Experimental investigation of cavitation inception in a confined liquid layer by laser-induced pressure pulses

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Can pre-existing bubbles protect the structure?

Cluster response $\Delta p = 20$ atm
Reducing damage:

Does **cavitation inception** plays a role on the system’s dynamics for strong impacts?

It is not obvious it will occur!!!

If we manage, it is interesting because it is a reversible **fracture** process.
Reducing damage:

The appearance and propagation of cracks dissipate a large amount of energy.

It is an irreversible process!!!
Proof of concept:

High intensity pressure waves in confined water to see if we can observe cavitation

Experimental setup at IRDL, ENSTA-Bretagne:

Quanta Ray Pro 350-10
Spectra-Physics
$E_{\text{max}} = 3.7 \text{ J}$
$\lambda = 1064 \text{ nm}$
Focal region: 3 mm
Power $\approx 0.5 \text{ GW/cm}^2$
Proof of concept:

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**Advantage:** Controllable, small volume ($e = 250, 400, 750 \mu m$)
Proof of concept:

High intensity pressure waves in confined water to see if we can observe cavitation

Advantage: Controllable, small volume \((e = 250, 400, 750 \mu m)\)

Disadvantage: short pulse duration (high frequency)

The shorter the pulse duration, the higher the energy to induce cavitation
Proof of concept:

High intensity pressure waves in confined water to see if we can observe cavitation.

Characteristic times

Excitation $\approx 10$ ns ($f = 0.1$ GHz)

Wave propagation in Al $\approx 0.1$ $\mu$s

Wave propagation in Water $\approx 0.13$-$0.5$ $\mu$s

Wave propagation in PMMA $\approx 1$ $\mu$s
First qualitative observations:

Focal region:

\[ D = 3.3\text{mm} \]

Water thickness:

\[ e = 750 \, \mu\text{m} \]

Framerate:

300000 fps

Video duration:

1 ms
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Video duration: \( 1 \, \text{ms} \)

\[ E = \begin{cases} 5 \% & \text{if } D = 3.3 \text{mm} \\ 10 \% & \text{if } e = 750 \, \mu\text{m} \\ 20 \% & \text{if } 300000 \, \text{fps} \\ 40 \% & \text{if } 1 \, \text{ms} \\ 80 \% & \text{else} \end{cases} \]
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Water thickness: \( e = 750 \ \mu \text{m} \)

Framerate: 300000 fps

\( E = 5 \% \)

\( E = 10 \% \)

\( E = 20 \% \)

\( E = 40 \% \)

\( E = 80 \% \)
Influence of the fluid’s properties

- More viscosity, smaller radius

- Less secondary cavitation activity

\[ E = 5, 10, 20, 40, 80 \% \]

Water  
Glycerol
t=0 \mu s Water

E = 5\%

E = 10\%

E = 20\%

E = 40\%

E = 80\%

Glycerol
$t=3.3 \ \mu s$ Water

Glycerol

E = 5 %

E = 10 %

E = 20 %

E = 40 %

E = 80 %
$t=6.6 \ \mu s$ Water

- $E = 5\%$
- $E = 10\%$
- $E = 20\%$
- $E = 40\%$
- $E = 80\%$

Glycerol
Short times $t < 6.6 \mu s$ Bubble Inception $E \geq 10\%E_{max}$
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Influence of fluid properties on PVDF measurements: $PDVFsignal \propto P$
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-WATER

-GLYCEROL

-At short times some features are common for samples with both fluids
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-Signal saturates for $E > 60\%$
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- At short times some features are common for samples with both fluids
- Signal saturates for $E > 60\%$
- Glycerol attenuates the high frequency content faster
- Unknown answer to When does bubble nucleates?
Can we see something externally? (e.g. back face velocity)
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Measurement with the HV probe (or PVD: Photon Doppler Velocity)
Measurement with the VISAR (PIMM, Arts et Metiers)
We compare the two measurement techniques for Glycerol

**VISAR**

\[ V_{\text{face}} \propto P \]

**PVDF sensor**

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**VISAR**

\[ V_{\text{face}} \propto P \]

**PVDF sensor**

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PIMM, Arts et Metiers

Similar qualitative measurements (also for water)

But only appropriate for extremely fast events
t=13.3 μs First cav activity in bulk

E = 5 %

E = 10 %

E = 20 %

E = 40 %

E = 80 %
$t = 30 \, \mu s$: Max cav activity in bulk

$E = 5 \%$

$E = 10 \%$

$E = 20 \%$

$E = 40 \%$

$E = 80 \%$
Measurement with the HV probe

- Fast dynamics at $t > 8 \mu s$ (after bubble inception)
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- Evidence of negative velocities (e.g. tension states)
  For this example $p = -170 MPa$
What about longer times?
Long time evolution

Pressure fluctuations are significant while bubbles are *active*

WATER

\[ E = 20\% \]
Long time evolution

Pressure fluctuations are significant while bubbles are *active*

**WATER**

![Image of water with different volume fractions](image)

- $E=20\%$
- $E=60\%$

![Graphs showing pressure fluctuations over time](image)
Long time evolution

Pressure fluctuations are significant while bubbles are *active*

**GLYCEROL**

\[ E=20\% \]

\[ E=80\% \]
Long time evolution \text{WATER}

- Very fast bubble appearance $t < 20 \mu s$
- Bubble expansion $20 < t < 200 \mu s$
- Bubble collapse $t_{\text{collapse}} \approx 200 - 300 \mu s$
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Long time evolution WATER

\[ R_{\text{max}} [\text{mm}] \approx 4 \sqrt{E_0 [\text{J}]} \]

If we consider only the energy to displace the liquid:

\[ E = p_0 \pi R_{\text{max}}^2 e \]

- \( p_0 \): reference pressure
- \( e \): liquid thickness
Long time evolution **GLYCEROL**
Long time evolution **GLYCEROL**

\[
R_{\text{max}}[\text{mm}] \approx 1.65 \sqrt{E_0[\text{J}]}
\]
Bubble’s Lifetime

Bubbles in glycerol grow less but they can last even longer than in water

$E = 2.25 \text{ J}$
Rayleigh-like bubble collapse

\[ T_c \approx R_{\text{max}} \sqrt{\frac{\rho_l}{\rho_0}} \]

\[ U^* = \frac{R_{\text{max}}}{T_c} \sqrt{\frac{\rho_l}{\rho_0}} \]

For 3D free bubbles

Small confinement level increases the collapse velocity

For Re < 1000 viscosity starts playing a role (small \( e \), viscous liquids)

As \( e \) decreases, the collapse time increases

![Graph showing data points for different confinement levels](image)
Rayleigh-like bubble collapse

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Conclusions

$t < 6.6\mu s$ Bubble Inception in focal region $E \geq 10\% E_{max}$

$t \approx 10 - 30\mu s$ Cavitation inception in the bulk $E \geq 20\% E_{max}$

$t \leq 60 - 600\mu s$ Long term bubble dynamic effects
Conclusions

- It is possible to induce cavitation in confined geometries by laser-induced pressure pulses
  \[ p \approx \text{GPa}, \ t \approx 10 \text{ ns} \]
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PDVF measurements reveal long time pressure fluctuations in the sample directly attributed to the dynamic response of bubbles and the interactions with the plates.
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▶ The bubble’s maximum radius depends:
  ▶ Input energy \( E_0 \)
  ▶ Fluid characteristics (elasticity, viscosity?)

▶ Secondary cavitation is observed out of the impact zone for large \( E_0 \).

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Paris-Brest cake