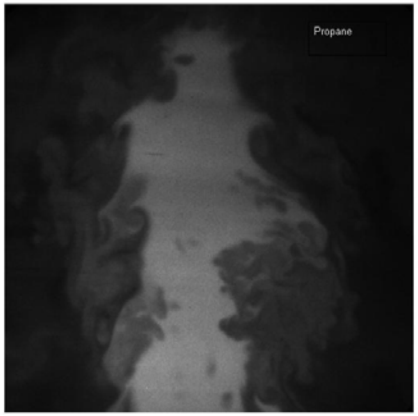
Roma, September 19 2014



Mixing of two fluids density-matched with variable viscosity

Luminita DANAILA

Context and collaborations:

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PhD: B. Talbot, L. Voivenel

Technical help: A. Vandel, G. Godard

Outline

I. The importance of variable-viscosity flows

II. Tools. Experimental investigation

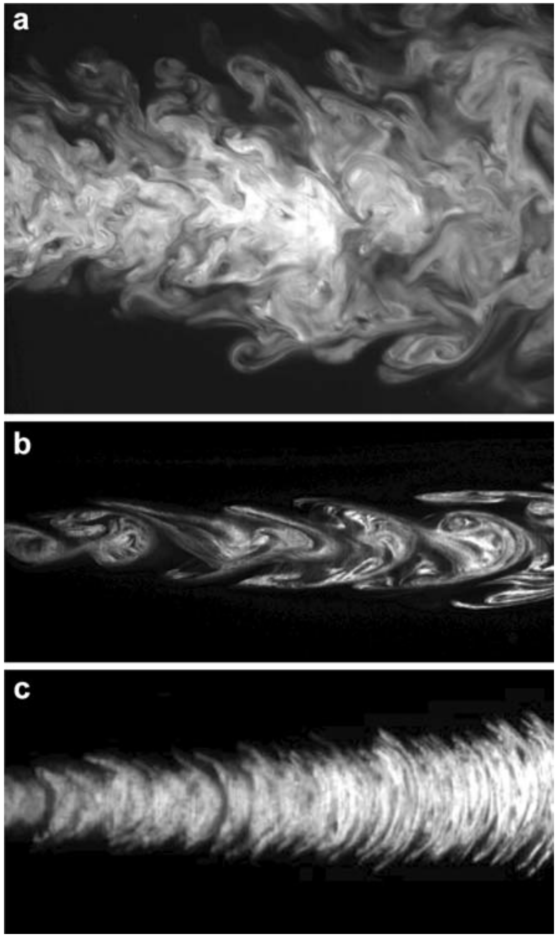
III. Results

- a) Instantaneous aspect and phenomenology
- b) One-point statistics. Three questions
- c) Two-point statistics. Energy transfer at a scale r

IV. Summary

I. Variable-viscosity flows. The importance

- **Many practical applications**



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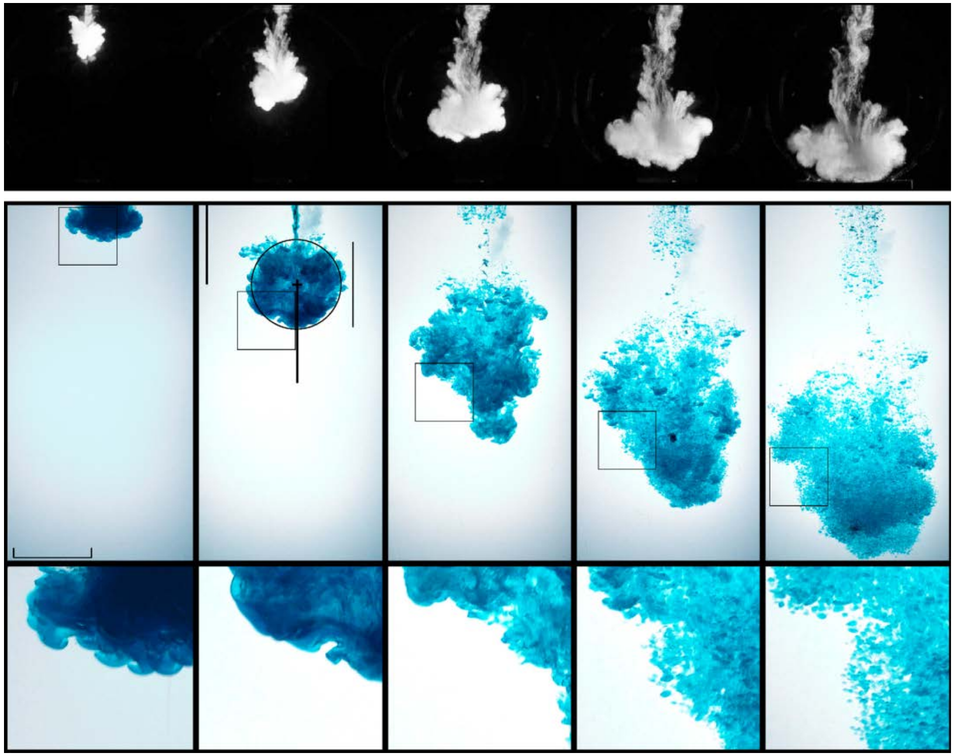
Chhabra, Shibra and Prasad, Exp. Fluids 2005



Duguet et al. Earth Planetary Science 2014

I. Variable-viscosity flows. The importance

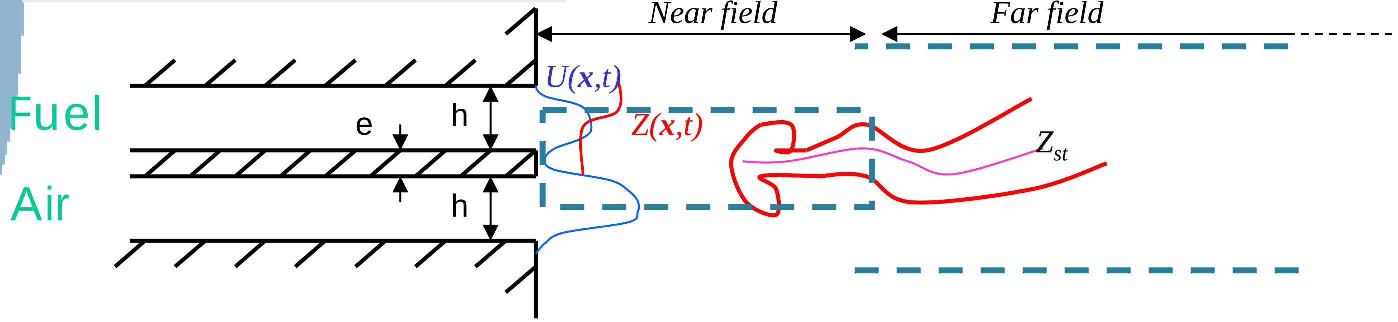
- **Many practical applications**

- **Both reactants (fuel and oxidizer) are generally injected through distinct channels**

  → merging zone followed by a non-reacting, quasi isothermal partially premixed region

  → strong effect of turbulence (large and small scales) on the flame stabilization, structure or propagation

Two-stream coflowing jets



I. Variable-viscosity flow. The importance

Fundamental viewpoint:

Prediction of small-scale statistics (universal …)

For relatively large Reynolds numbers

Kolmogorov Theory, 1941, 1962..

Two key-parameters:

The kinematic viscosity

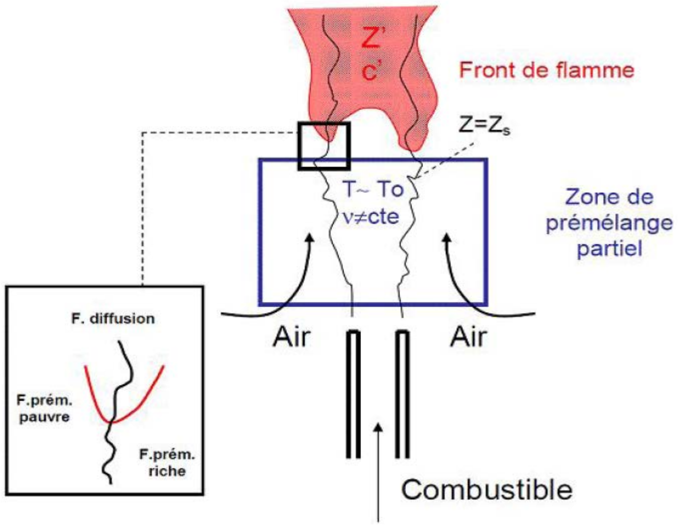
The mean kinetic energy dissipation rate

μ,ρ et $<\varepsilon>$

Similar questioning for the scalar

Real flows: mixing of several fluids

Variable density and/or viscosity



Need for theory and predictions for real flows➔ Focus on variable visc

Lee and Girimaji PRL 2008

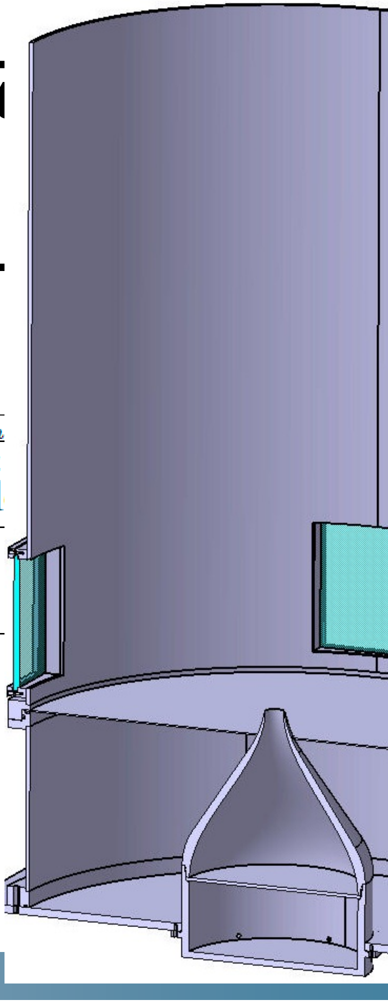
II. Experimental investigation

Propane jet issuing into air

Air= 5 times more viscous than the propane

Comparison between C3H8-air jet and a ‘classical’ air-ar jet

Simultaneous measurements of velocity-scalar (concentration)



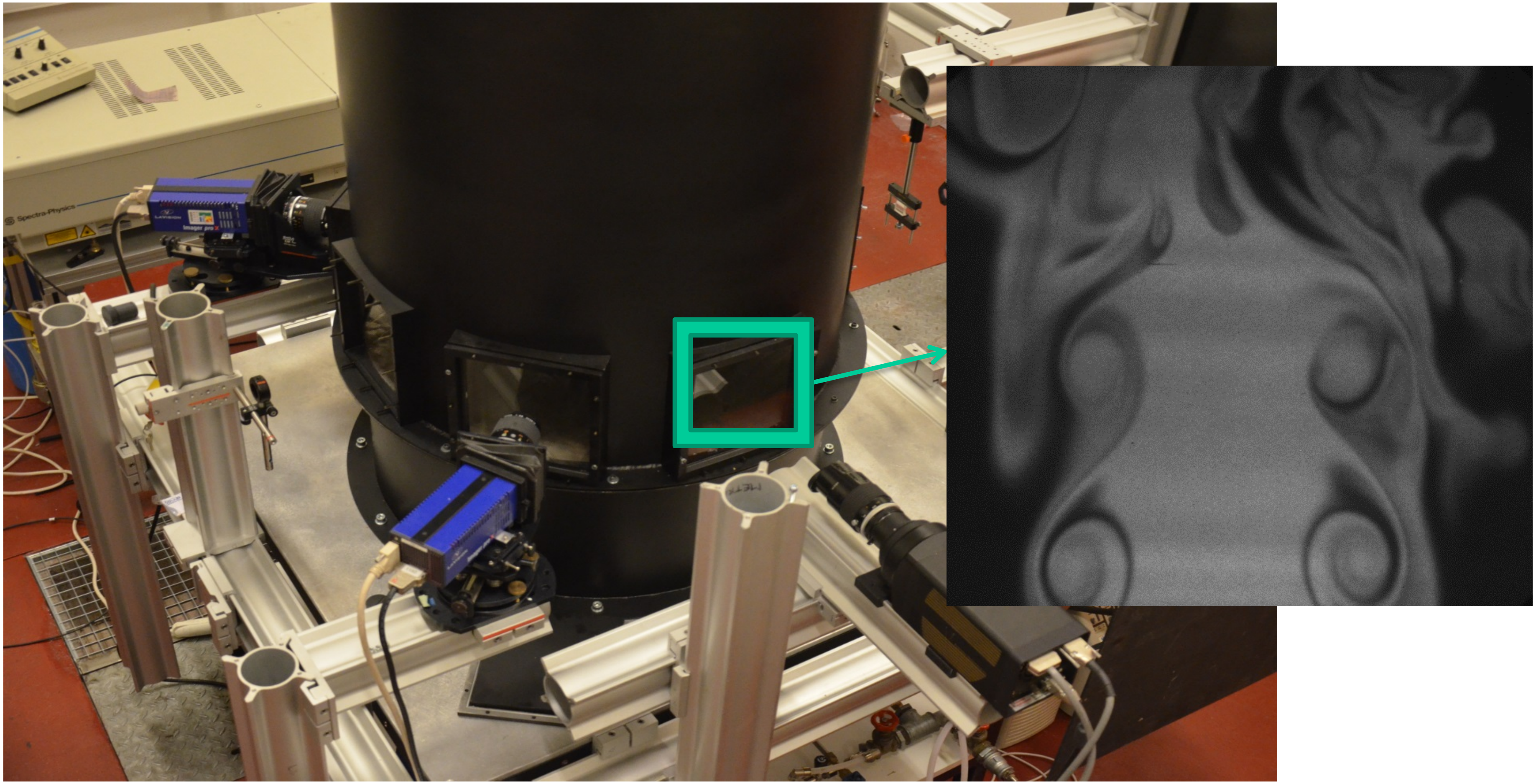
Case	Injected Fluid	Coflowing Fluid	U_0 (m/s)	U_{coflow} (m/s)	Re_D	M_0 $(kg \cdot m^{-1} \cdot s^{-2})$	$R_v = \frac{\nu_h}{\nu_l}$ h=higher, l=l
CVF	Air	Air	10.5	0.15	3300	130	1
VVF	C_3H_8	Oxidizer	8.5	0.15	9200	130	5.5

Table 1. Experimental flow conditions.

Talbot et al., Exp. In Fluids 2009

L. Voivenel et al., 2014

II. Experimental investigation



II. Experimental investigation. Time-resolved measurements of velocity and scalar

How to measure U and c (simultaneous, time-resolved)

Planar Techniques **PIV + PLIF**	**Comments** - Too low spatial resolution for such near-fields - Seeding difficulties due to the near wall proximity
Temporal Techniques **Laser Doppler Velocimetry (LDV) + Raman Scattering** **« Double » Hot-Wire Anemometry** **Hot-Wire Anemometry + Rayleigh Scattering**	- **Conditioned scalar** by velocity measurements (biaised by seeding), C3H8-Air, Mathematical model required Dibble et al. 1987 - for **inert mixtures only** (He-Air, CO2-Air), Way& Libby 1979, Chassaing 1979 - **Conditioned velocity** by scalar measurements (biaised by Shot-noise), C3H8-Air, CH4-Air, Pitts *& al*. 1983

Velocity and scalar measurements

Time-resolved measurements of velocity and scalar

Probes volumes
Rayleigh (dxL) : 80x200µm
Hot-wire (d,L) : 2.5 µm, 400µm (L/d ~ 160)
Axial distance between volume probes = 800 µm

Detection, conditioning, filtering

Sampling rate Fs = 100 kHz

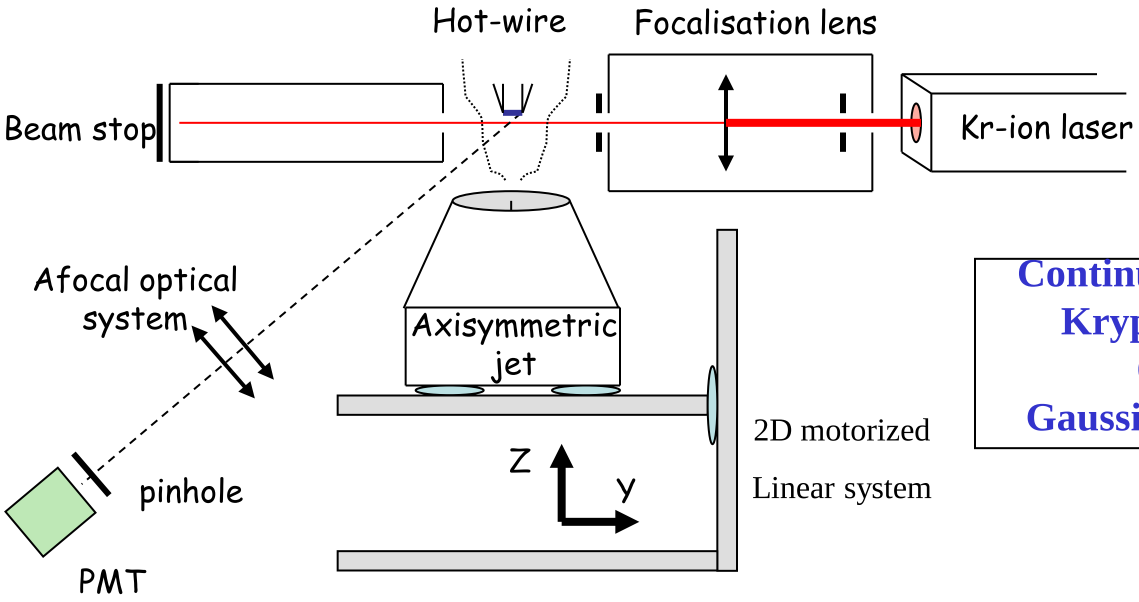
Filtering at 50 kHz (Fs/2) for velocity

Filtering at 35 kHz (Rayleigh)

Low noise PMT : < 0.15 nA

afocal optical system, f/D = 1.5

Fc (Hot-Wire) ~ 40 kHz

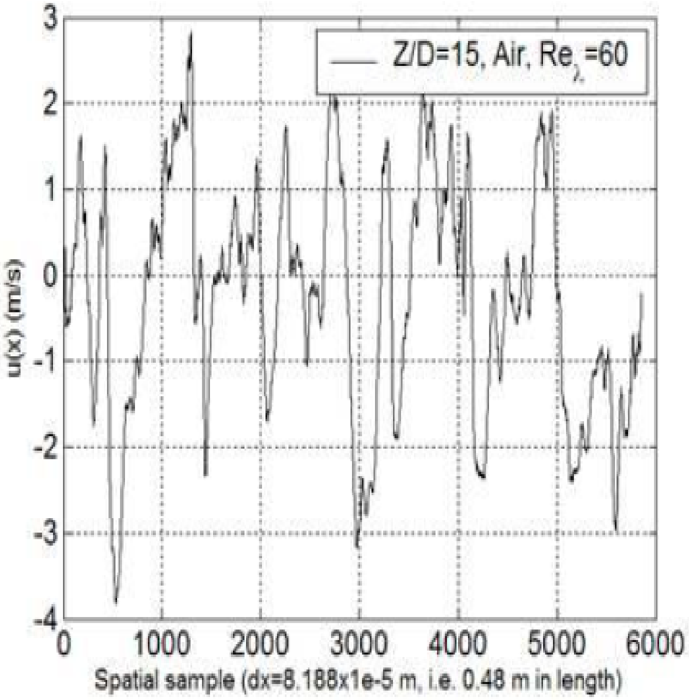


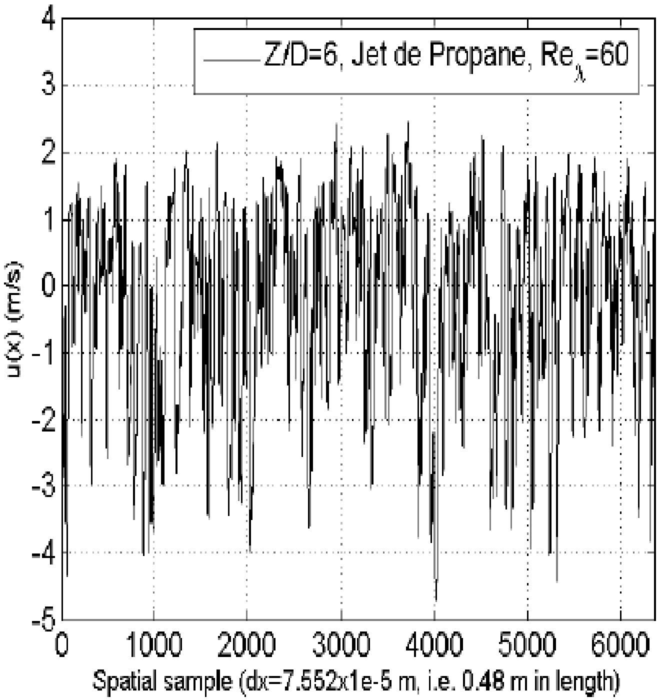
Continuous ion Laser
Krypton 676 nm
6 Watts
Gaussian laser beam

Round Jet
d = 5 mm
D_{coflow}=80 mm

B. Talbot et al., Exp. Fluids 2009

III. Results. Instantaneous signals



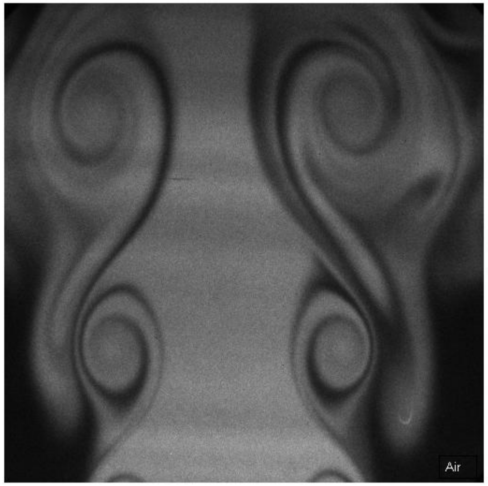


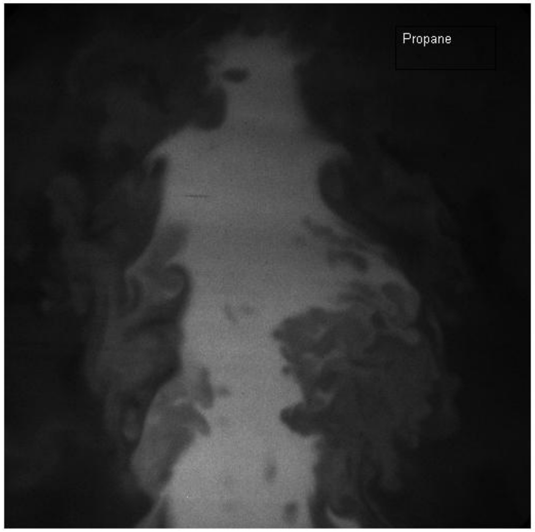
Over the same spatial extent:

Air: presence of turbulent structures (ramps)

Propane: closer to the injection, but more regular signal= much more important gradients

III. Results. Instantaneous images (PLIF on acetone and anisole)





Over the same spatial extent:

Air: typically two pairs of annular vortices (KH)

Propane: a hint of annular vortices close to the injection, but

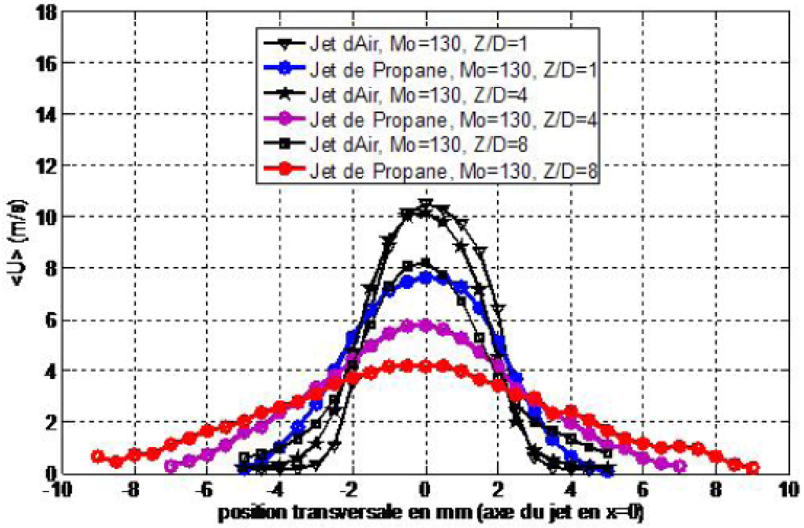
much more important gradients, much more turbulent

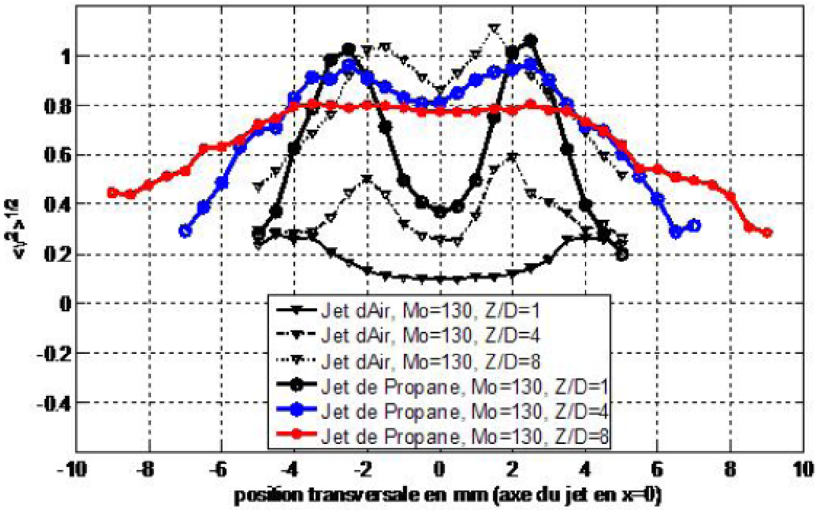
Axisymmetry is clearly broken

III. Results. Statistics: one-point

Propane jet issuing into air

Air= 5 times more viscous than the propane





→Decay of the longitudinal velocity: 30% larger in VVF

→Entrainment + important

→Isotropy and self-similarity are more rapidly achieved

III. Results. Scenario

Scenario:

-Density variations: NO

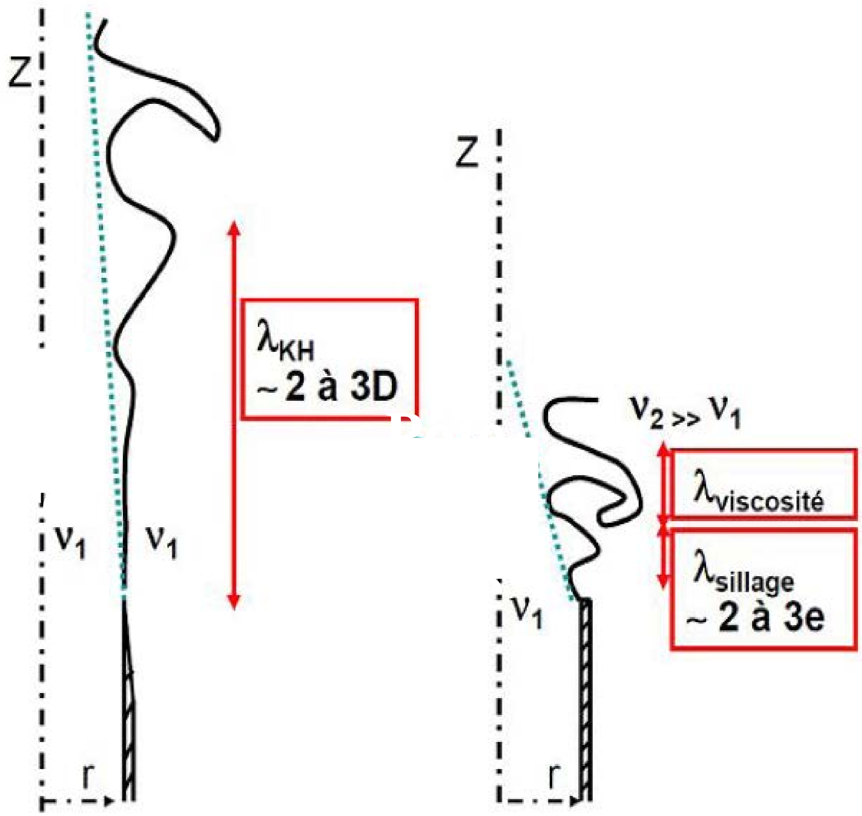
-Viscosity effects: YES

Effects:

-increase of fluctuations

-increase of velocity gradients

-increase of the dissipation



III. Results. Phenomenology

Islands of viscous fluid enticed into the jet core

↓

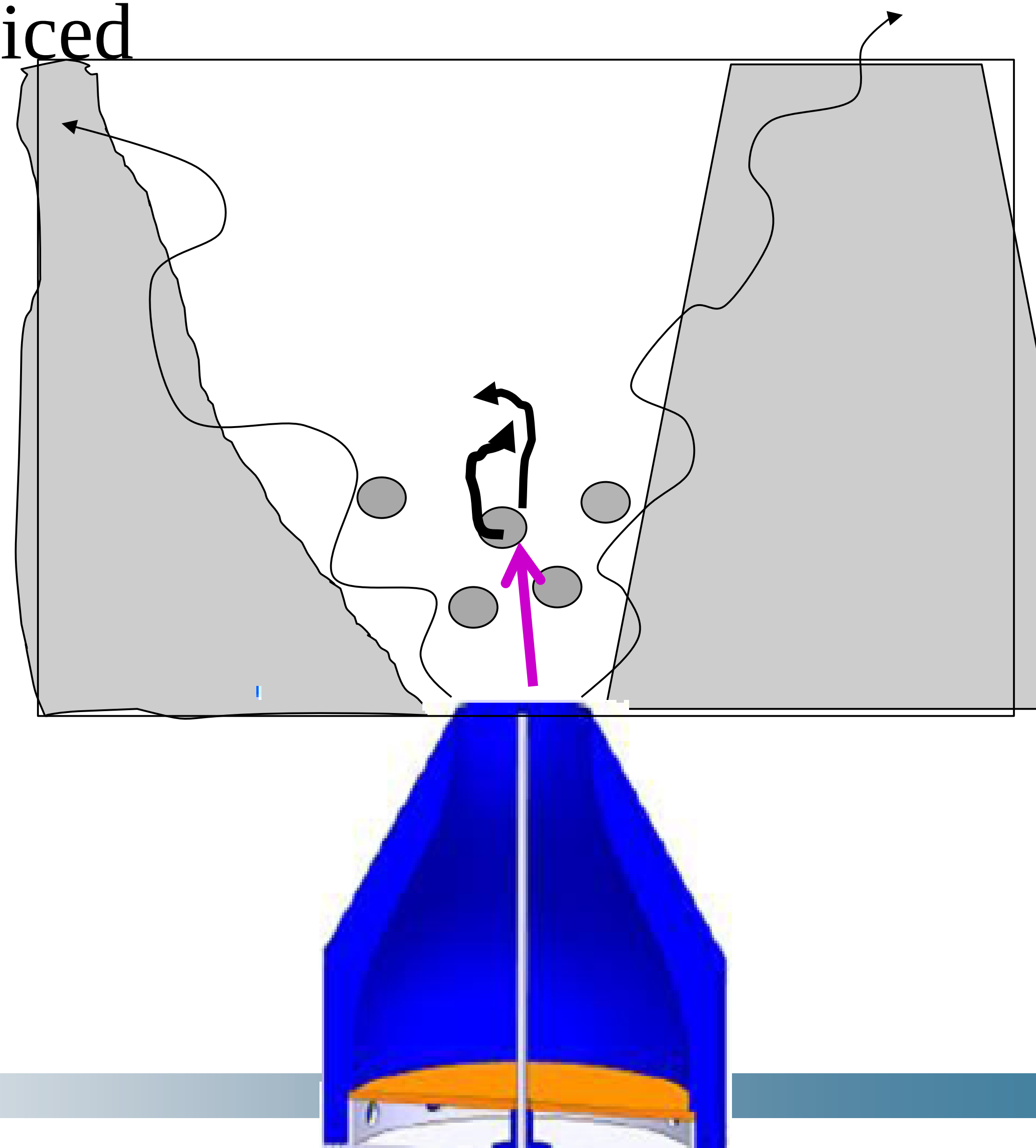
Stagnation points

↓

Fluctuations

↓

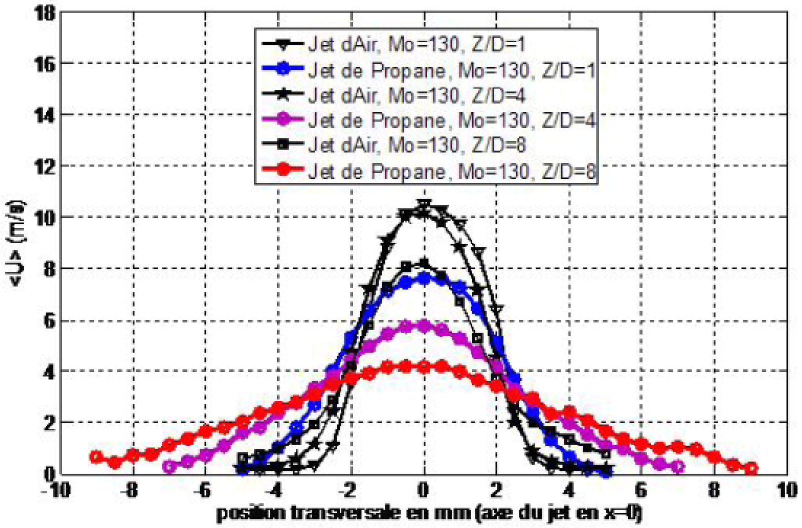
‘Mixing’ increase



III. Results. One-point statistics. Three questions

1) Downstream evolution of the

Axial mean velocity U



2) The definition of a « true »

Reynolds number

3) The transport equation of the kinetic-energy➔

complete definition of the mean energy dissipation rate

Question 1

$$Navier - Stokes ... + \frac{\partial}{\partial x_j}\left(\mu(c)\frac{\partial u_i}{\partial x_j}\right)$$

$$\frac{\partial[\overline{U}^2 + \overline{u'^2}]}{\partial x} + \frac{1}{r}\frac{\partial}{\partial r} r(\overline{U}\cdot\overline{V} + \overline{u'v'}) =$$

$$-\frac{1}{\rho}\frac{\partial\overline{P}}{\partial x} + \overline{\nu}\nabla^2\overline{U} + \overline{\nu'\nabla^2 u'} \boxed{+ \overline{\nabla\nu\cdot\left(\overrightarrow{\overrightarrow{s}}\right)_{i=1}}}$$

Supplementary terms ← viscosity gradients

➔

Rapid decay of the longitudinal mean velocity

Question 2: The true Reynolds number

- Inertial term: $\mathcal{I} = \overline{U}\frac{\partial \overline{U}}{\partial x} \sim U_0^2/D;$
- Viscous term 1: $\mathcal{V}_1 = \overline{\nu}\nabla^2\overline{U} \sim \overline{\nu} \cdot U_0/D^2;$
- Viscous term 2:

$$\mathcal{V}_2 = \overline{\nabla\nu \cdot \left(\overrightarrow{\overrightarrow{s}}\right)_i} \sim \Delta\nu \cdot u_i'/L_v^2,$$

Question 2: The true Reynolds number

- Reynolds number definition

$$Re_t = \frac{\mathcal{I}}{\mathcal{V}_1 + \mathcal{V}_2} = \frac{1}{\frac{\overline{\nu}}{U_0 \cdot D} + (R_v - 1)\frac{\nu_l}{U_0 \cdot D}\left(\frac{D}{L_v}\right)^2}$$

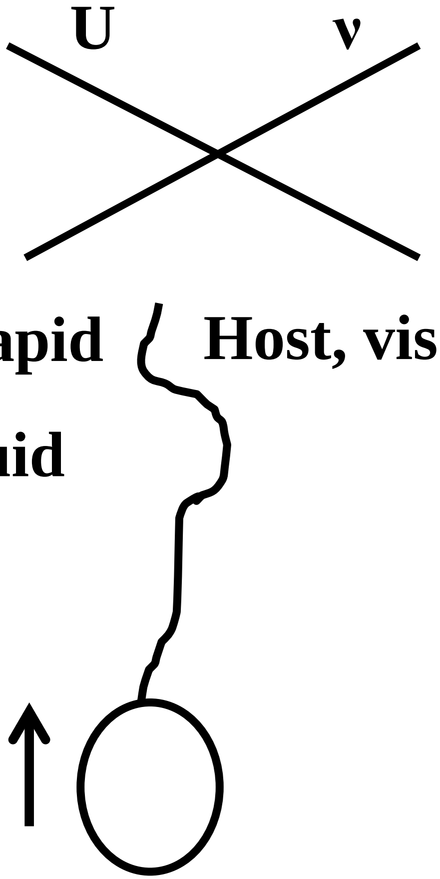
- In the very near field : $Re_t = \dfrac{U_0 \cdot D}{\nu_h}$

*Campbell, I. H. & Turner, J. S., 'The influence of viscosity on fountains in magma chamber' Journal of Petrology, **1986**, 27, 1-30*

J. Turner- J. Fluid Mech. 1986

Talbot et al., Physica Scripta 2013

Question 2: The true Reynolds number: further relevance mixing or unmixing?



Counter-gradient configuration

Rapid fluid

Host, viscous fluid

Velocity u

Scale l

Condition to mix: $u^2 >> \nu_h \dfrac{du}{dn} \approx \nu_h \dfrac{u}{l}$

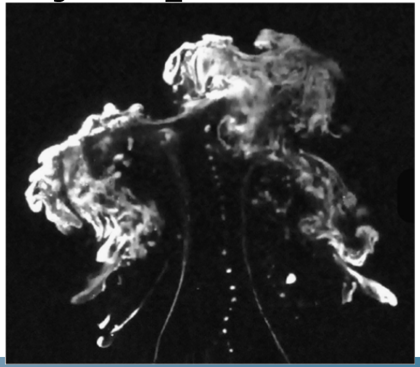
$$\frac{ul}{\nu_h} >> k$$

k may depend on th

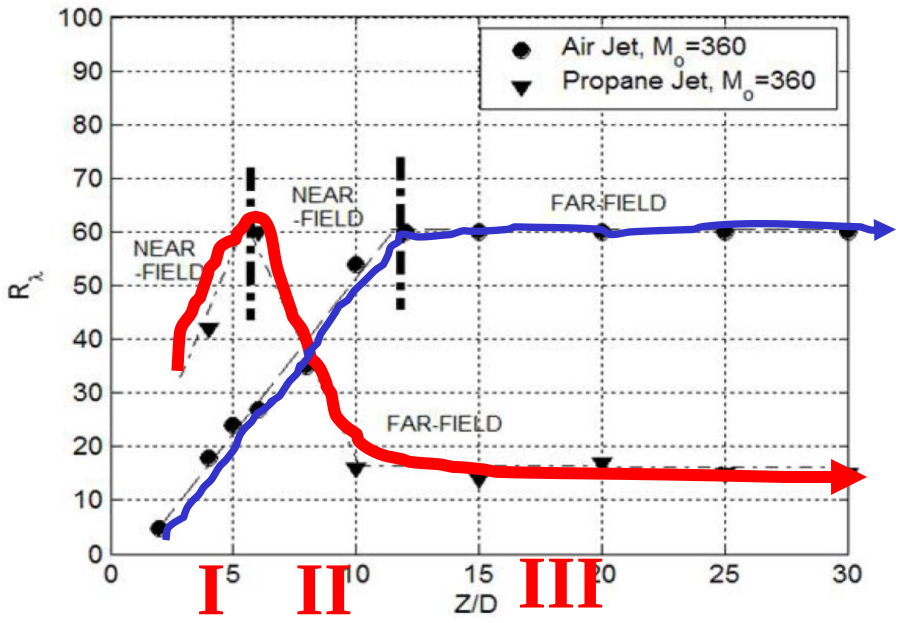
$$\boxed{\frac{ul}{\nu_l} >> k\left(\frac{\nu_h}{\nu_l}\right)}$$

Unmixing

Mixing….



Another effect of viscosity increase: Reduction of turbulence Reynolds number



$$R_\lambda = \frac{(u_1'^2)^{1/2}\lambda_T}{\langle \nu \rangle}$$

Is self-similarity respected?

- In classical turbulent flow (cst. viscosity): $Re_\lambda \sim \sqrt{Re_D}$

→ Good agreement for air/air jet (ReD=5400)

→ Re$_l$ should be higher for propane/air flow (ReD=15400 !!)

- Different evolution with axial direction

IV. Summary

Variable-viscosity flow = propane jet into air

(the host fluid is more viscous)-- A close look to the very near field

Importance: more rapid mixing (combustion, chemical industry)

Experiments:→ rapid decay of the longitudinal velocity U

→ apparent increase of the mean energy dissipation rate

→ narrower Restricted Scaling Range (diminished Reynolds)

→increase of the local Schmidt number

Questions: → transport equation for the longitudinal velocity U

→true Reynolds number

→total kinetic energy dissipation= enhanced with respect to the classica

→ Viscosity gradients→ islands→ increase of strain →

helps enhance energy transfer and cascade …

→ Viscosity increase directly inhibits…..