Shear instabilities in the context of liquid atomization

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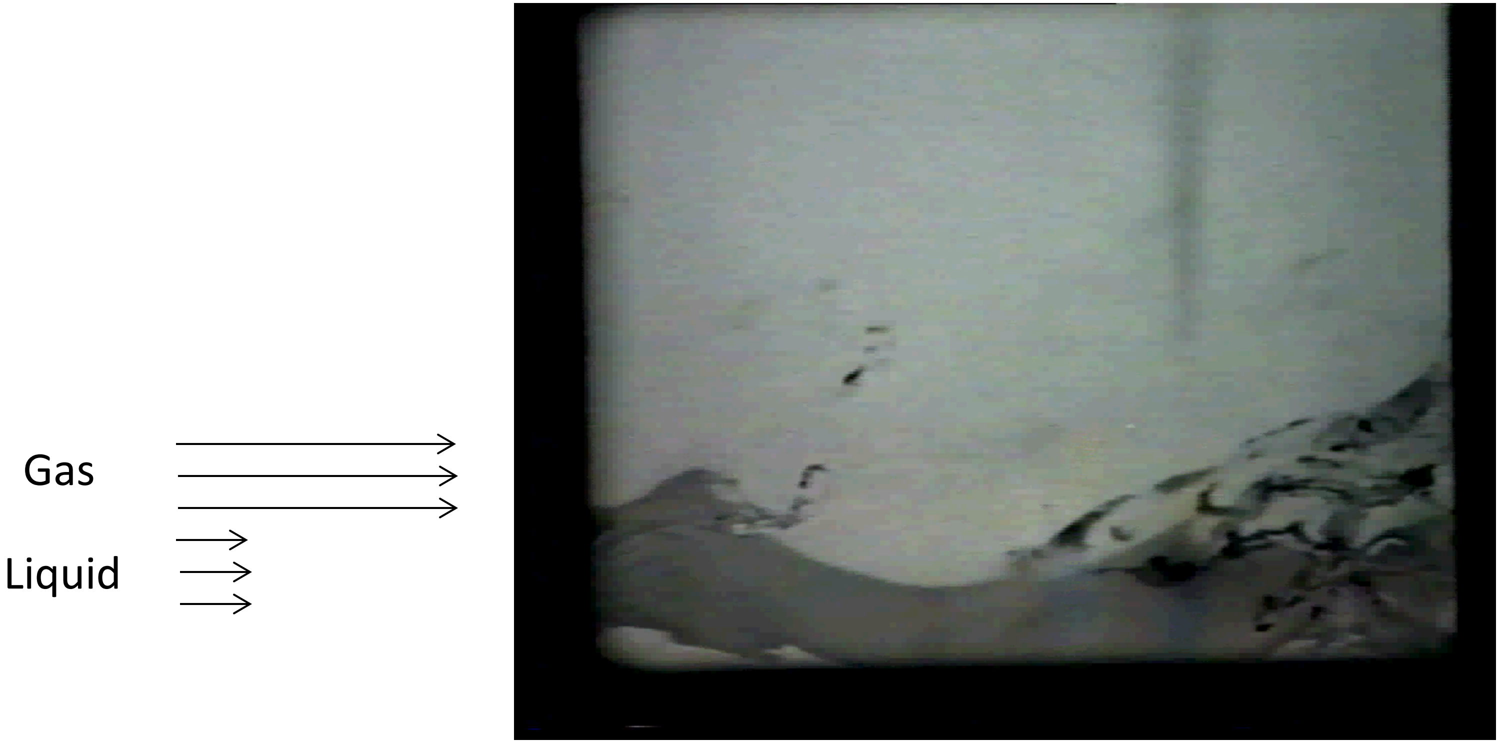
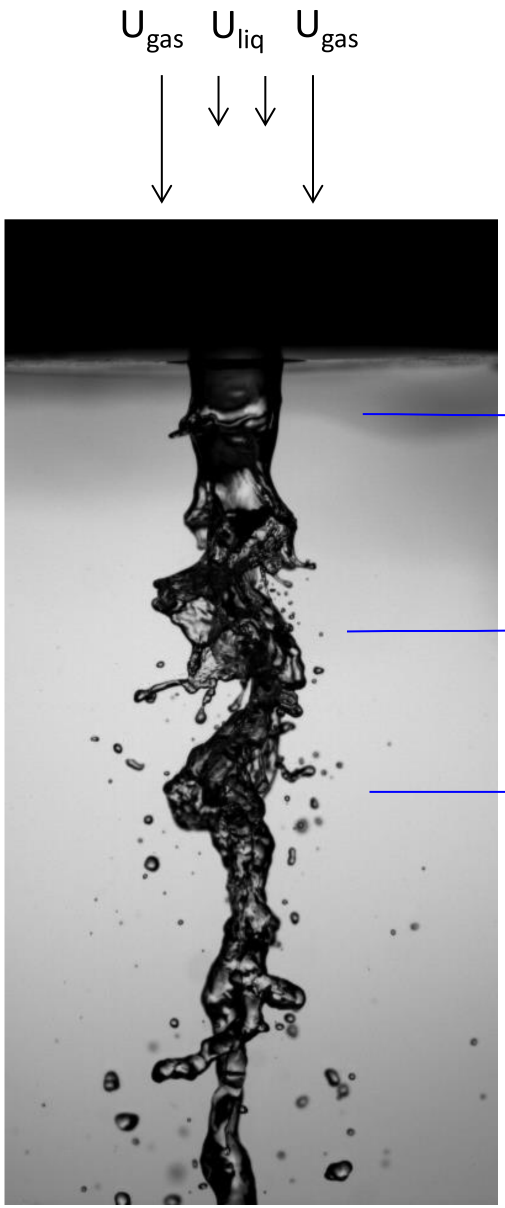


U_G=22 m/s, U_L=0,42 m/s
L. Raynal, 1997

Liquid atomization

Successive mechanisms in spray formation



Longitudinal shear instability

Transversal instability: Ligament formation

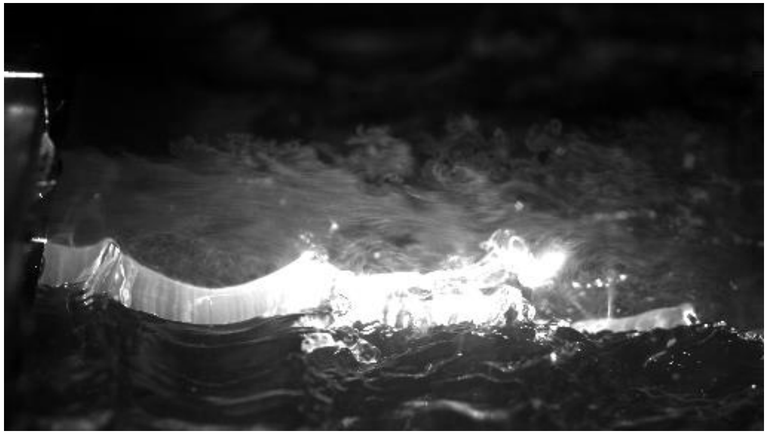
Droplet formation

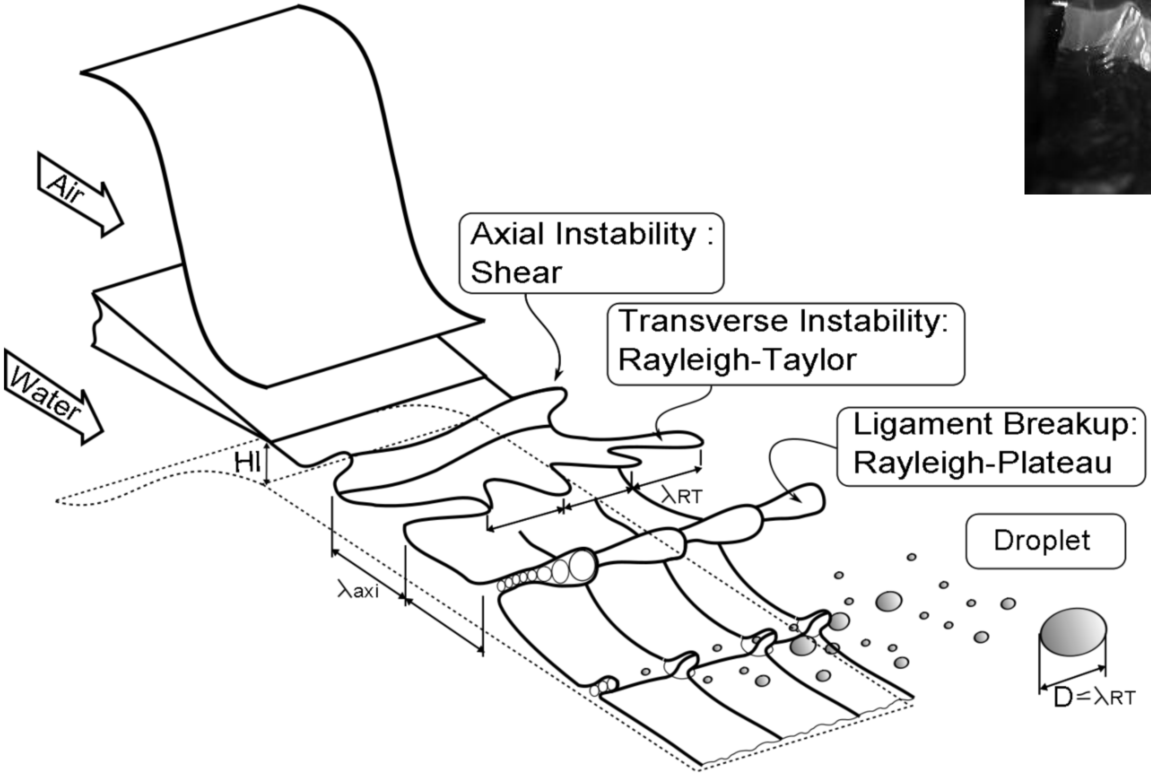
Flapping instability

Shear instability

Thesis of Sylvain Marty

Mixing layer configuration





1. Mechanism?

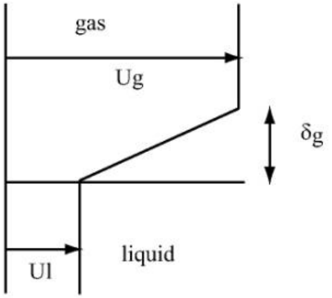
- Raynal (1997) and Marmottant & Villermaux (JFM 2004):

Simple temporal **inviscid** stability analysis accounts for experimental scaling of wavelength/frequency:

$\lambda \sim (\rho_l/\rho_g)^{1/2}\delta_g$ and $f \sim (\rho_g/\rho_l)U_g/\delta_g$

Basically: $d(ec)/dt = \rho_g u_i u_j D_{ij}$

$\rho_l u^2 \omega = \rho_g u^2 Ug/\delta_g$



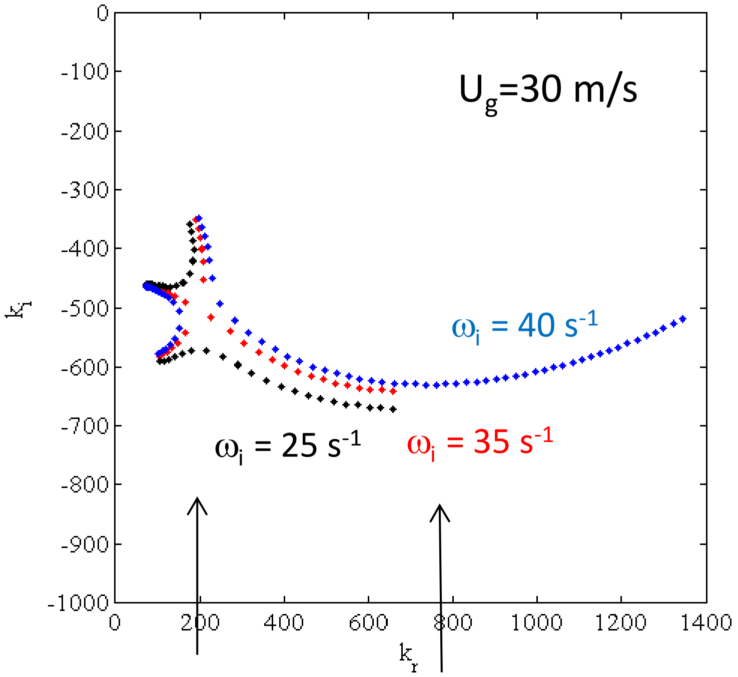
- Temporal viscous stability analysis fails miserably (wrong f, λ, velocity etc): why does **simpler inviscid approach** succeed in the 1st place??

Nature of instability: inviscid or viscous??

Effect of confinement

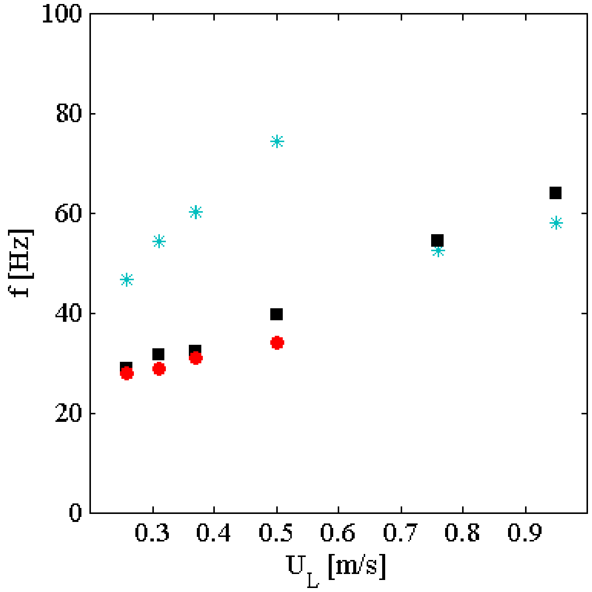
- Inclusion of finite liquid thickness in spatio temporal analysis:

  $\Rightarrow$ Collision with confinement branch!!!



$\omega_{r\ pinching}$ = 324 s^{-1} $\omega_{r\ max}$ = 484 s^{-1}

Reduction in frequency!



■ : experiments

● Prediction when confinement is included

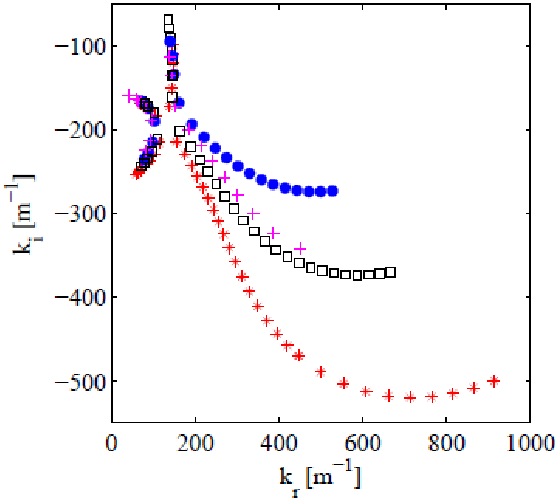
* : prediction of Otto et al (2013)

Inviscid vs viscous

Though shear mode is indeed viscous at ki_{max}

- Energy budget at pinch point shows that
  (work of Reynolds stresses in gas) >> (work of viscous stresses at interface)

- Pinch point location unaffected by change in viscosity (down to ν/100)



- <u>Interpretation</u>: "Resonance" due to confinement triggers instability in a range of k where mechanism is inviscid!

- Justifies relevance of **simplified inviscid approach**

2. Impact of turbulence on shear instability?

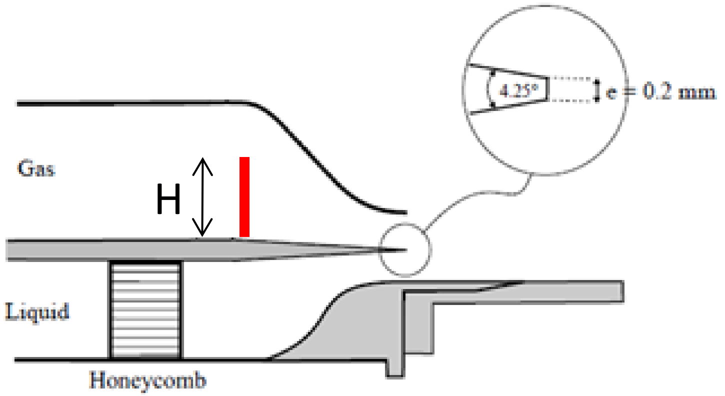
- Reproducibility issues in the mixing layer experiment: additional parameter?

- Experimental evidence that frequency of the shear instability not only depends on mean values, but also on intensity of velocity fluctuations in gas stream

- Experiment to quantify this?

Forcing of turbulence

1) Passive forcing (obstruction of varying height H)



Forcing produces same mean velocity profile, but differing turbulence intensity profiles.

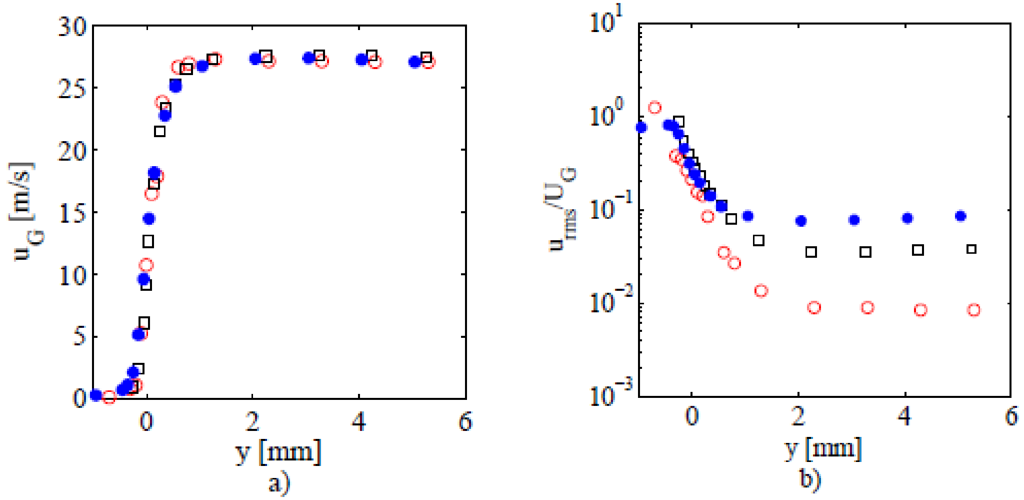
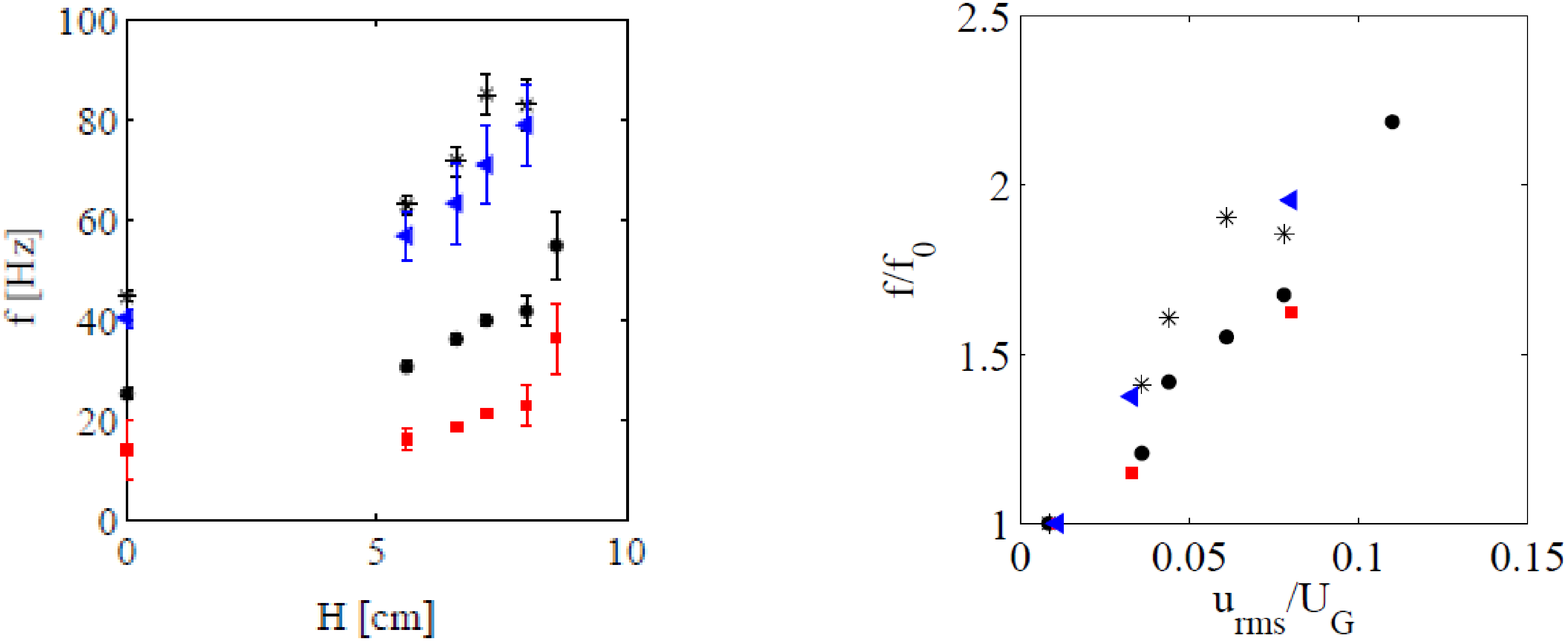


FIG. 3. (color online) Hot-wire velocity profiles for $U_G = 27$ m/s and varying obstruction heights H: ○: $H = 0$; □: $H = 5.6$ cm ; ●: $H = 8$ cm ; a) Mean velocity profile. b) Turbulence intensity u_{rms}/U_G.

Forcing of turbulence

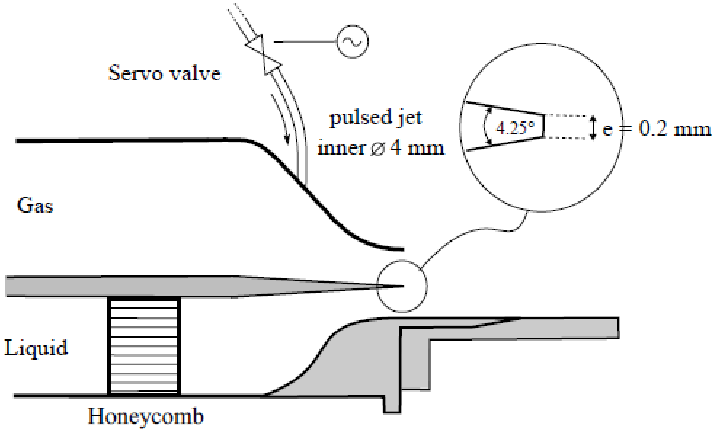


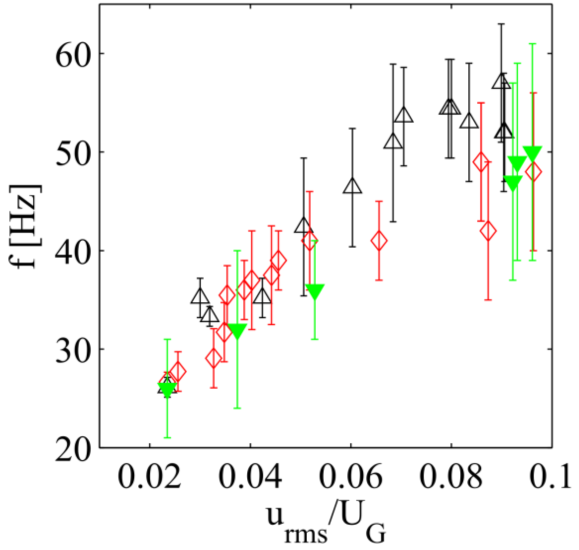
● U_G = 27 m/s U_L=0.28 m/s
■ U_G = 17.5 m/s U_L=0.28 m/s
◀ U_G = 40 m/s U_L=0.28 m/s
* U_G = 27 m/s U_L=0.95 m/s

Frequency increases with height of obstacle/turbulence intensity

Forcing of turbulence

2) Pulsed jet method →





U_G = 27 m/s U_L=0.28 m/s and pulsed jet forcing at:

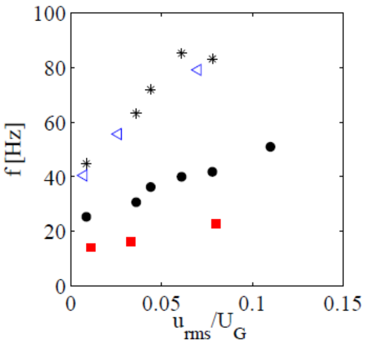
▼ f= 17 Hz

△ f= 34 Hz

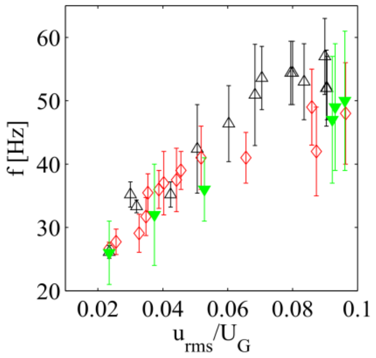
◇ f= 70 Hz

Frequency increases with turbulence intensity whatever the forcing method

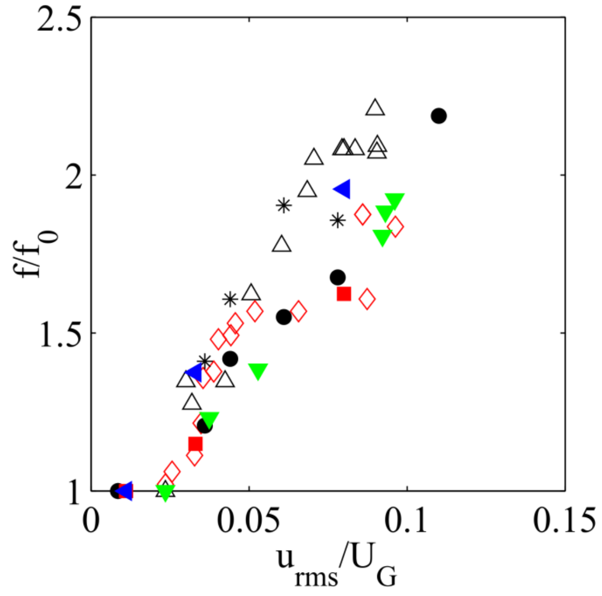
Forcing of turbulence



Obstacle



Pulsed jet



- All data collapse when plotted as a function of u'/U_G
- Independent of U_G , U_L and forcing method

Impact on wavelength

u'/U = 2.3%
f= 26Hz and λ ~ 3.4 cm

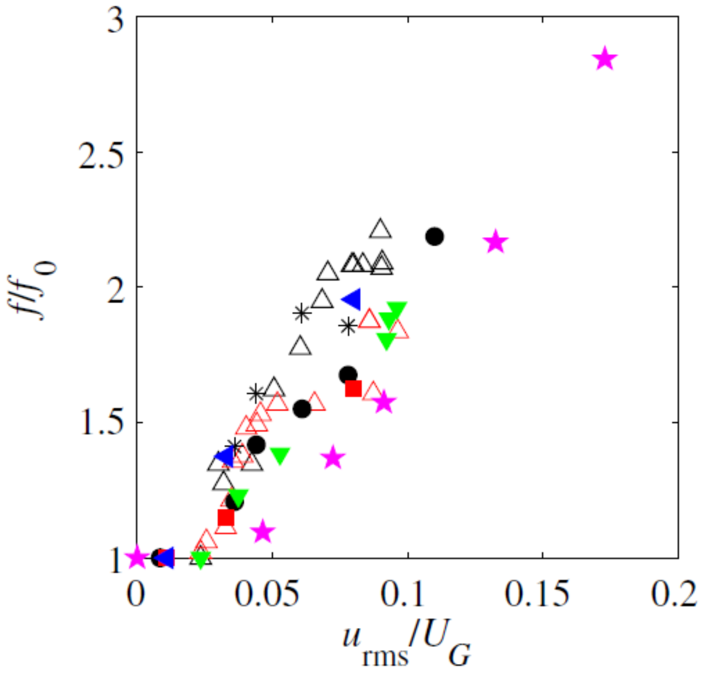
u'/U = 9%
f= 53Hz and λ ~ 1.6 cm

- Wavelength decreases with turbulence intensity
- Wave velocity $\lambda f \approx$ constant $\approx \dfrac{\sqrt{\rho_G}U_G+\sqrt{\rho_L}U_L}{\sqrt{\rho_G}+\sqrt{\rho_L}}$ (Dimotakis 1986)

Stability analysis?

Assumption: turbulent intensity modelled via Newtonian eddy viscosity, and injected in spatiotemporal stability analysis:

$$\rho u_{rms}^2=\mu_{g\,turb}U_g/\delta_g \quad \rightarrow \quad u_{rms}/U_g=\sqrt{\frac{\nu_{g\,turb}}{U_g\,\delta_g}}$$



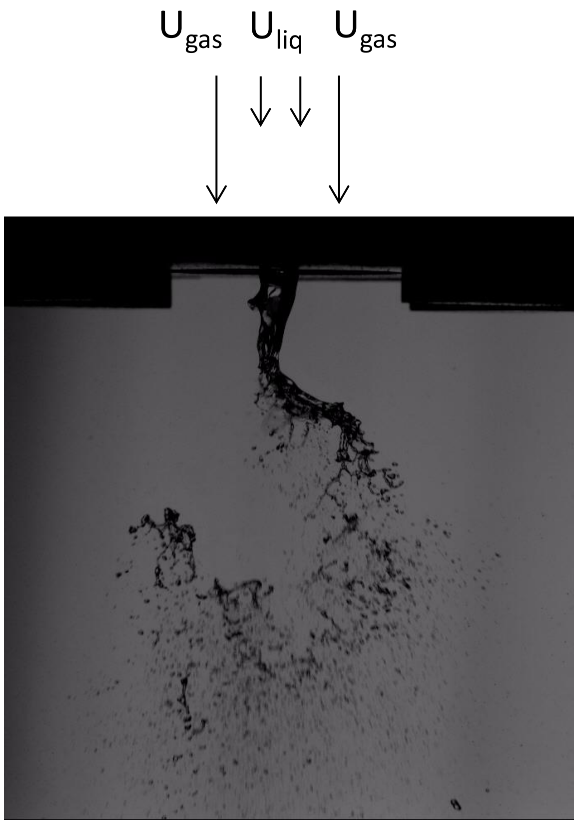
★ : stability analysis prediction with eddy viscosity

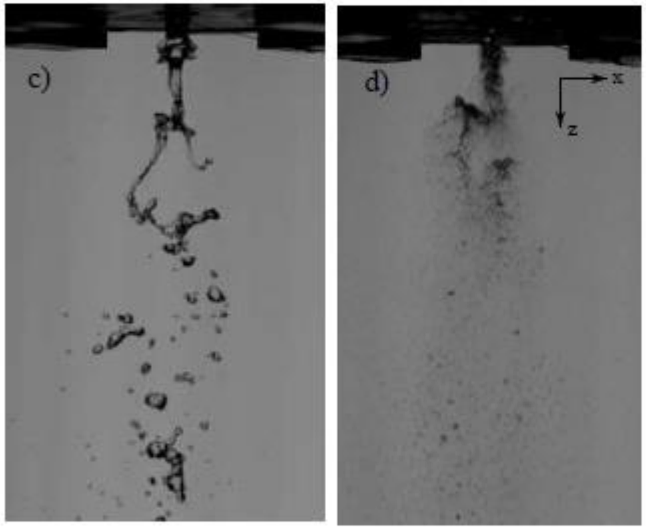
All other symbols: experimental data

Matas et al, PRL 2015

3. Flapping instability

Thesis of Antoine Delon (co-adv. with A. Cartellier)



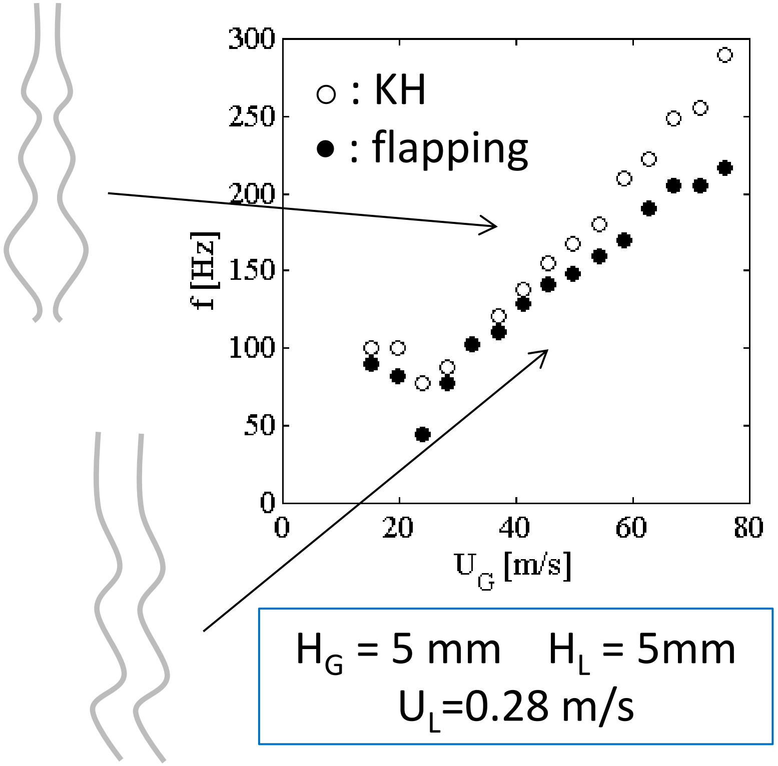


U_{gas} = 26 m/s U_{gas} = 98 m/s

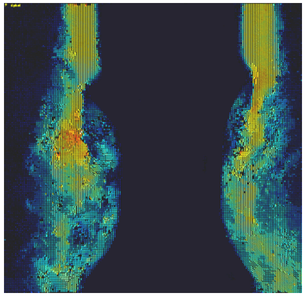
Instability present over wide range of velocities

Frequency of flapping instability

- Capture of jet via image processing → break-up length, amplitude, frequency for several geometries
- Flapping frequency close to but smaller than axisymmetric KH waves frequency



H_G = 5 mm H_L = 5mm
U_L=0.28 m/s

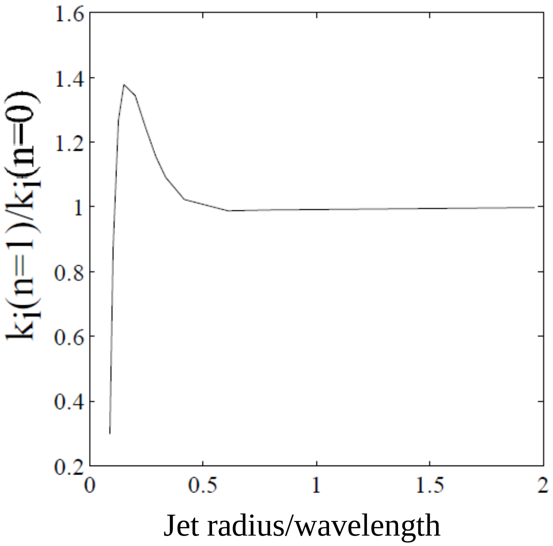


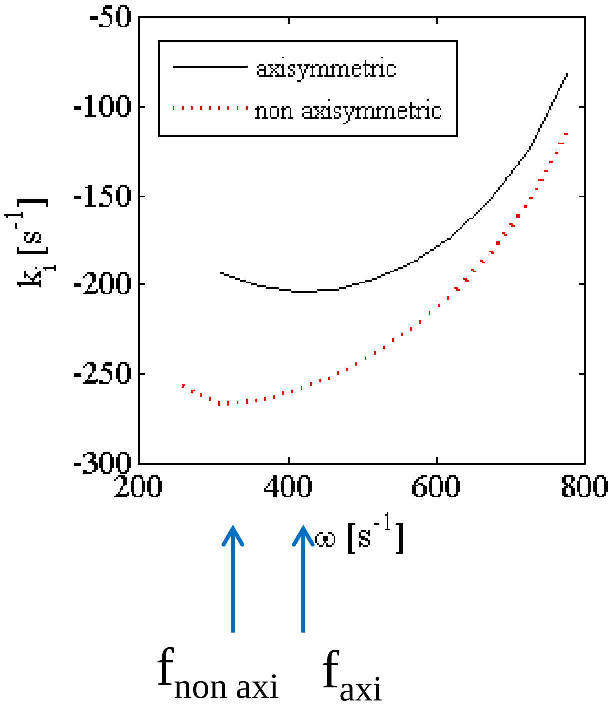
PIV

Mechanism: shear instability waves ⇒ vortices
⇒ distortion of liquid jet

Stability of non axisymmetric modes?

- Stability of non axisymmetric (n=1) modes investigated within inviscid hypothesis





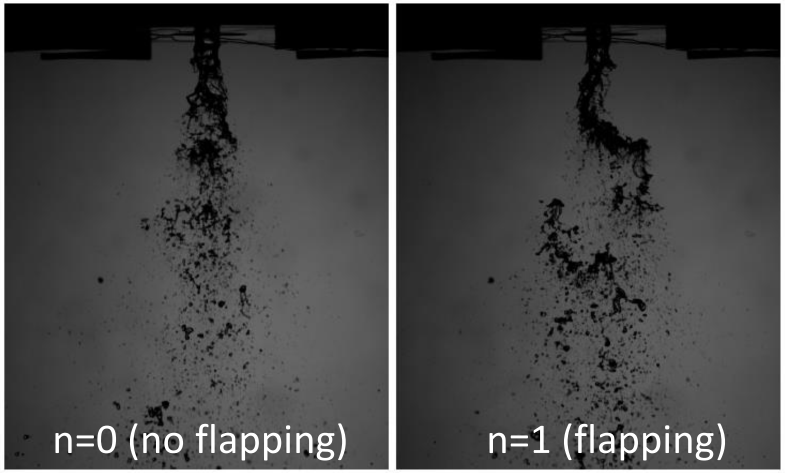
H_G = 5 mm
H_L = 5 mm
U_L=0.28 m/s
U_G=24 m/s

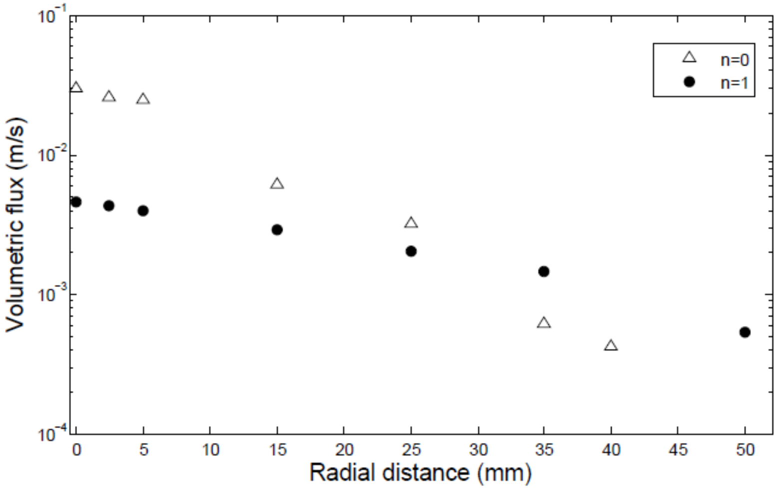
- Helical modes predicted to be more unstable than axisymmetric ones and associated frequency 20% smaller

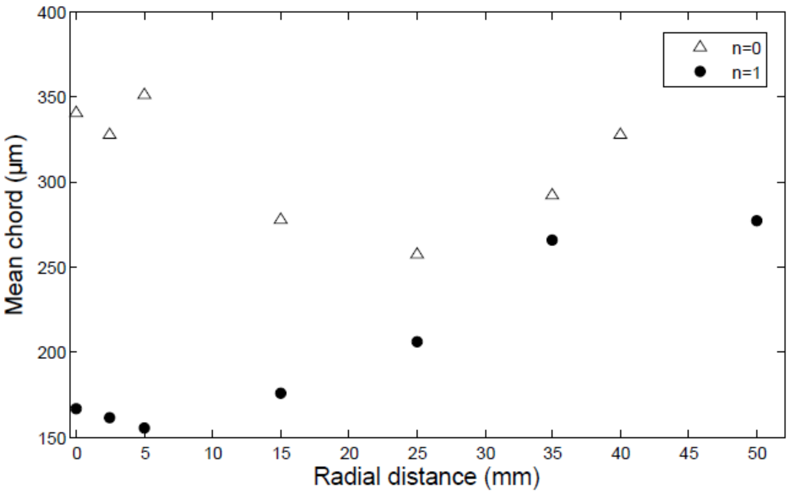
→ Good agreement with experiments!

Impact on spray

Modification of velocity profile in injector →
forcing of flapping at fixed U_G and U_L



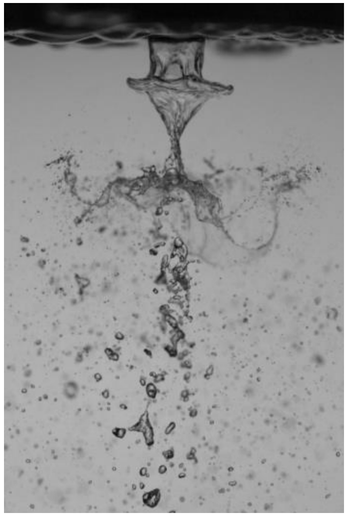




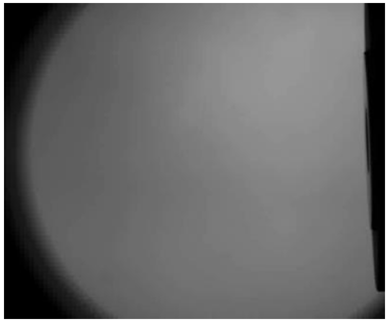
Optical probe measurements: Liquid redistributed differently when flapping is present: small droplets near axis, large droplets in periphery

Further atomization configurations

- Assisted atomization of a two-phase jet:



- Atomization of a jet of FC-72 injected in a depressurized reservoir (P=5 mbars):



- Rapid depressurization of a liquid: entrainment of FC-72 by its own vapour