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Single Bubble Collapse at Audible Frequencies and High Amplitudes

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ICTS INTERNATIONAL CENTRE for THEORETICAL SCIENCES
TATA INSTITUTE OF FUNDAMENTAL RESEARCH

THERMASMART Thermal Management of Microprocessors

EPSRC Engineering and Physical Sciences Research Council

Phenomenon and motivation

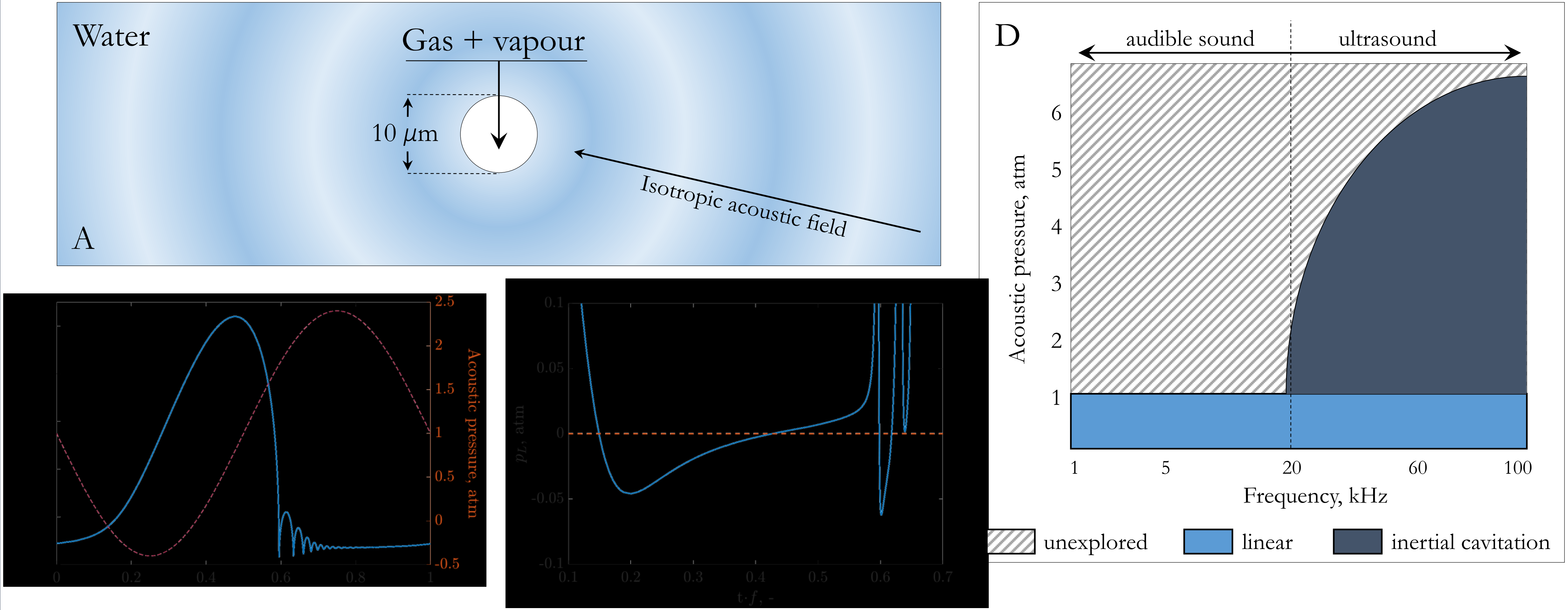


Figure 1. A) Schematic of the system; B) Bubble dynamics; C) Liquid pressure; D) Unexplored parameters space.

Governing equation

Bubble wall motion (Keller-Miksis equation with effect of bulk viscosity)

$$\left(1-\frac{\dot{R}}{c_l}\right)R\ddot{R}+\frac{3}{2}\left(1-\frac{\dot{R}}{3c_l}\right)\dot{R}^2=\left(\frac{R}{\rho_l c_l}+\frac{\lambda_l+2\mu_l}{\rho_l^2 c_l^2}\right)(\dot{p}_l-\dot{p}_\infty)+\left(1+\frac{\dot{R}}{c_l}\right)(p_l-p_\infty)$$

Gas temperature (quasi-equilibrium assumption)

$$\dot{T}_g=\frac{-T_g\frac{\partial p_g}{\partial T_g}dV+S\kappa_g\frac{\partial T_g}{\partial r}\Big|_{r=R}-S\sum_{i=1}^{N_S}\Psi_i\left[u_i^0(T_g)-u_i^0(T_g^{\mathrm{i}})\right]-V\sum_{j=1}^{N_R}r_j^{\mathrm{net}}\Delta^r u_j^0}{n_{TOT}\bar{c}_{vg}}$$

Non-equilibrium phase change (Hertz-Knudsen equation)

$$\dot{m}=\frac{\alpha}{\sqrt{2\pi\mathcal{R}}}\left(\frac{p_{sat}(T_{li})}{\sqrt{T_{li}}}-\frac{\Gamma x_{H_2O}p_g}{\sqrt{T_{gi}}}\right)$$

[1] R. Löfstedt, B. P. Barber, and S. J. Putterman, Physics of Fluids A: Fluid Dynamics 5, 2911 (1993).

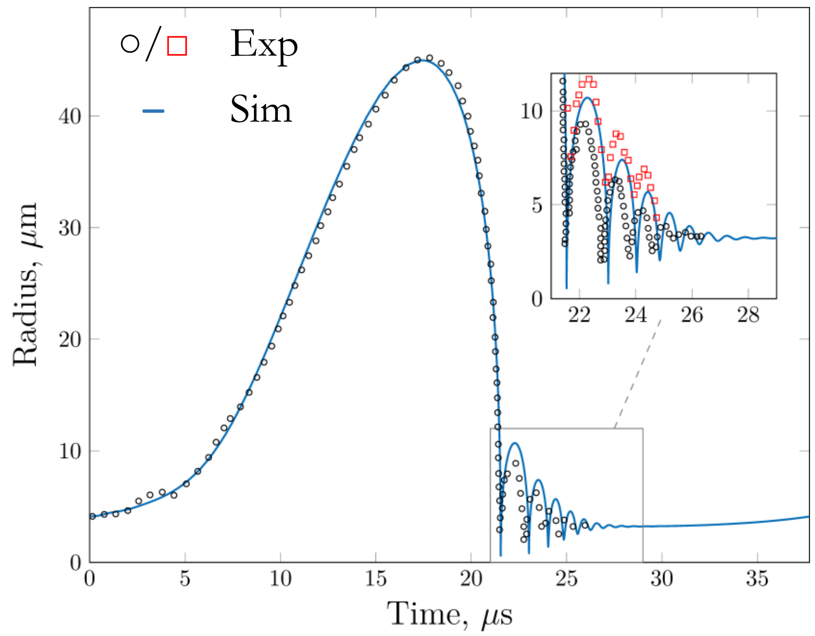


Figure 2. Model validation against experimental data of bubble radius from Löfsted et al. [1]

Physical properties

Gas phase	*Liquid phase*
Redlich – Kwong EOS NASA polynomials Chapman – Enskog theory	IAPWS R6-95 EOS

Low vs. high frequency: the main collapse

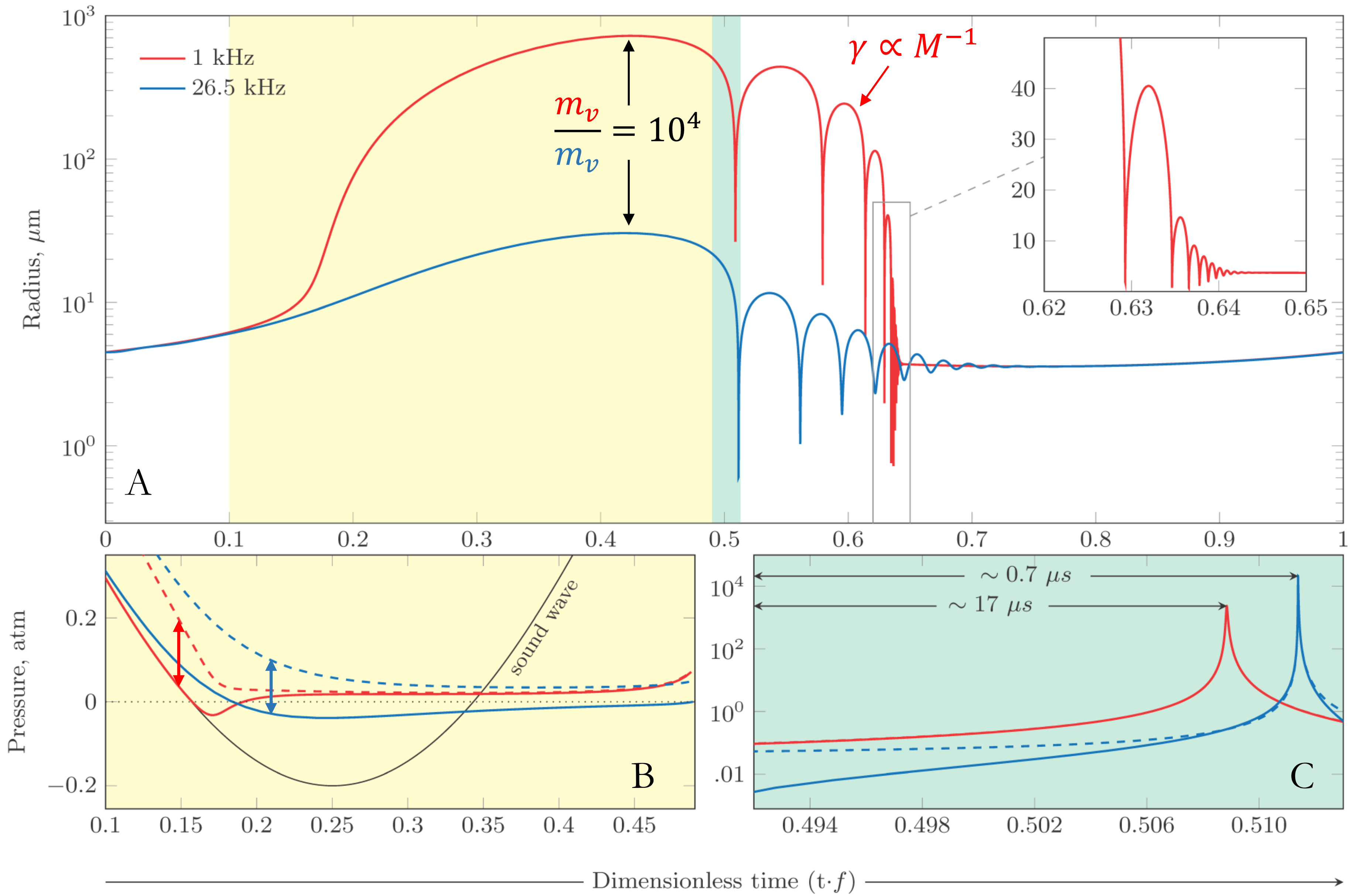


Figure 3.

A) Bubble radius dynamics at low and high frequency;

B) Liquid and gas pressures during bubble expansion;

C) Liquid and gas pressures at collapse.

Low vs. high frequency: the rebounds

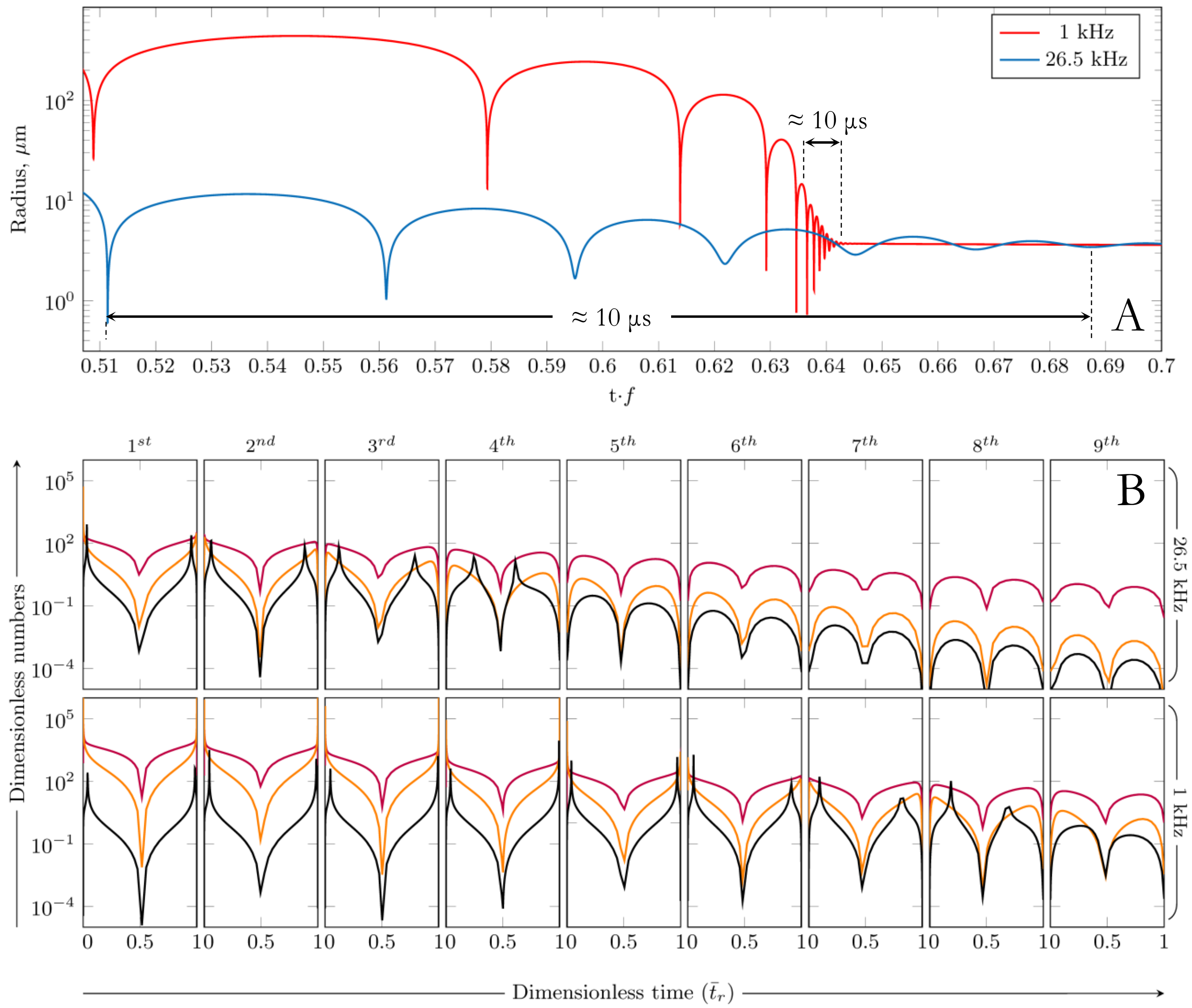


Figure 4. A) Inset of the rebounds following the main collapse. B) Dimensionless numbers evolution for each rebound.

Key aspects

1. Large bubble prevents viscosity and surface tension damping effect.
2. For same size, oscillations have same time scale regardless of driving frequency.

Bubble wall dimensionless numbers

Reynolds: $Re = \frac{R|\dot{R}|\rho_l}{\mu_l}$

Weber: $We = \frac{R|\dot{R}|^2\rho_l}{\sigma_l}$

Pressure: $\Pi_g = \frac{|\dot{R}|^2\rho_l}{p_g}$

Different dynamics

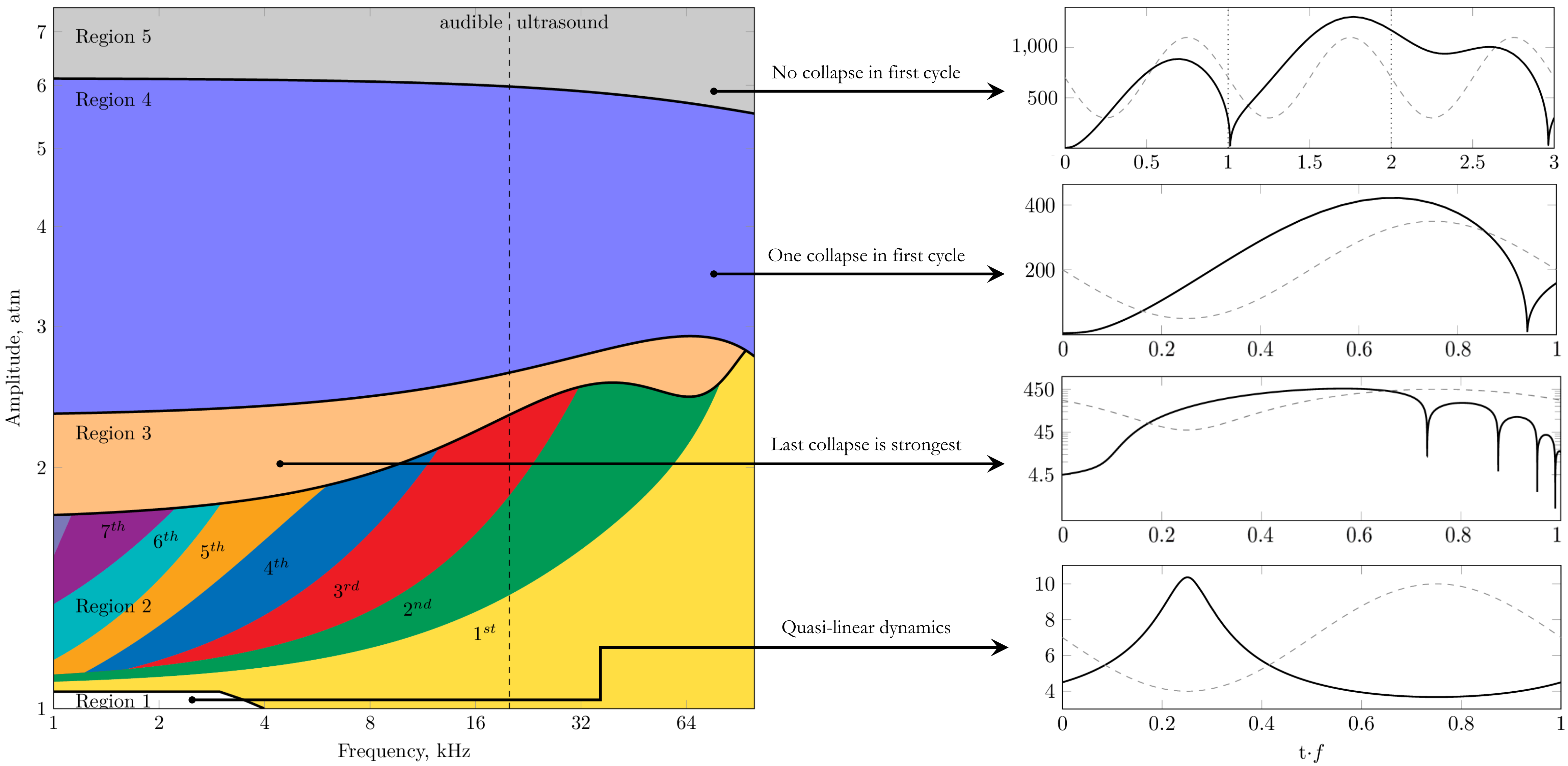


Figure 5. Division of the parametric space by typology of bubble dynamics within one acoustic cycle.

Gas phase chemistry

$$N_2, O_2, H_2O, Ar \xrightarrow{\text{collapse}} H_2, H, O, OH, HO_2, H_2O_2, N, NH, NH_2, NH_3, NNH, NO, NO_2, N_2O, HNO$$

GRI 3.0 combustion mechanism

1 $2O + M \rightleftharpoons O_2 + M$
H_2: 2.4, H_2O: 15.4, Ar: 0.83

2 $O + H + M \rightleftharpoons OH + M$
H_2: 2, H_2O: 6, Ar: 0.7

3 $O + H_2 \rightleftharpoons H + OH$
4 $O + HO_2 \rightleftharpoons OH + O_2$
5 $O + H_2O_2 \rightleftharpoons OH + HO_2$
6 $H + O_2 + M \rightleftharpoons HO_2 + M$
O_2: 0, H_2O: 0, N_2:0, Ar: 0

7 $H + 2O_2 \rightleftharpoons HO_2 + O_2$
8 $H + O_2 + H_2O \rightleftharpoons HO_2 + H_2O$
9 $H + O_2 + N_2 \rightleftharpoons HO_2 + N_2$
10 $H + O_2 + Ar \rightleftharpoons HO_2 + Ar$
11 $H + O_2 \rightleftharpoons O + OH$
12 $2H + M \rightleftharpoons H_2 + M$
H_2: 0, H_2O: 0, Ar: 0.63

13 $2H + H_2 \rightleftharpoons 2H_2$
14 $2H + H_2O \rightleftharpoons H_2 + H_2O$
15 $H + OH + M \rightleftharpoons H_2O + M$
H_2: 0.73, H_2O: 3.65, Ar: 0.38

16 $H + HO_2 \rightleftharpoons O + H_2O$
17 $H + HO_2 \rightleftharpoons O_2 + H_2$
18 $H + HO_2 \rightleftharpoons 2OH$
19 $H + H_2O_2 \rightleftharpoons HO_2 + H_2$
20 $H + H_2O_2 \rightleftharpoons OH + H_2O$
21 $OH + H_2 \rightleftharpoons H + H_2O$
22 $2OH(+M) \rightleftharpoons H_2O_2(+M)$
H_2: 2, H_2O: 6, Ar: 0.7

23 $2OH \rightleftharpoons O + H_2O$
24 $OH + HO_2 \rightleftharpoons O_2 + H_2O$
25 $OH + H_2O_2 \rightleftharpoons HO_2 + H_2O$

25 $OH + H_2O_2 \rightleftharpoons HO_2 + H_2O$
26 $OH + H_2O_2 \rightleftharpoons HO_2 + H_2O$
27 $2HO_2 \rightleftharpoons O_2 + H_2O_2$
28 $2HO_2 \rightleftharpoons O_2 + H_2O_2$
29 $N + NO \rightleftharpoons N_2 + O$
30 $N + O_2 \rightleftharpoons NO + O$
31 $N + OH \rightleftharpoons NO + H$
32 $N_2O + O \rightleftharpoons N_2 + O_2$
33 $N_2O + O \rightleftharpoons 2NO$
34 $N_2O + H \rightleftharpoons N_2 + OH$
35 $N_2O + OH \rightleftharpoons N_2 + HO_2$
36 $N_2O(+M) \rightleftharpoons N_2 + O(+M)$
H_2: 2, H_2O: 6, Ar: 0.625

37 $HO_2 + NO \rightleftharpoons NO_2 + OH$
38 $NO + O + M \rightleftharpoons NO_2 + M$
H_2: 2, H_2O: 6, Ar: 0.625

39 $NO_2 + O \rightleftharpoons NO + O_2$
40 $NO_2 + H \rightleftharpoons NO + OH$
41 $NH + O \rightleftharpoons NO + H$
42 $NH + H \rightleftharpoons N + H_2$
43 $NH + OH \rightleftharpoons HNO + H$
44 $NH + OH \rightleftharpoons N + H_2O$
45 $NH + O_2 \rightleftharpoons HNO + O$
46 $NH + O_2 \rightleftharpoons NO + OH$
47 $NH + N \rightleftharpoons N_2 + H$
48 $NH + H_2O \rightleftharpoons HNO + H_2$
49 $NH + NO \rightleftharpoons N_2 + OH$
50 $NH + NO \rightleftharpoons N_2O + H$
51 $NH_2 + O \rightleftharpoons OH + NH$
52 $NH_2 + O \rightleftharpoons H + HNO$
53 $NH_2 + H \rightleftharpoons NH + H_2$
54 $NH_2 + OH \rightleftharpoons NH + H_2O$
55 $NNH \rightleftharpoons N_2 + H$
56 $NNH + M \rightleftharpoons N_2 + H + M$
H_2: 2, H_2O: 6, Ar: 0.7

57 $NNH + O_2 \rightleftharpoons HO_2 + N_2$
58 $NNH + O \rightleftharpoons OH + N_2$
59 $NNH + O \rightleftharpoons NH + NO$
60 $NNH + H \rightleftharpoons H_2 + N_2$
61 $NNH + OH \rightleftharpoons H_2O + N_2$
62 $H + NO + M \rightleftharpoons HNO + M$
H_2: 2, H_2O: 6, Ar: 0.625

63 $HNO + O \rightleftharpoons NO + OH$
64 $HNO + H \rightleftharpoons H_2 + NO$
65 $HNO + OH \rightleftharpoons NO + H_2O$
66 $HNO + O_2 \rightleftharpoons HO_2 + NO$
67 $NH_3 + H \rightleftharpoons NH_2 + H_2$
68 $NH_3 + OH \rightleftharpoons NH_2 + H_2O$
69 $NH_3 + O \rightleftharpoons NH_2 + OH$
70 $HO_2 + OH \rightleftharpoons H_2O + O_2$

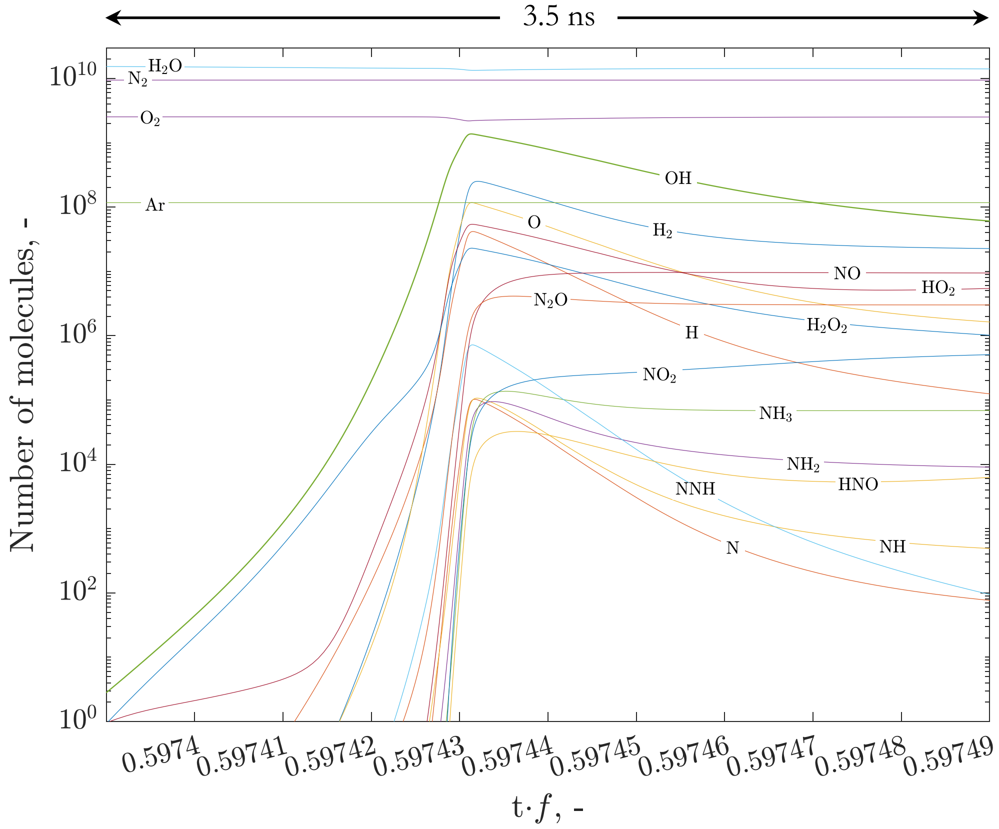
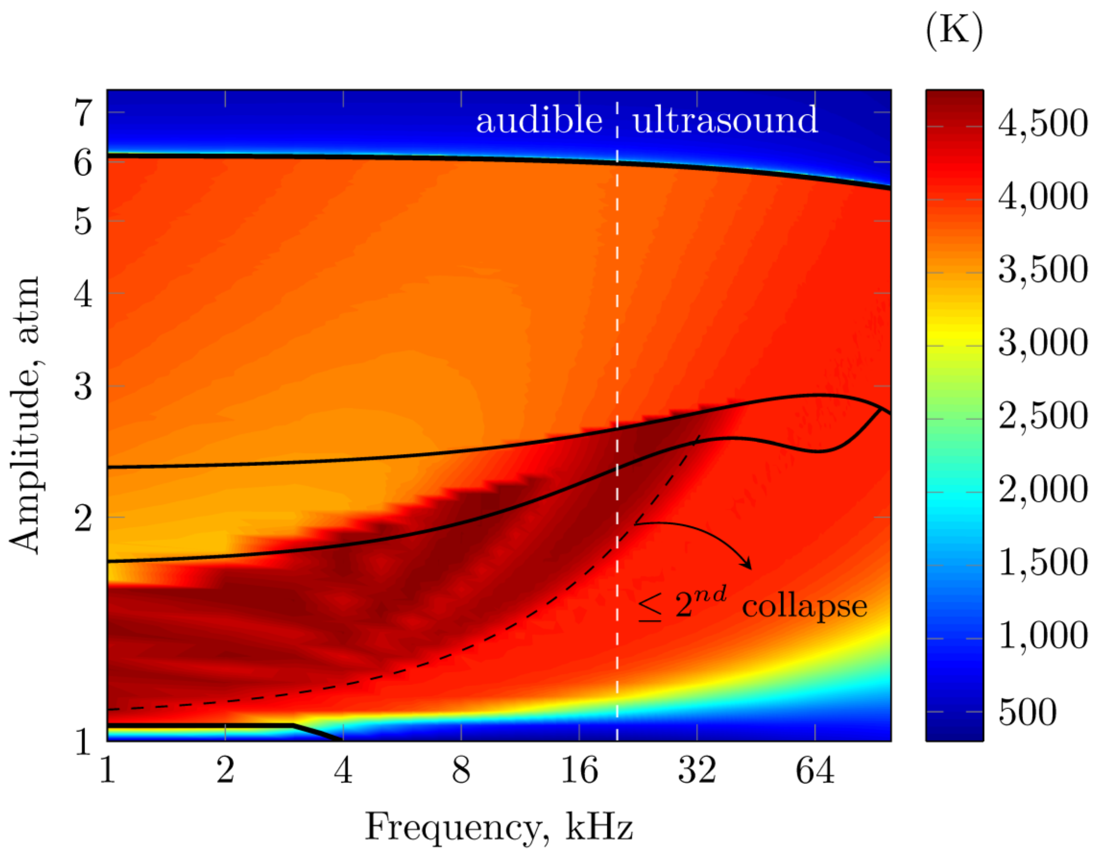
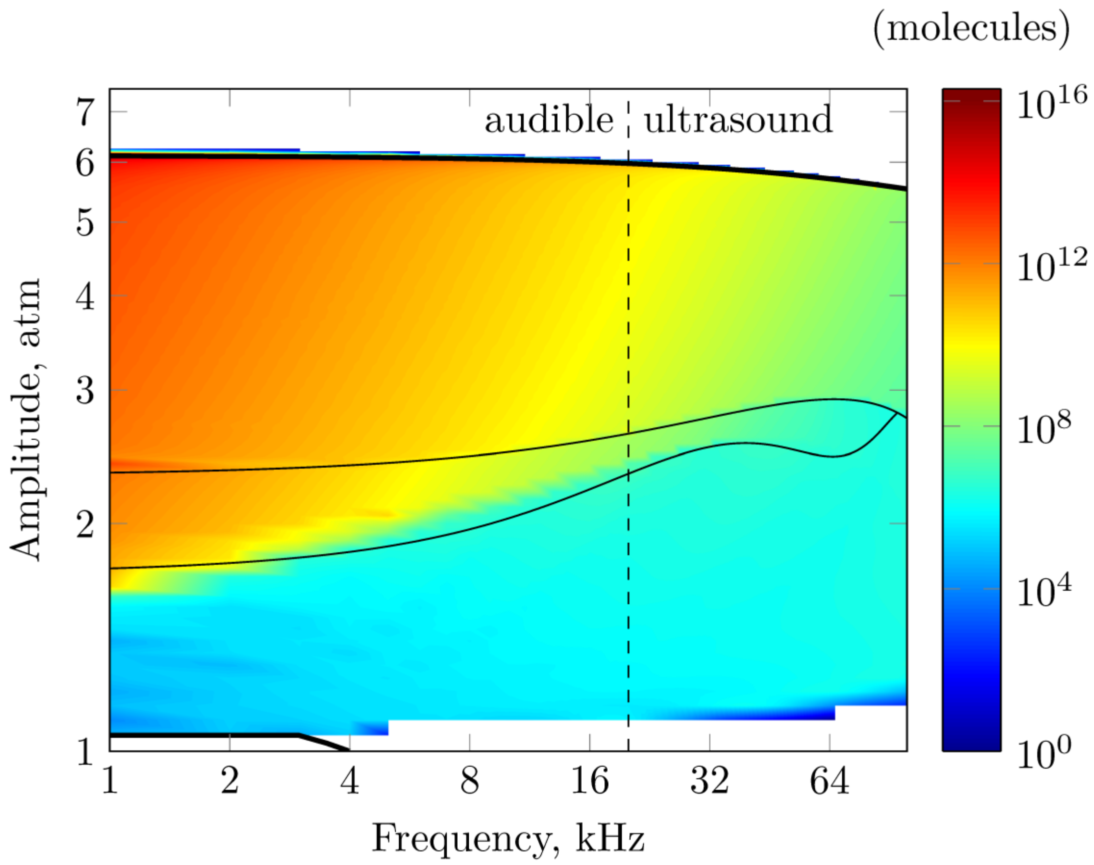


Figure 6. Simulated reaction network kinetics for a 5µm air bubble collapsing at 26 kHz and 1.4 atm.

Temperature and chemistry



A) Maximum temperature during one acoustic cycle



B) Number of OH radicals in the molecules at the end of the cycle

Figure 7. Maximum temperature and produced amount of hydroxyl radicals within one acoustic cycle in the explored parametric space.

Can we use low frequency sound in sonochemistry?

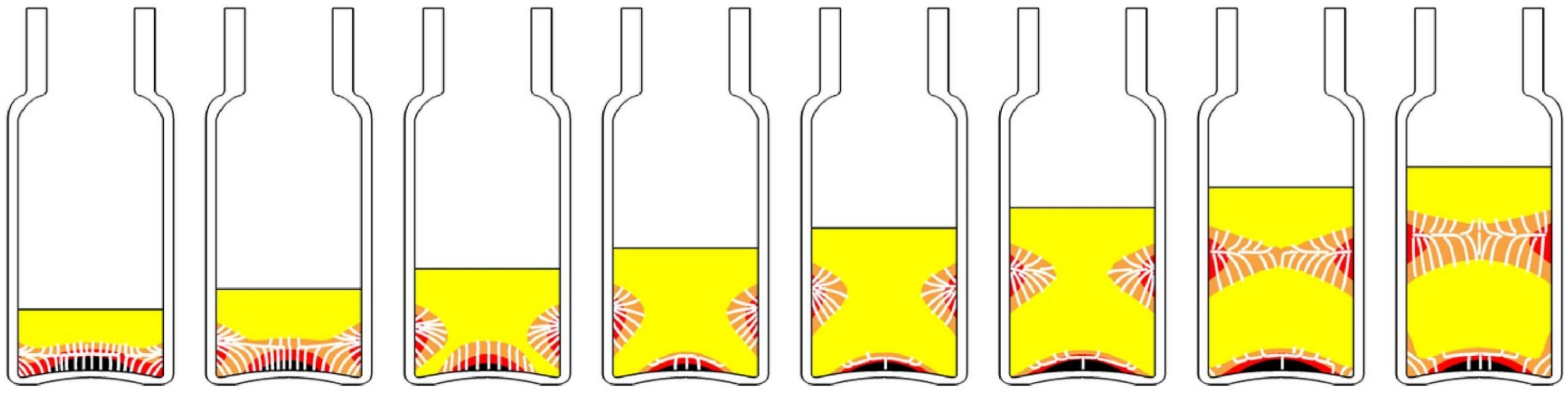
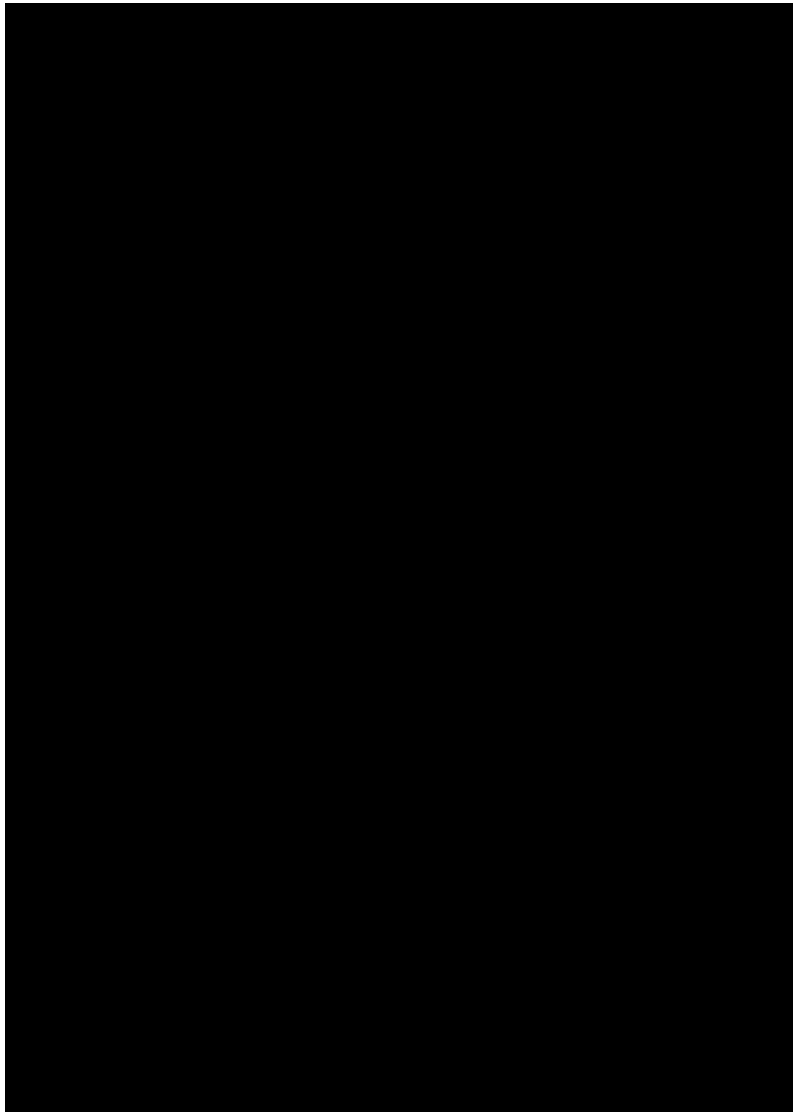


Figure 8. Change of acoustic field in bubbly water with size of propagating medium[1].

- Implementation of rectified diffusion in the model equations.
- Evaluation of Rayleigh-Taylor and parametric instabilities.

[1]Louisnard, O., et al., 2015. Prediction of the acoustic and bubble fields in insonified freeze-drying vials. Ultrasonics sonochemistry, 26, pp.186-192.

Future work



Video 1. Appearance of acoustic streamers in a 18 kHz acoustic standing wave.