Influence of an additional liquid flow on the acoustic field induced by power ultrasound (20 and 40 kHz)
Experimental and numerical determinations

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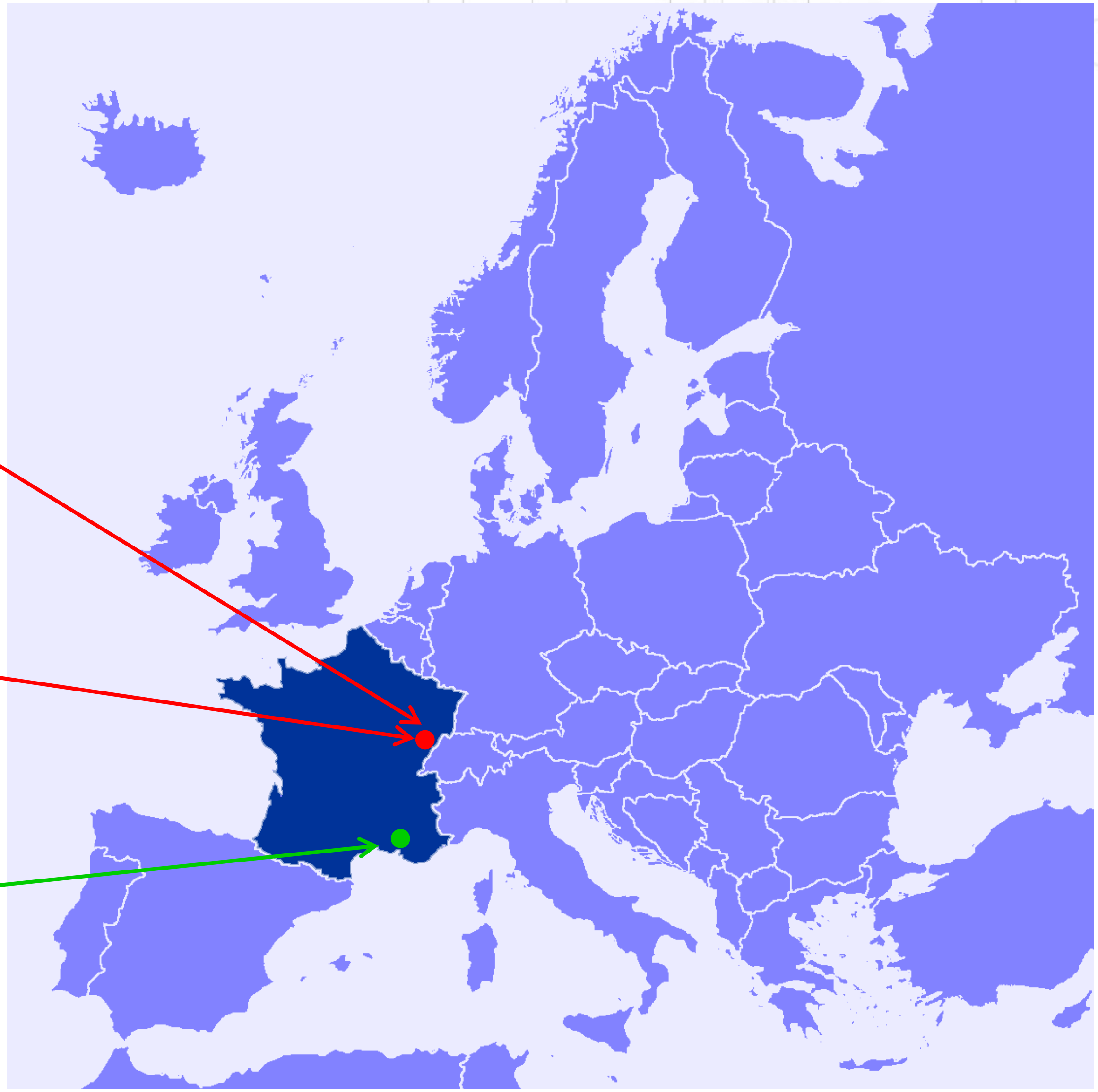
Collaboration :
2 laboratories, 1 company

- UTINAM Institute
  (BESANCON, France)
- FEMTO-ST Institute
  (BELFORT, France)
- Navyclean
  (MARSEILLE, France)



Context and objectives

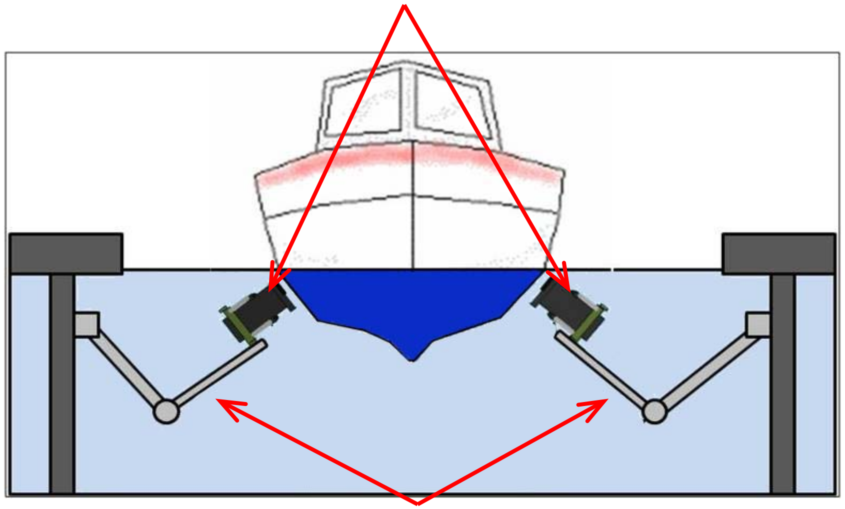
Context

- Power ultrasound : promising tool in numerous industrial applications (extraction, emulsification, cleaning…)

  → cleaning application

Objectives

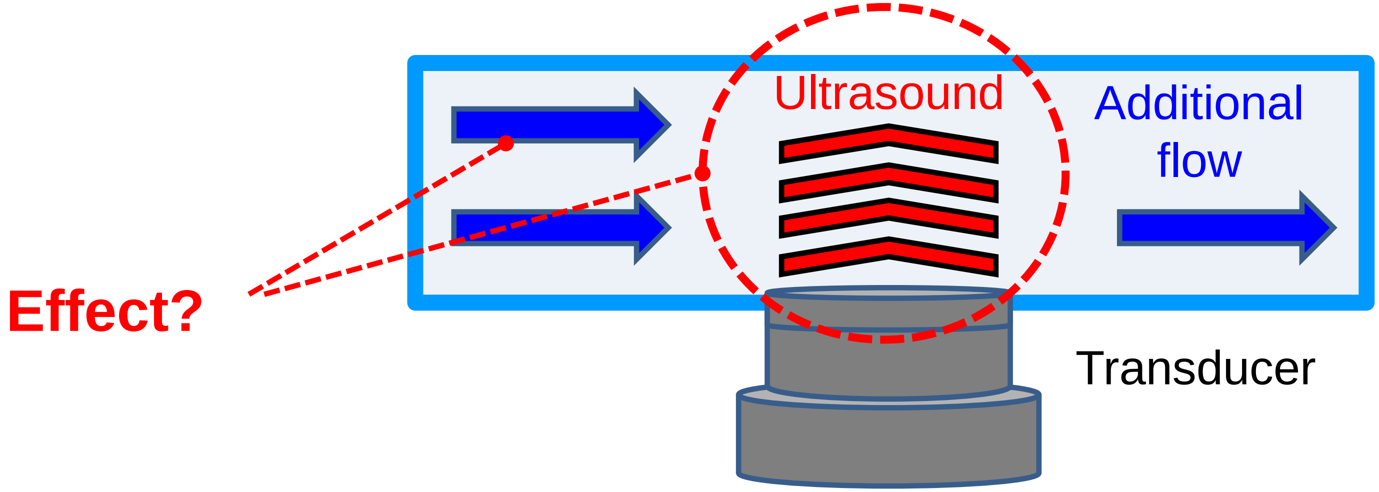
- development of a cleaning station for boat hull (1)
  - In situ
  - Automated tool
  - Environmentally friendly : specific wastewater treatment and no antifouling



(1) G. Mazue et al. , "Large-scale ultrasonic cleaning system: Design of a multi-transducer device for boat cleaning (20 kHz)", Ultrasonics Sonochemistry, 2011.

Context and objectives

- cleaning application : aspiration + displacement of the cleaning tool = additional liquid flow → influence on ultrasonic field & cleaning efficiency?
- presence of an additional flow : also true for other applications (ex: electrochemistry : oxide waste and/or production [1])

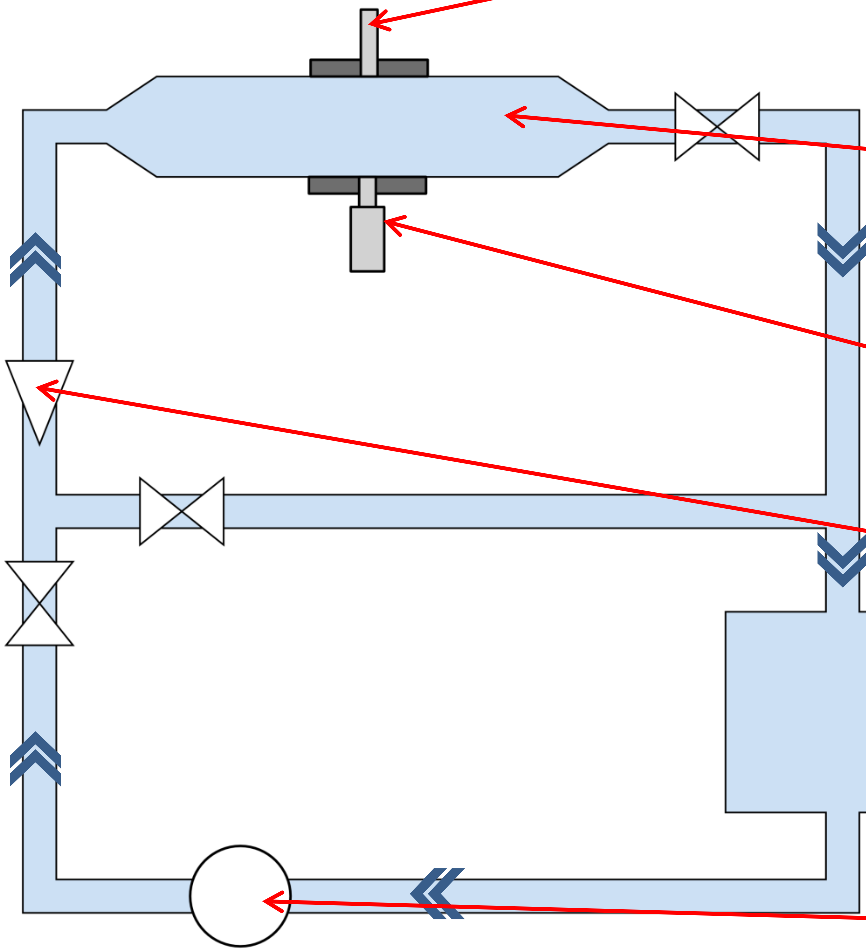


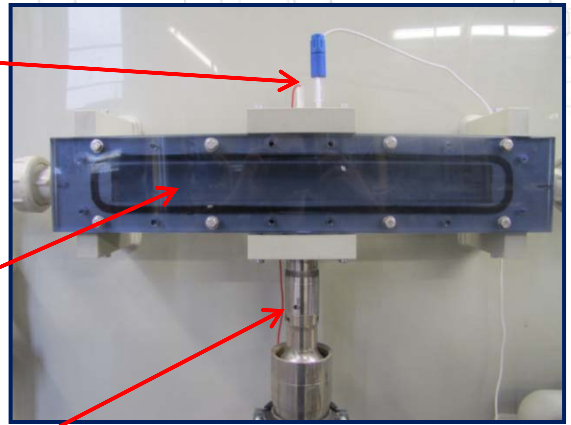
Objective : study the influence of a liquid flow on an ultrasonic field

(1) J. Gonzalez-Garcia et al., "Electrosynthesis of hydrogen peroxide via the reduction of oxygen assisted by power ultrasound". Ultrasonics Sonochemistry, 2007.

Material & methods

Experimental setup





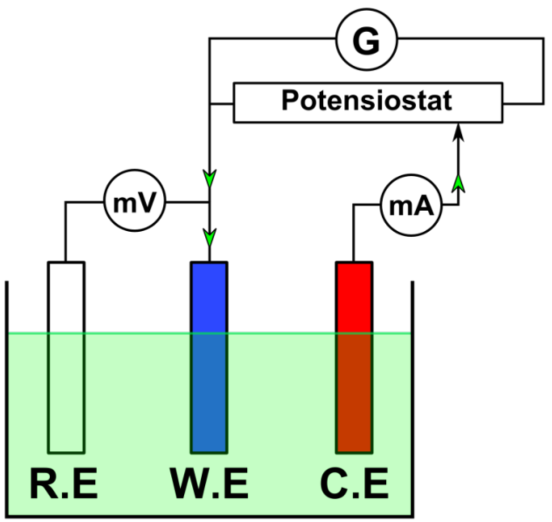
Control parameter :
Reynolds number (flow rate)

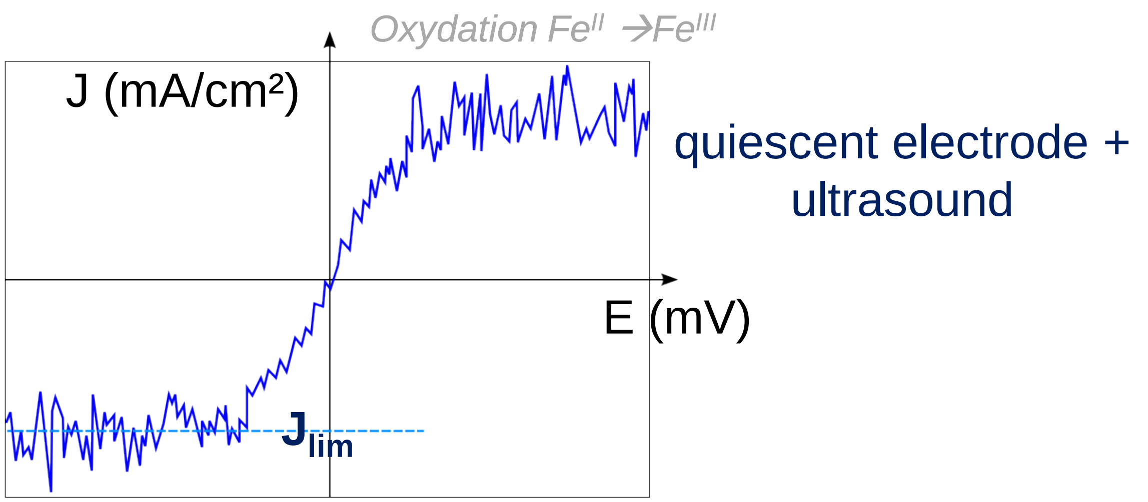
- Two methods of measurements:
  - PIV (streaming)
  - Electrochemical (stirring)

Material & methods : electrode

Electrochemical measurements

- Classic method: 3 electrodes linked to potentiostat measurements
  - Electrolyte : reversible Fe^{II}/Fe^{III} couple
  - Sonoelectrochemical voltammograms →typical sigmoid : current density increases with potential until reaching a plateau → mass transfer limited potential





Current Density versus Potential (J = f(E) curve)

Material & methods : electrode

- Current density → mass transfer coefficient and Sherwood number

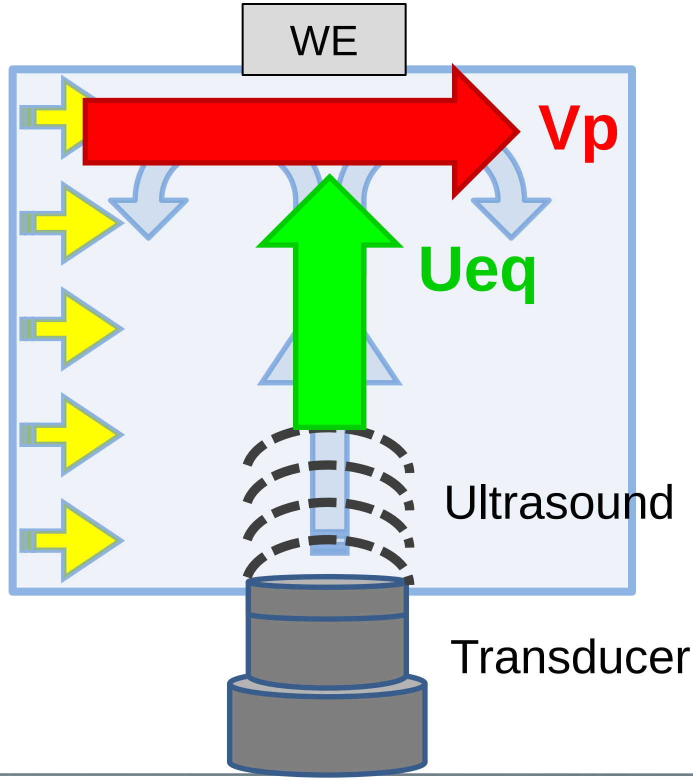
- Equivalent velocities determined from electrochemical measurements :

  - equivalent flow velocity [(1)]

$$U_{eq} = \frac{1}{(0{,}45.\, n.F.C_{Sol})^2}.D^{-4/3}.\nu^{1/3}.\ J^2.r$$

  - parietal equivalent velocity [(2)]

$$V_P = \frac{1}{(0{,}6\, n.F.C_{Sol})^2}.D^{-4/3}.\nu^{1/3}.J^2.d^{2/3}\ .x^{1/3}$$



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(1) B. Pollet et al. "Transport limited currents close to an ultrasonic horn equivalent flow velocity determination", J. of the Electrochemical Society, 2007.
(2) G. Mazue, PhD Thesis, University of Franche Comté, 2012.

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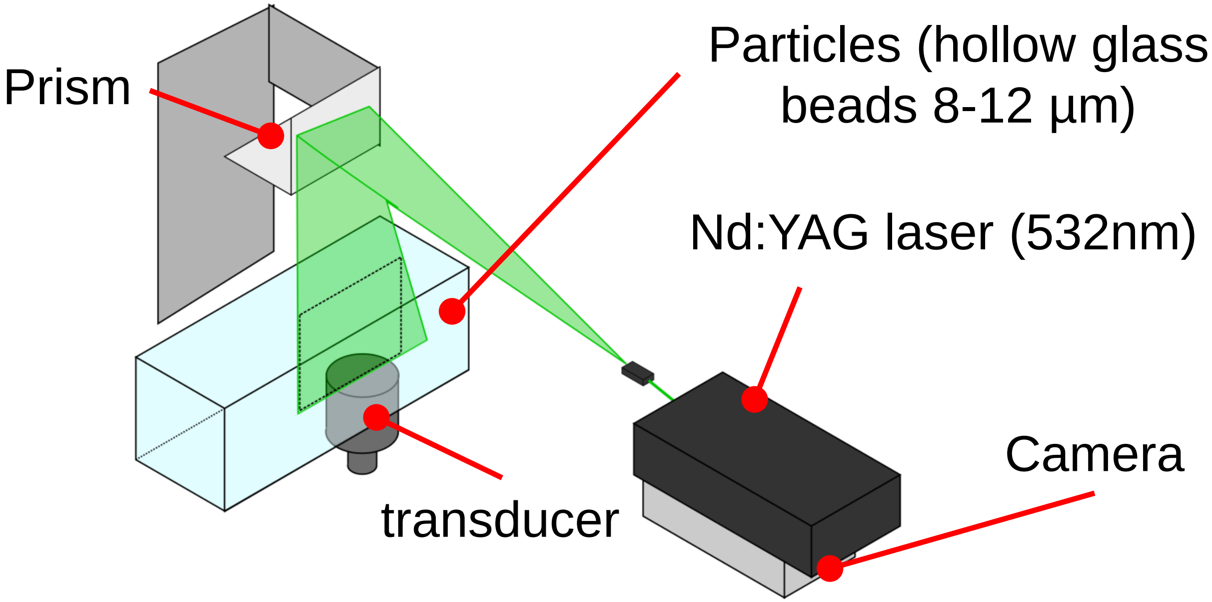
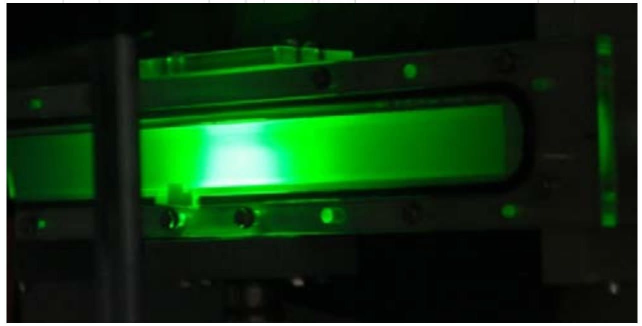
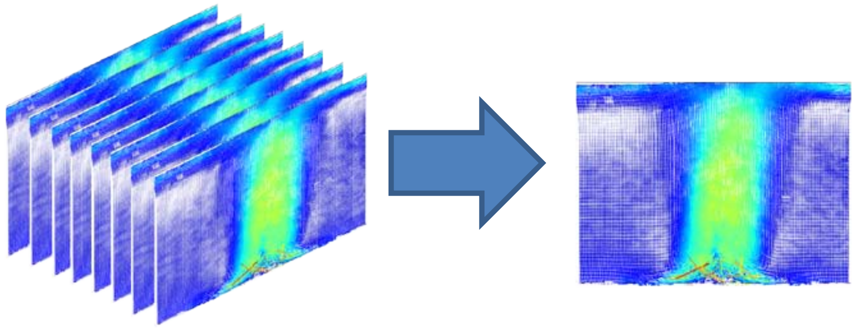
Material & methods : PIV







- Image processing : with PYV software [1,2] (developed at the Femto-st institute)
- Temporal average on 100 instantaneous vector fields → one mean vector field → Mean spatial velocity $\mathbf{U_{PIV}}$

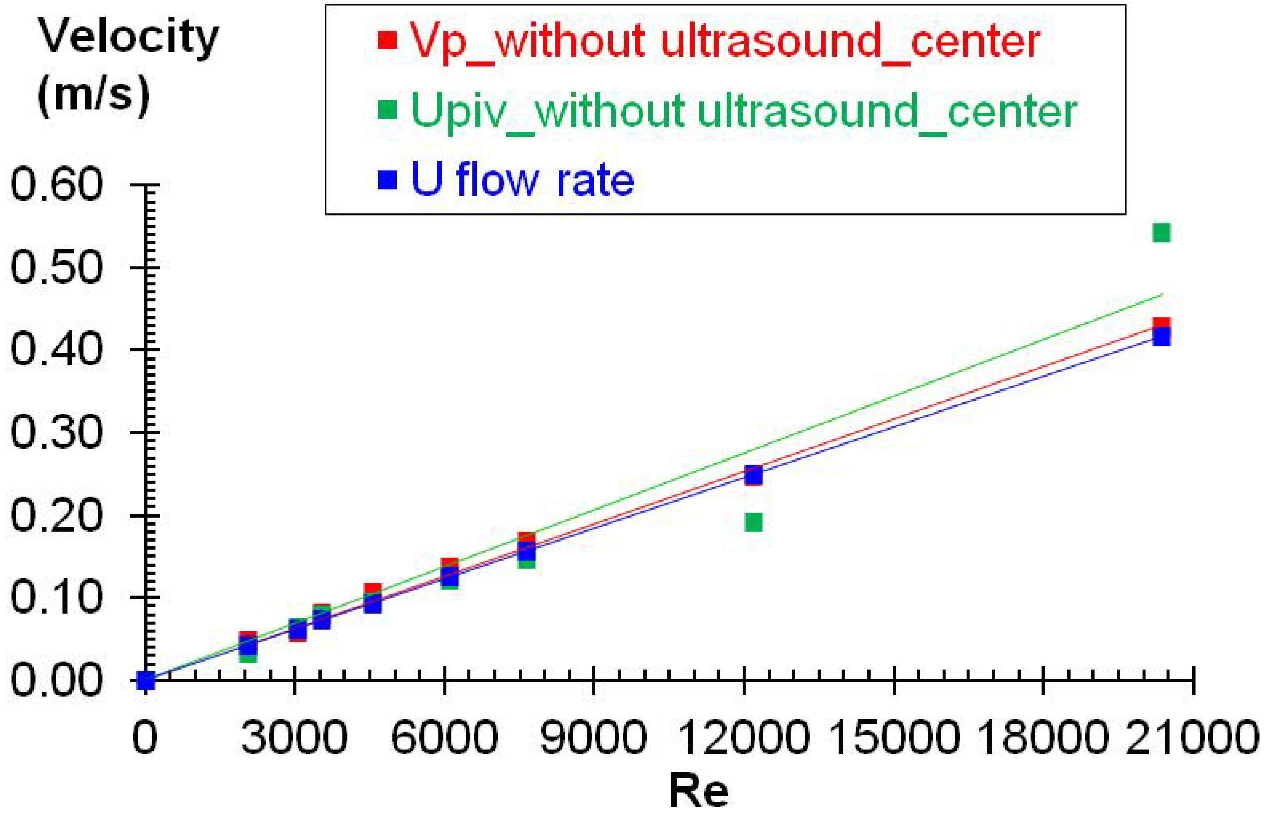
(1) D. Bonnet et al. "PYV: A PIV processing software in Python", proc. of Euroscipy, 2011.
(2) D. Bonnet et al., "Simultaneous PIV measurements in the intake manifold's runners of a running automotive engine", proc. of 15th ISFV, 2012.

Experimental results & Analysis

Velocities from flow rate, PIV and electrochemical measurements without ultrasound

- Identical trend
- Identical values

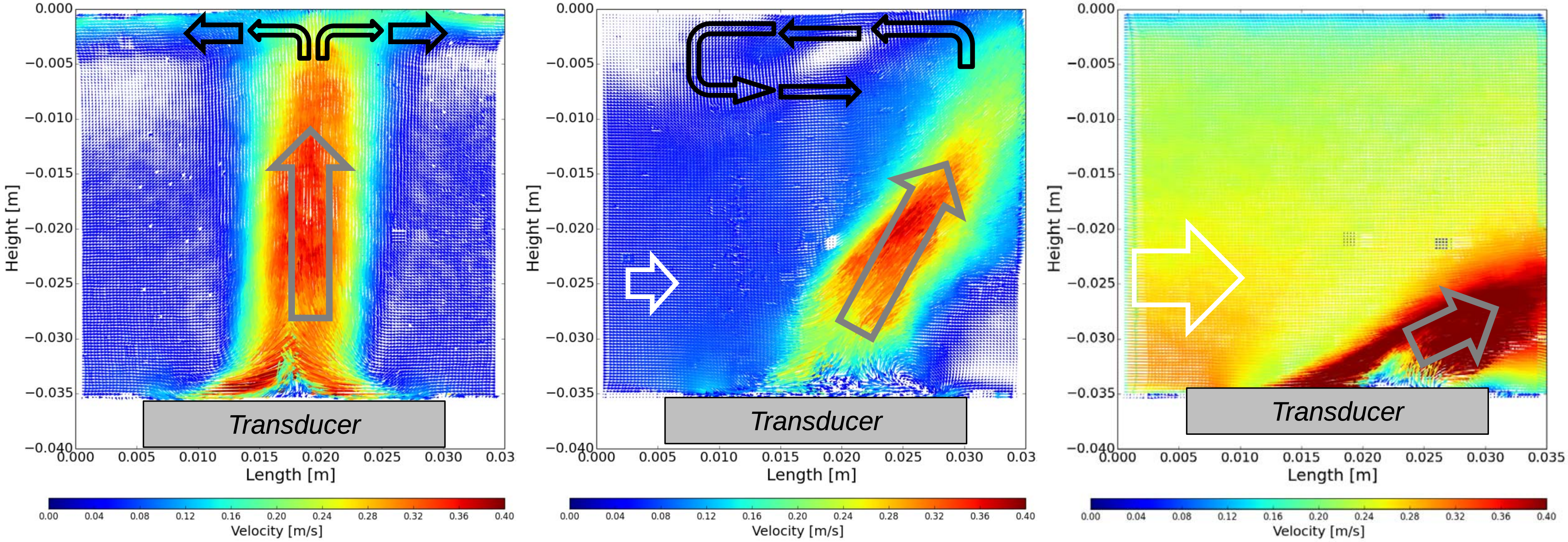
Methods Validation



Previous results (cf. ESS 13)

With 20kHz transducer :

Plume related to the acoustic streaming

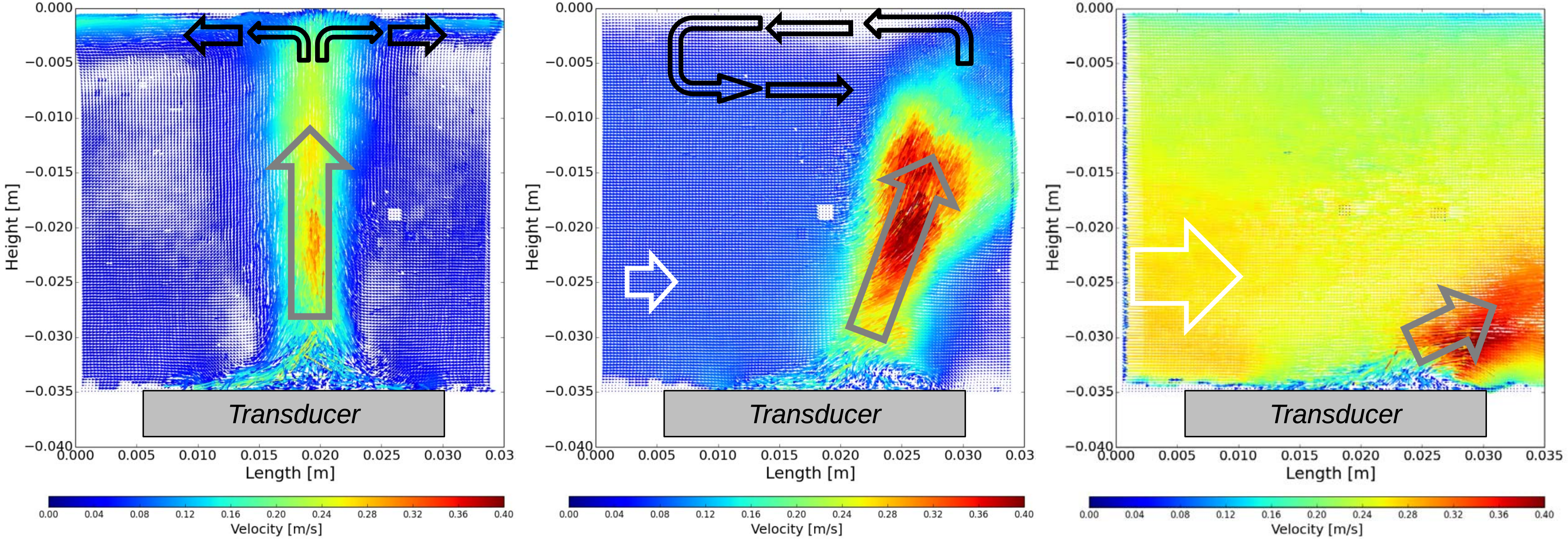


Re = 0 **Re = 3 300** **Re = 13 000**

Plume highly deflected by the additional flow

Experimental results & Analysis

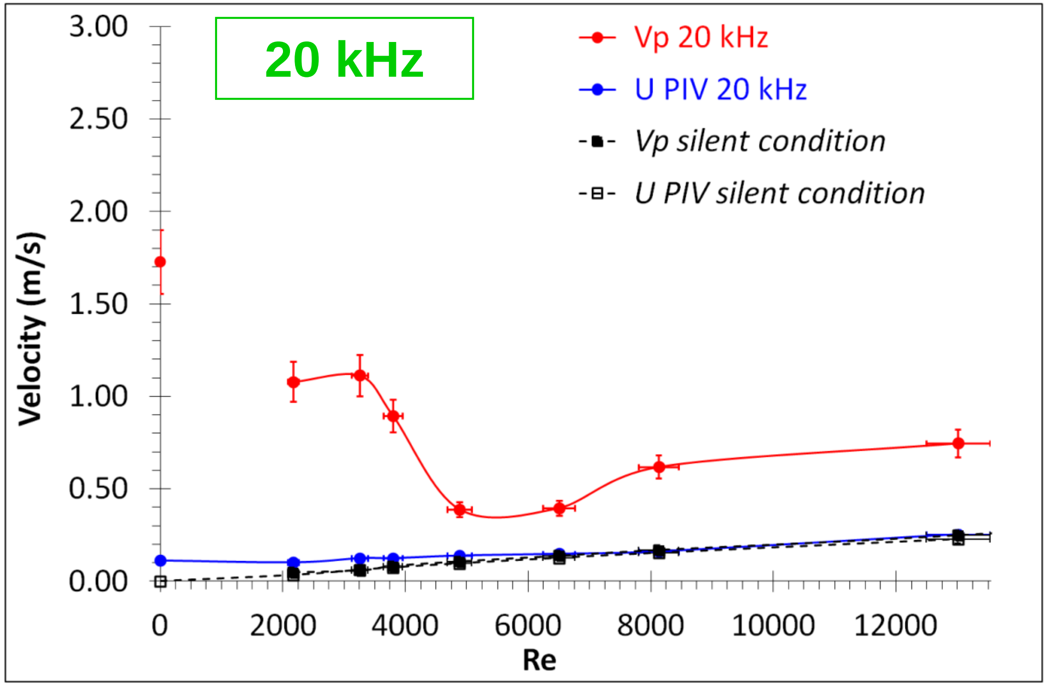
With 40kHz transducer :

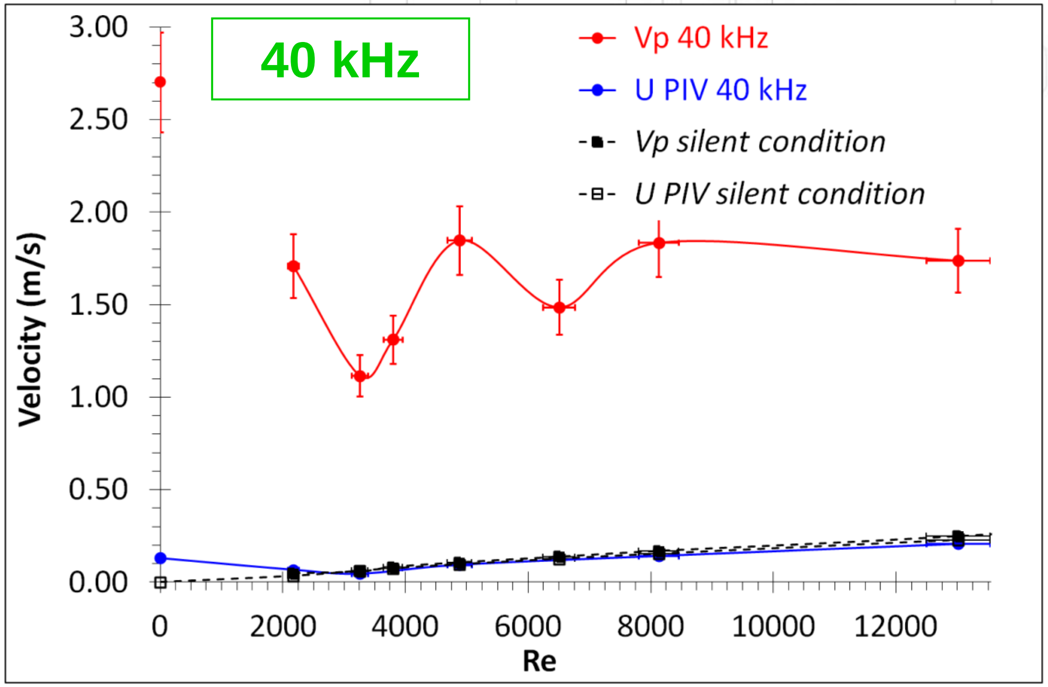


Re = 0 | **Re = 3 300** | **Re = 13 000**

Same behavior than with 20 kHz.
Some differences in the flow structure

Experimental results & Analysis





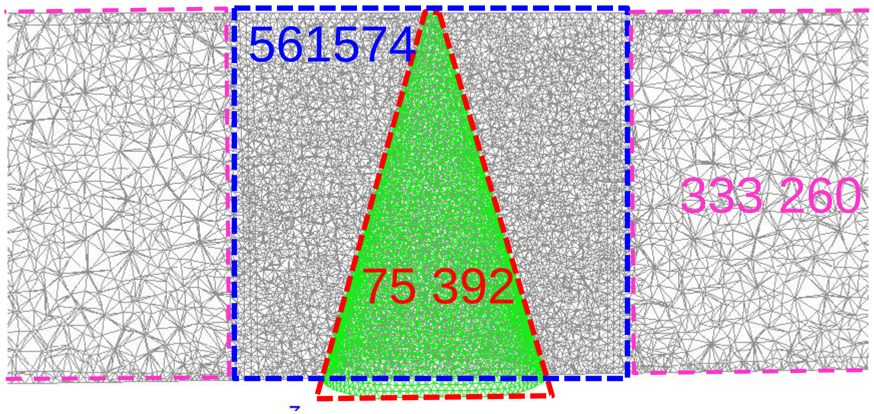
- Ultrasound contribution :
  - PIV: only at small Re
  - electrochemical : all Re

- PIV represents only the streaming : frequency of collapse of cavitation bubble too high to be detected by PIV
- Electrochemical : takes into account both cavitation (stirring effect) and streaming

Both methods:
Relevant + different information

Numerical simulation

- Using Ansys
- No phase change taking into account
- Fluid/fluid volume. Mesh= tetrahedron cells
  - Full canal (400 mm x 35 mm x40 mm) --> over 970 000 cells
  - Visualisation area : refined mesh (35 mm x 40 mm)
  - Streaming : refined mesh, cone



- Boundary conditions:

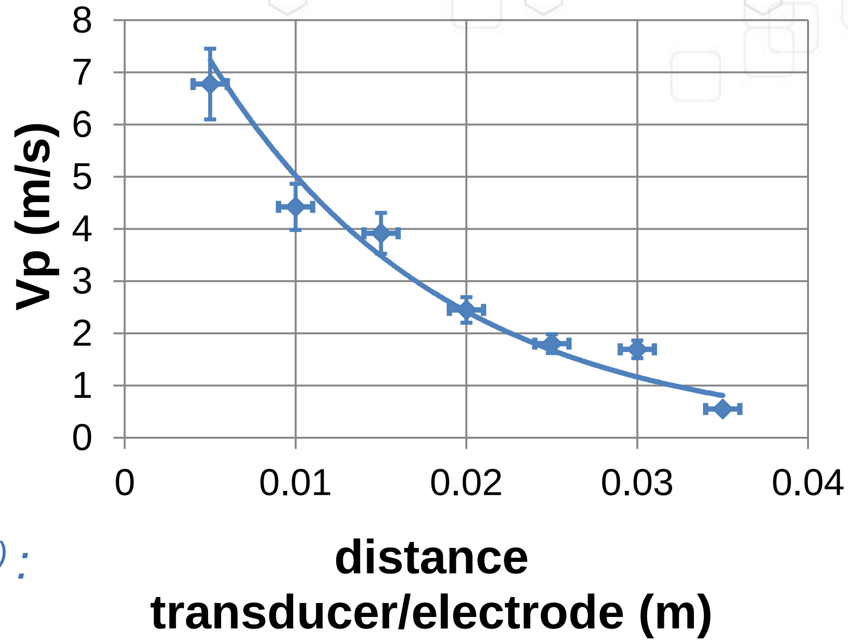
Location	Type
Inlet of the canal	Velocity (from PIV in silent condition)
Outlet of the canal	Pressure (atmospheric)
Surfaces in contact with ambient air	Convection coefficient h=10 $W.m^{-2}.K^{-1}$

Numerical simulation

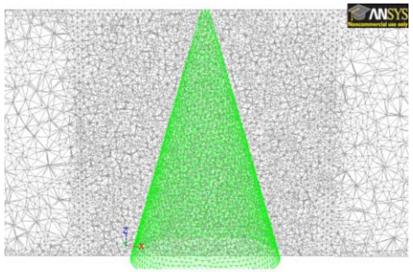
- Transducer : Not modeled
- Streaming :
  - source term → Imposed a body force [1] (coded in a UDF)

$$F_z = \frac{2\alpha I_0}{c} \exp(-2\alpha z)$$

    - *acoustic intensity I_0 → by calorimetry [2,3] : for 20kHz, I_0 =14,1 W.cm^{-2}*
    - *absorption coefficient α → experimentally determined : for 20kHz, α=36m^{-1}*



  - Choice of a cone shape (related to cavitation field in litterature [4])

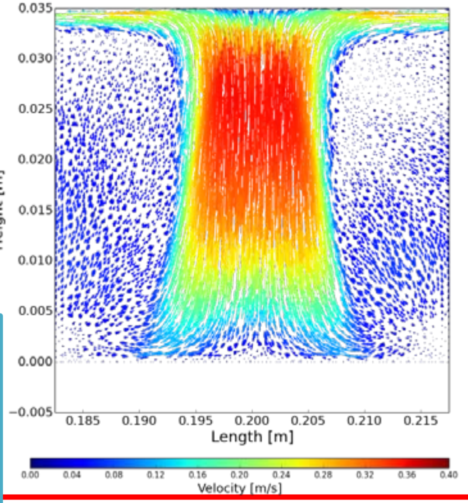


- Natural convection : Boussinesqu

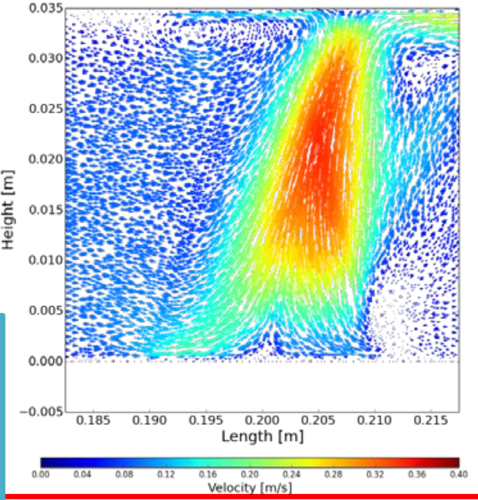
(1) W. Nyborg, "Acoustic streaming", W.P Mason (Ed.), Physical Acoustics, 1965
(2) T.J. Mason, et al., "Quantifying Sonochemistry -Casting Some Light On A Black Art", Ultrasonics, 1992.
(3) F. Ratoarinoro et al., "Power measurement in sonochemistry", Ultrasonics Sonochemistry, 1995.
(4) A. Moussatov et al., "cone-like bubble formation in ultrasonic cavitatipn field", Ultrasonics Sonochemistry, 2003

Numerical simulation : 20 kHz

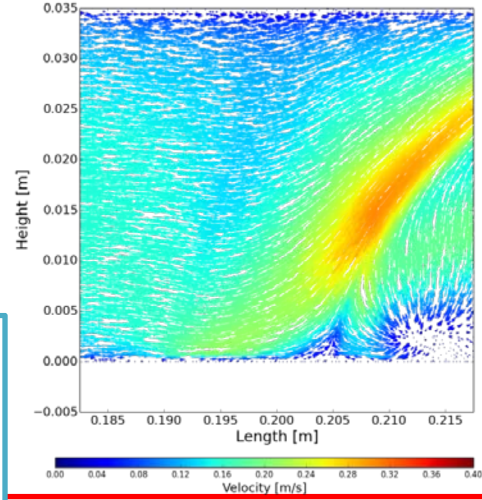
CFD



Re = 0

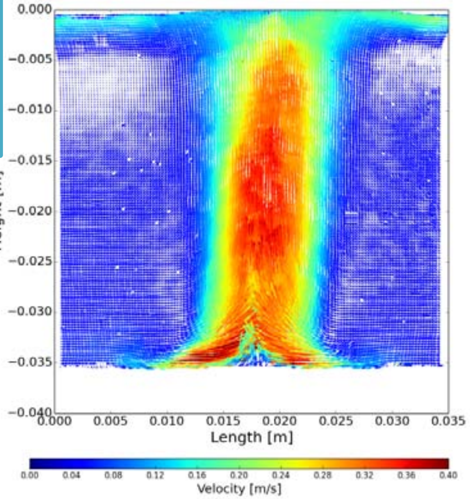


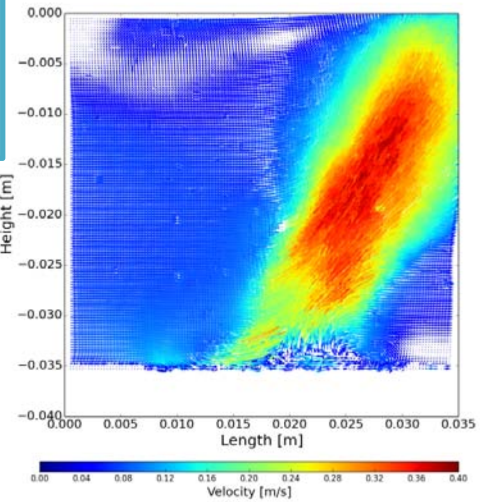
Re = 3300

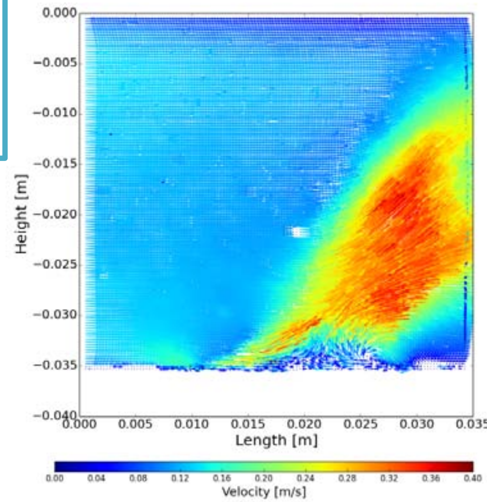


Re = 6500

PIV







Same velocity magnitude. Identical influence of the additional flow

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Numerical simulation

Comparison CFD and PIV results:

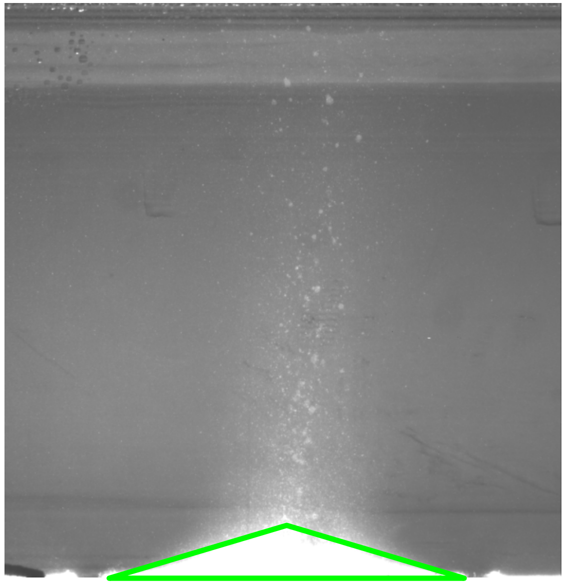
- Velocities : same order of magnitude
- Influence of additional liquid flow : same trend
- Shape of the plume : some differences → related to cavitation's bubble cone?

  - Cone shape determination from experimental results : image processing
    - *Average of 200 images*
    - *Thresholding*
    - *Edge detection*

  } Geometry of the cone-shape

  ⇩

  To be used in CFD



Conclusion & prospects

In conclusion, with an additional flow :

- PIV measurements:
  - Acoustic flow highly impacted for Re>6000 : plume deflected
  - Streaming
- Electrochemistry measurements :
  - all tested Re : always an activity on the wall, higher than in silent conditions
  - Streaming and cavitation
- For our specific application → distance between surface to be cleaned and transducer shorter (< 1cm) → boat hull cleaning by ultrasound should be relevant.

Ultrasound system with an additional liquid flow remains efficient

Conclusion & prospects

Numerical simulation :

- First results showed good agreement for :
  - Order of magnitude of velocities
  - Influence of the additional liquid flow
- General shape of the plume : to be improved

Promising first results

Undergoing & Prospects of this work:

- CFD more accurate :
  - geometric parameters of the cone
  - model with phase change
- Extend experimental & numerical study (40kHz, liquid viscosity...)

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