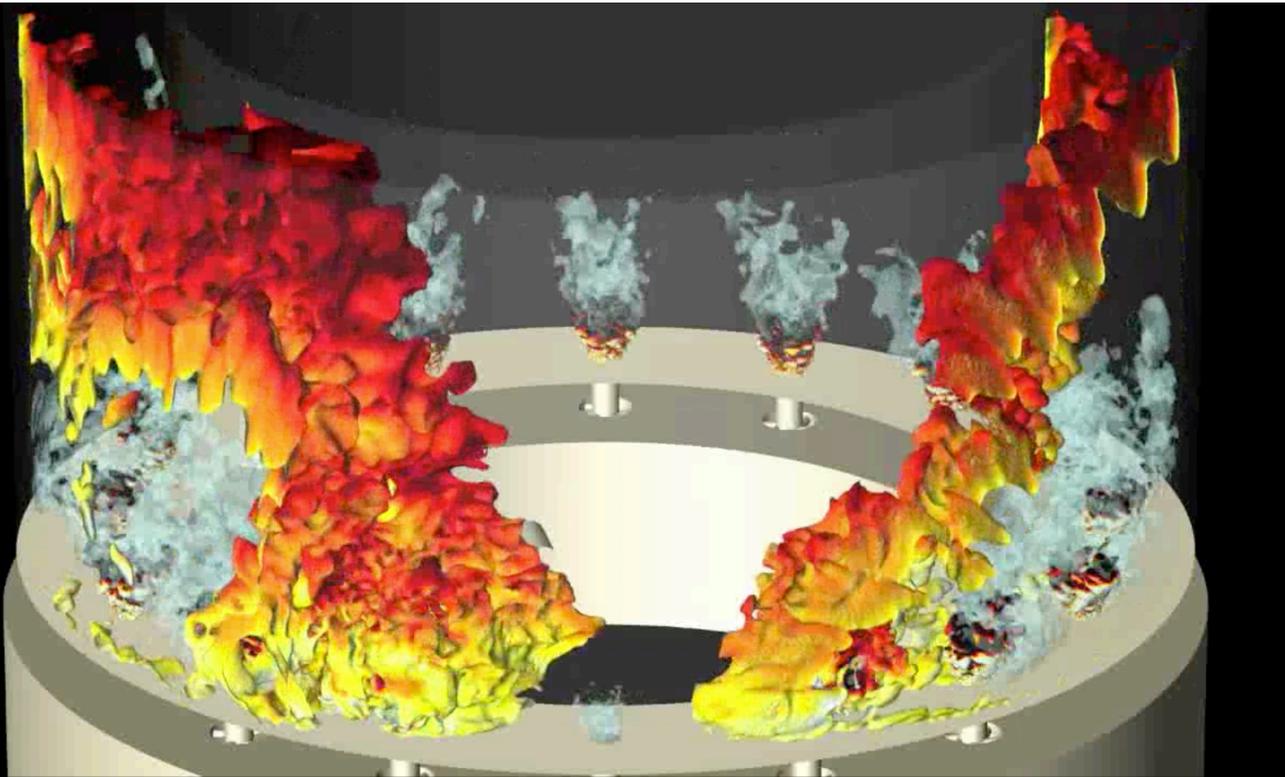
### Ignition sequence of an annular multi-injector combustor

Maxime PHILIP, Matthieu BOILEAU, Ronan VICQUELIN, Thomas SCHMITT,  
Daniel DUROX, Jean-François BOURGOUIN, Sébastien CANDEL

Ecole Centrale Paris, EM2C laboratory, CNRS, FRANCE

## Quelles mathématiques pour contribuer dans ces applications ?

- Formuler les modèles mathématiques
- Analyser mathématiquement ces modèles – comportement qualitatif
- Discrétiser ces équations / Analyse numérique et Convergence
- Simuler sur un ordinateur – nouvelles architectures de calcul - calcul intensif



## Quelles mathématiques pour contribuer dans ces applications ?

- Formuler les modèles mathématiques
- Analyser mathématiquement ces modèles – comportement qualitatif
- Discrétiser ces équations / Analyse numérique et Convergence
- Simuler sur un ordinateur – nouvelles architectures de calcul - calcul intensif

