THERMODYNAMIC ANALYSIS OF HIGH-PRESSURE SONOREACTOR
IMPACT OF CHOSEN TECHNICS IN EFFICIENCY
AND HEAT RELEASE PROBLEM

Bertrand GUATARBES, Laurent MARLIN, Guillaume BAREIGTS, Frederic PLANTIER

Laboratory of Thermodynamics and Energetics of Complex Fluids LFCR UMR 5150
INTRODUCTION

**Bubbles creation:**
- Temperature increase: Boiling
- Pressure decrease: Cavitation

Cavitation, destructive effect but useful in nature and in industry:

**Acoustic cavitation** → **Sonochemistry / Sonocrystallization...**

*Gogate, P. R. (2008). "Cavitational reactors for process intensification of chemical processing applications: A critical review." Chemical Engineering and Processing 47: 515-527*
**STUDY CONTEXT**

*Initial study: Enhanced oil recovery*

**Problematic:**

Study of acoustic cavitation at laboratory scale for high pressure till **150 Bar**

**Development of high-pressure sonoreactor**

Utilization of piezoelectric transducer

\[ f_R = 40 \text{ kHz} \]
\[ P = 50 \text{ W} \]
\[ m = 286 \text{ g} \]

PZT Material
Aluminum horn

Technique easier to enforce at ambient pressure* than at high-pressure

H\(_2\)O+CO\(_2\) degassed in a crystallizer

main training plane of cavitation bubbles

Design of high-pressure sonoreactor:

**Outside transducer**

- Pressure control
- PZT Horn
- Varying pressure \( dP \) (standing wave)
- CAVITATION BUBBLE

**Inside transducer**

- Calorimetric study
- Phenomenological study

* Developed in collaboration with Dynaflow Inc (http://www.dynaflow-inc.com/Products/ABS/Acoustic-Bubble-Spectrometer.htm)
CO2 dissolved in pure water

Binary mixtures H₂O + CO₂ at (T, Ps)

Initial state of experiment
Pini = Ps+dP

(H₂O)_L + (CO₂)_L

(H₂O)_L + (CO₂)_V

~CpΔT + ΔH_CO₂

ΔP∞_V + ΔH_CO₂
Switch on power $W$ from 0 to 50W

Increase of pressure $\rightarrow$ Degassing CO2

Boiling or Cavitation Bubbles?

![Graph showing boiling and cavitation phenomena](image-url)
**Impact of acoustic power for degassing**

\[ W + (P \cdot \frac{dV}{dt} + V \cdot \frac{dP}{dt}) = \frac{dU}{dt} \]

\[ \frac{dP}{dt}(t) = f(\text{ultrasonic power}) \]

\[ \frac{dP}{dt} = K(W) \cdot \ln\left(\frac{t}{t_0}\right) \]
$K = \text{Identification criterium of bubbles}$

$W_s = P_{ac} - P_{ini}$

$P_{ini} = P_{ac} - P_s$
Identification of bubble category

$P=f(W)$

- **Boiling**
- **Cavitation**
**EFFICIENCY OF CHOSEN TECHNICS**

\[ \frac{dP_{ac}}{Ps} \text{ for } W=50W \]

**Outside transducer**

\[ \frac{dP_{ac}}{Ps} < \frac{1}{10} \]

**Inside transducer**

\[ \frac{dP_{ac}}{Ps} \sim \frac{1}{2} \]

**Inside transducer much better technicle for efficiency!**
Thermic study of ultrasonic transducer

\[ \text{Heat release/s} = W - m \cdot C_p \cdot \frac{dT}{dt} \]

\(~ 50 - 0.9 \times 290 \times 0.01 \sim 48 \text{J.s}^{-1} \)

\[ m(\text{H}_2\text{O}) = 600g \quad \text{Average } T \text{ increase } > 0.02 \text{ K.s}^{-1} \]
Use of imaging to better understand

Predominantly bubbles generated by boiling in contact with the PZT ceramic

Predominantly bubbles generated by cavitation under horn and in liquid

$H_2O + CO_2 \ Psat(CO_2) = 30\text{Bar} \ T=25^\circ C$
EVOLUTION OF BUBBLES IN SONOREACTOR

A complex phenomenon !!!

possible evolutions during the growth of bubbles

- Archimedes’ principle
- Stable cavitation and streaming
- Unstable cavitation
- Coalescence

What is interesting for SONOCRYSSTALLIZATION?
Sonocrystallization of gas clathrate, also a complex process* ...

- Process used for a long time but little understood
- Fundamental action: nucleation help (but counterproductive in growth phase)
- Bibliography: several ways to analyze

1st vision of phenomenon

Local Supersaturation

\[ \Delta P > 0 \]

2nd vision of phenomenon

Interface area increase between gas and liquid**


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1st vision of phenomenon

Local Supersaturation

- Local fall of pression: cavitation

2nd vision of phenomenon

Interface area increase between gas and liquid**

- Primary reason?

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From simple emulsion to cavitation...

In order:
- Emulsion H\(_2\)O/Cyclopentane 640fr/s (=Slow motionX25)
- Comparison with/without ultrawave
- Emulsion H\(_2\)O/Cyclopentane 24fr/s
- Cavitation Cyclopentane 640fr/s
- Cavitation H\(_2\)O/CO\(_2\) Ps=30Bar

Always presence of bubbles?
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1st vision of phenomenon
Local Supersaturation

2nd vision of phenomenon
Interface area increase between gas and liquid**

Primary reason?

For sonocrystallization, heat release to avoid !!!

Strong difference of efficiency with inside and outside ultrasonic transducer

With inside ultrasonic transducer: heat release problem

In sonoreactors, different complex phenomena

Sonocrystallization, complex process with primary reason: cavitation?

For sonocrystallization, outside ultrasonic transducer better choice
Sonocrystallization of $CO_2$ clathrate hydrate or organic

Gas Clathrate = Host molecule that traps guest molecule (if host molecule $H_2O = hydrate$)

**α-Hydroquinone**
Native form, stable under amibiant conditions of P and T

**Guest Molecule**
Ar, Kr, N2, CH4, Xe, H2S, CO2, …

**β-Hydroquinone**
Clathrate form, Stable in presence of guest molecule under amibiant conditions of P and T

Applications:
- CO2 capture and separation
- Phase change materials

Development of new high-pressure sonoreactor without release heat problem

With ultrasound, can we promote synthesis?
Thanks
Video at various speed acquisition (24 à 1200 frame/s)

In order:
Mixture H₂O/CO₂ Ps=30Bar
- Slow motion (X4)
  (Stationary bubbles, streaming, coalescence)
- Normal speed
- Central bubble 1200im/s neon light (cycle 0,01s)
- Central bubble 1200im/s zoom
  (homogeneous nucleation, coalescence)

H₂O+CO₂, Pini=Ps(CO₂)=30Bar