キャビテーション流れのマルチスケール解析

東京大学工学系研究科
松本洋一郎

THE UNIVERSITY OF TOKYO

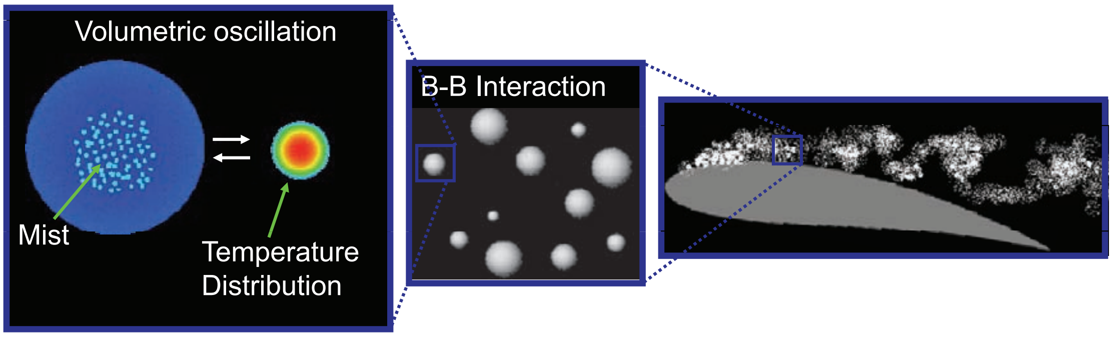
Fluids Engineering Lab. *FEL*

目次

- **はじめに**
- 単一気泡の挙動
- 気泡クラウドの挙動
- 流体機械のキャビテーションエロージョン
- おわりに

FEL

キャビテーションにおけるマルチスケールダイナミックス



Internal Phenomena of a Cavitation Bubble

Bubble Cloud

Cavitating Flow around a Hydrofoil

Micro

Mezzo

Macro

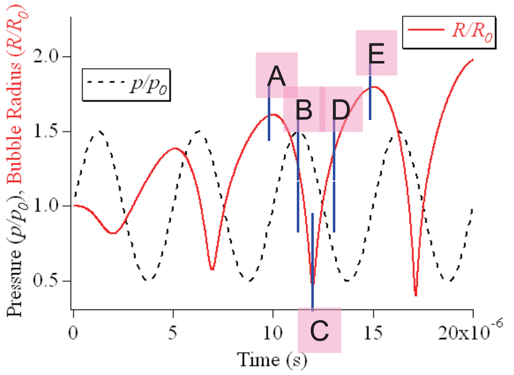
FEL

目次

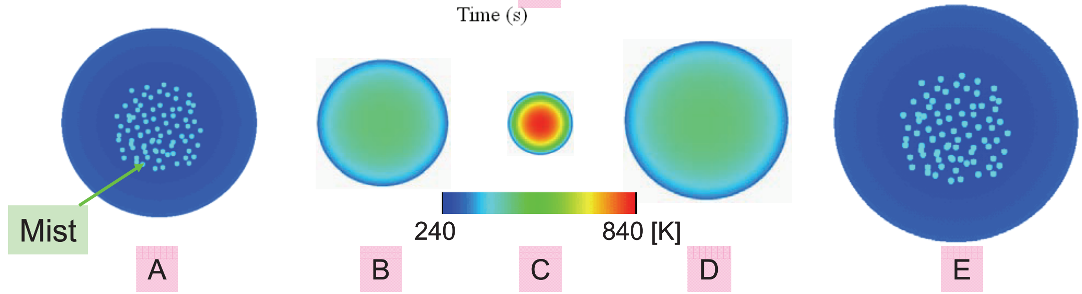
- はじめに
- **単一気泡の挙動**
- 気泡クラウドの挙動
- 流体機械のキャビテーションエロージョン
- おわりに

FEL

Time history of bubble radius



$R_0 = 13$ μm
$f_d = 0.2$ MHz
$p_0 = 100$ kPa
$\Delta p = 50$ kPa



Temperature distribution inside bubble

FEL

Assumptions

(1) Gases inside the bubble and the surrounding liquid move maintaining spherical symmetry.

(2) Gases inside the bubble obey the perfect gas law.

(3) Non-condensable gas obeys Henry’s law at the bubble wall.

(4) Classical theory for generation and growth of mist under quasi-equilibrium condition is applied, because the temperature inside the bubble does not change so rapidly .

(5) Coalescence and fragmentation of the mist are ignored.

(6) Mist has the same velocity as the gas mixture and the effect of diffusion by Brownian motion is assumed to be small and ignored.

(7) Viscosity of the liquid is ignored except at the bubble wall.

FEL

Governing equations of Direct Numerical Simulation (1)

Using simulation code developed by Takemura & Matsumoto (1994)

○ Full conservation equations in gas phase with mist
- Conservation equation of Mass
- Conservation equation of Momentum
- Conservation equation of Energy

○ Nucleation rate equation of mist by homogeneous condensation

○ Conservation equation of number density of mist

○ Energy equation in liquid phase

○ Diffusion equation of non-condensable gas in liquid

FEL

Governing equations of Direct Numerical Simulation (2)

Motion of bubble wall

○ Equation of bubble wall motion（Fujikawa & Akamatsu, 1980）

→ Considered
- Liquid compressibility (1st order approximation)
- Phase change at bubble wall

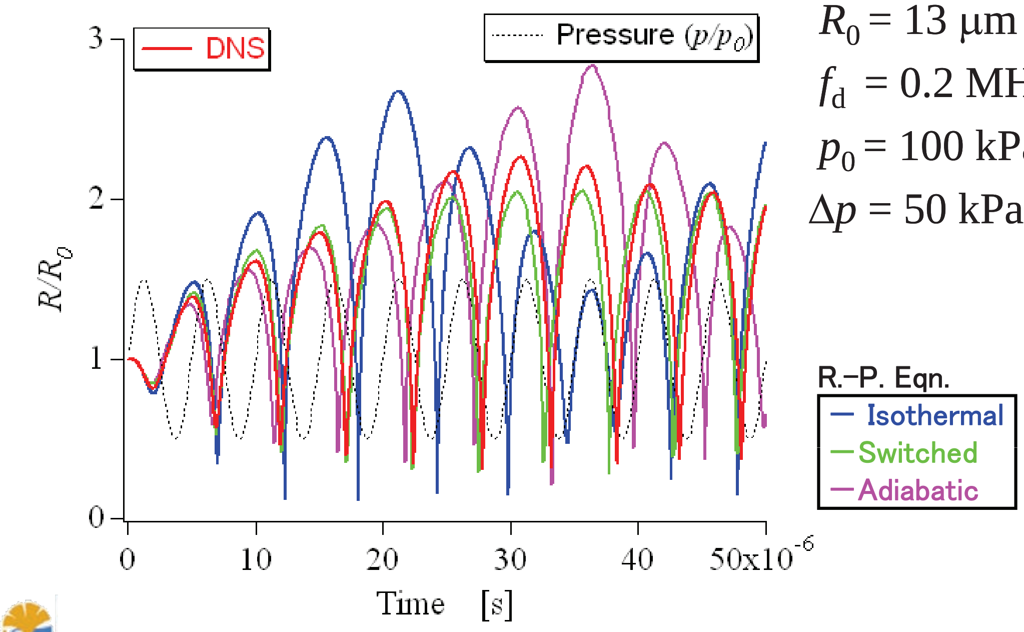
↓

$$
\begin{aligned}
&R\ddot{R}\left(1-\frac{2\dot{R}}{C_\infty}+\frac{\dot{M}}{\rho_{l\infty}C_\infty}\right)+\frac{3}{2}\dot{R}^2\left(1-\frac{4\dot{R}}{3C_\infty}+\frac{4\dot{M}}{3\rho_{l\infty}C_\infty}\right)-\frac{\ddot{M}R}{\rho_{l\infty}}\left(1-\frac{2\dot{R}}{C_\infty}+\frac{\dot{M}}{2\rho_{l\infty}}\right)\\
&-\frac{\dot{M}}{\rho_{l\infty}}\left(\dot{R}+\frac{\dot{M}}{2\rho_{l\infty}}\right)+\frac{p_{lA}-p_{lw}}{\rho_{l\infty}}-\frac{R(\dot{p}_{lw}-\dot{p}_{lA})}{\rho_{l\infty}C_\infty} = 0
\end{aligned}
$$

$$
p_{lw} = p_{mgw}-\frac{4}{3}\mu_l\left(\frac{\partial u_l}{\partial r}-\frac{u_l}{r}\right)_w-\dot{M}\left(u_{mgw}-\dot{R}\right)-\frac{2\sigma}{R}-\frac{4}{3}\mu_{mg}\left(\frac{\partial u_{mg}}{\partial r}-\frac{u_{mg}}{r}\right)_w
$$

FEL

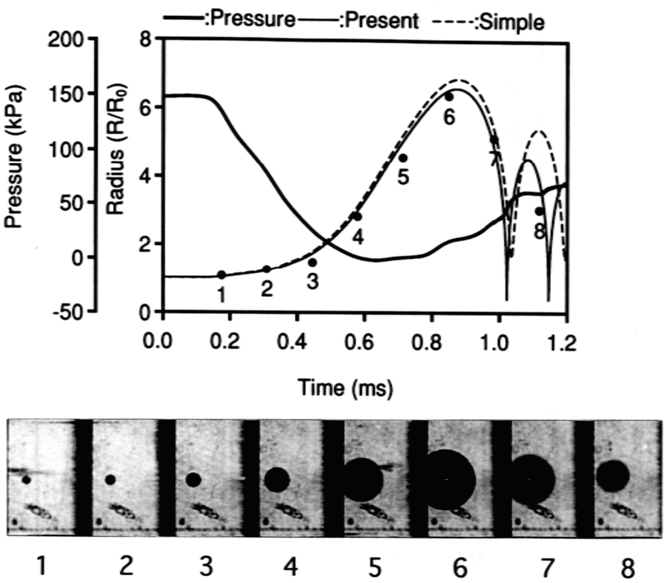
Time history of bubble radius



$R_0 = 13$ μm
$f_d = 0.2$ MHz
$p_0 = 100$ kPa
$\Delta p = 50$ kPa

FEL

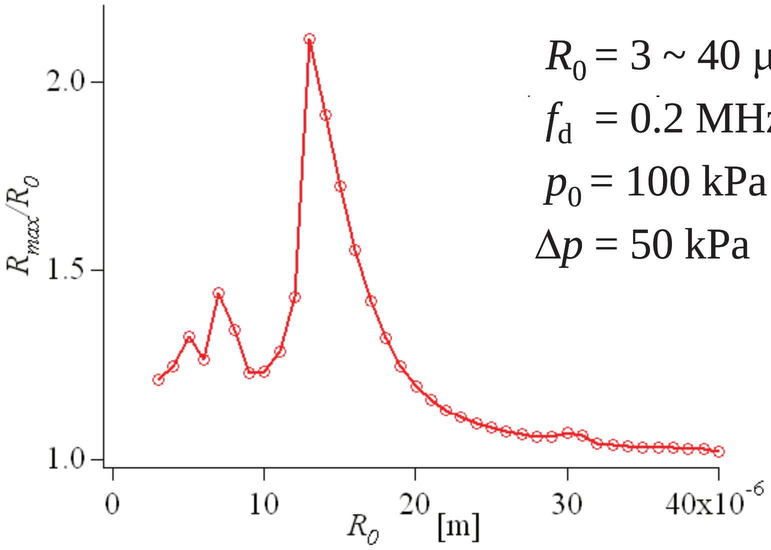
Bubble motion



Comparison between simulation and experiment

FEL

Maximum bubble radius

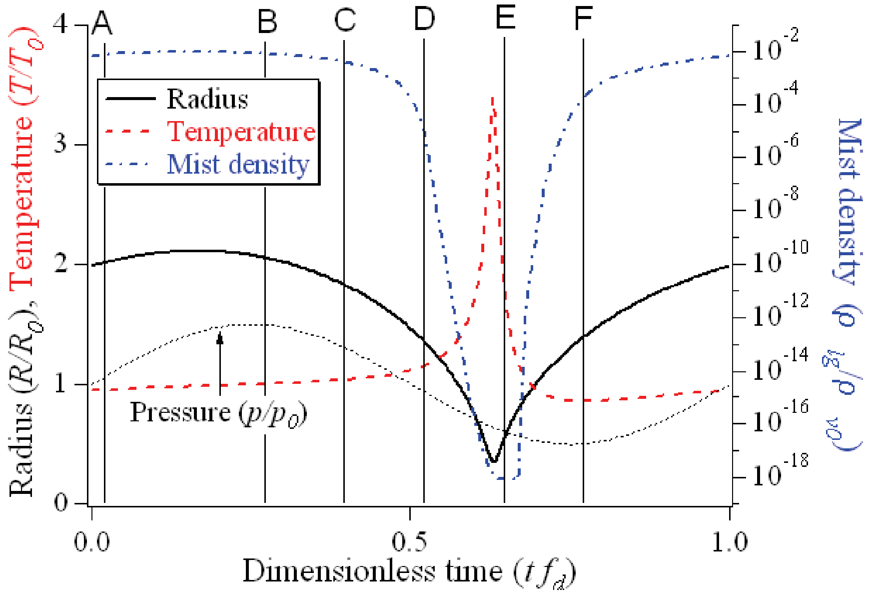


R_0 = 3 ~ 40 μm
f_d = 0.2 MHz
p_0 = 100 kPa
Δp = 50 kPa

FEL

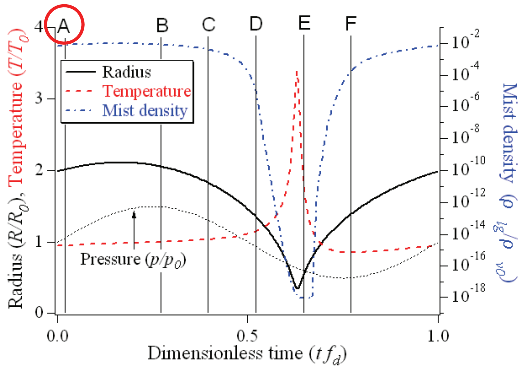
Time histories of bubble radius, temperature and mist density inside bubble

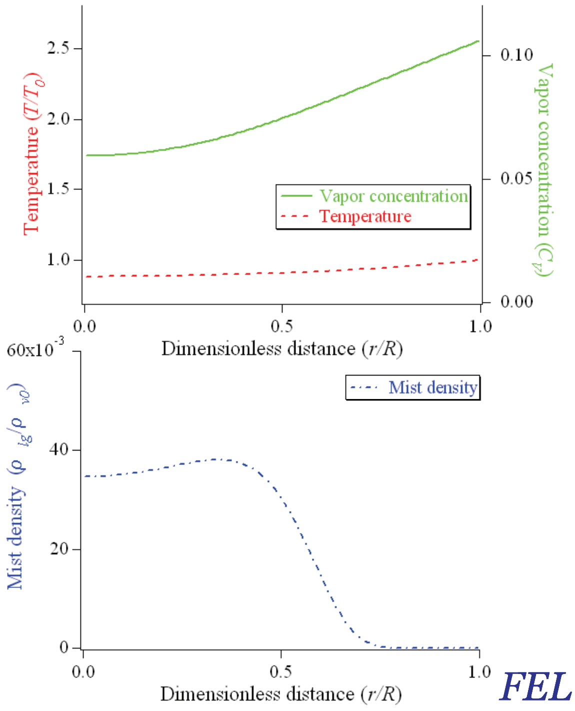
R_0 = 13 μm, f_d = 0.2 MHz, p_0 = 100 kPa, Δp = 50 kPa



FEL

Distributions of temperature, vapor concentration and mist density





A

$R_0 = 13\ \mu\mathrm{m}$

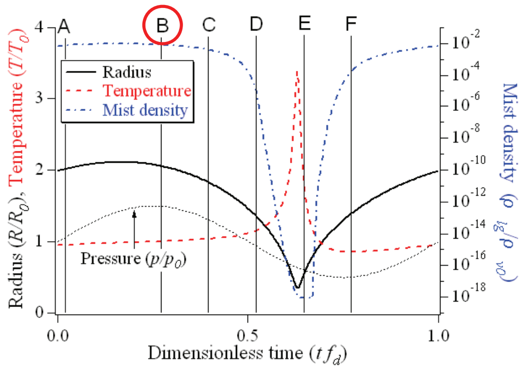
$f_\mathrm{d} = 0.2\ \mathrm{MHz}$

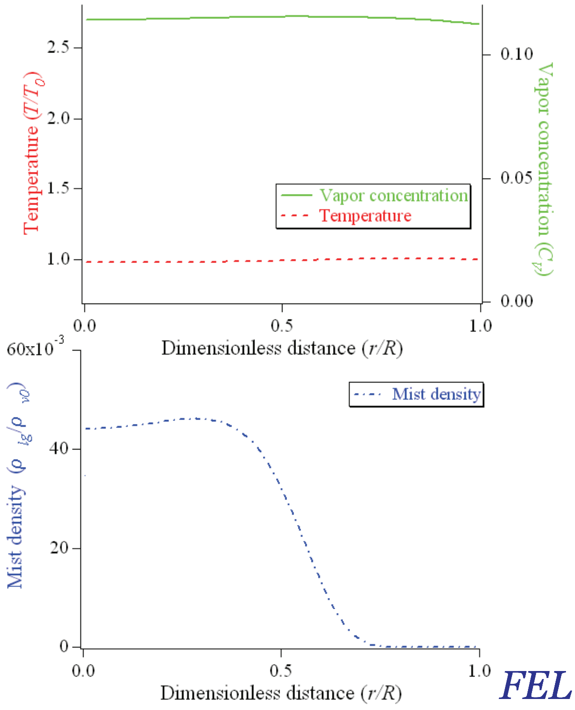
$p_0 = 100\ \mathrm{kPa}$

$\Delta p = 50\ \mathrm{kPa}$

FEL

Distributions of temperature, vapor concentration and mist density





B

$R_0 = 13\ \mu\mathrm{m}$

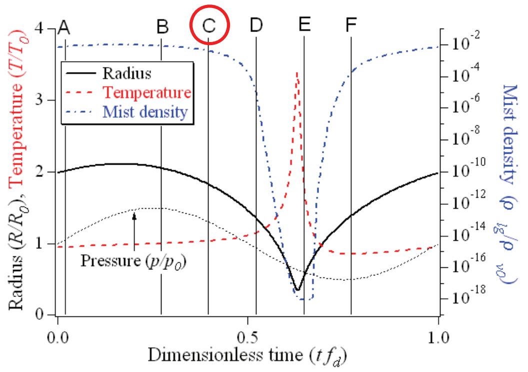
$f_\mathrm{d} = 0.2\ \mathrm{MHz}$

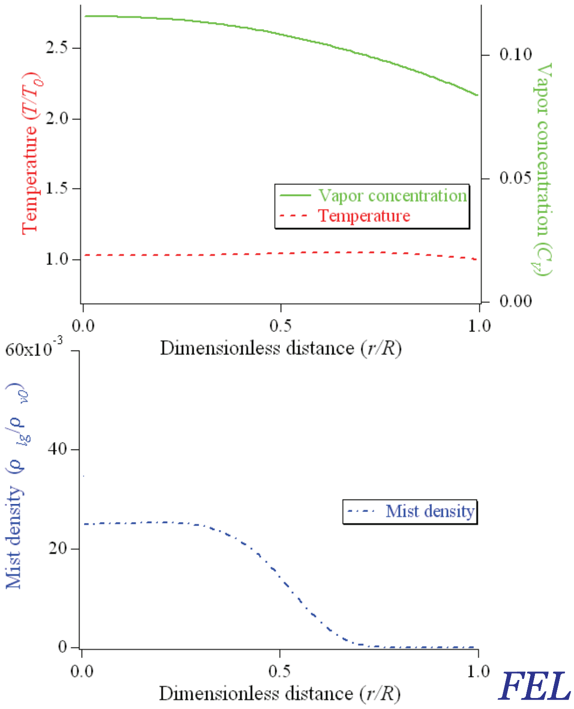
$p_0 = 100\ \mathrm{kPa}$

$\Delta p = 50\ \mathrm{kPa}$

FEL

Distributions of temperature, vapor concentration and mist density





C

$R_0 = 13\ \mu\mathrm{m}$

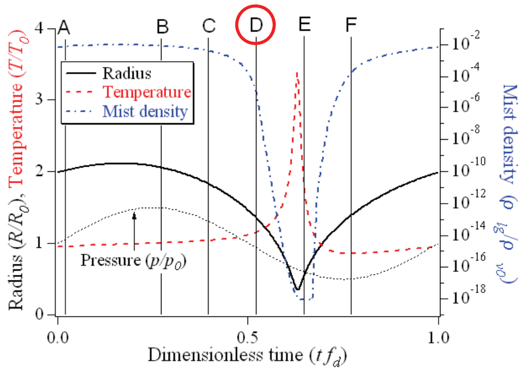
$f_\mathrm{d} = 0.2\ \mathrm{MHz}$

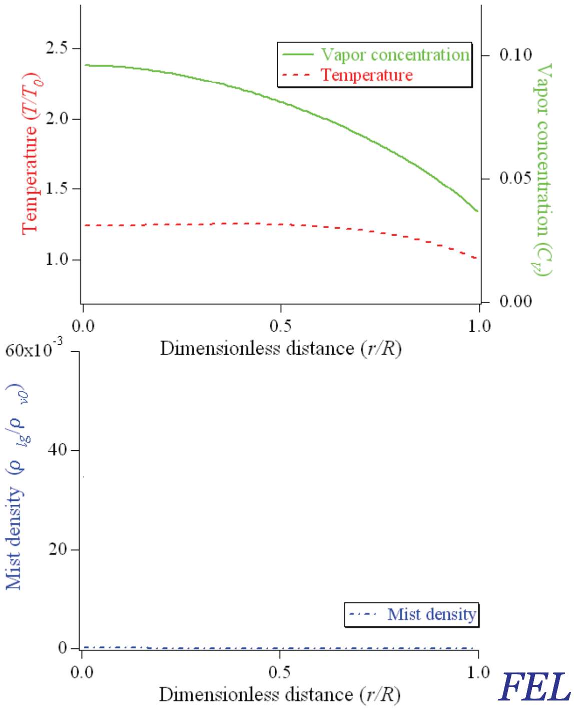
$p_0 = 100\ \mathrm{kPa}$

$\Delta p = 50\ \mathrm{kPa}$

FEL

Distributions of temperature, vapor concentration and mist density





D

$R_0 = 13\ \mu\mathrm{m}$

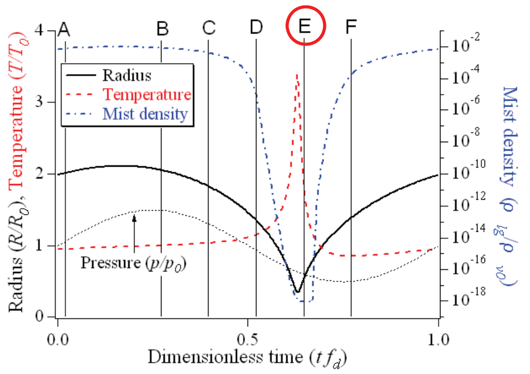
$f_\mathrm{d} = 0.2\ \mathrm{MHz}$

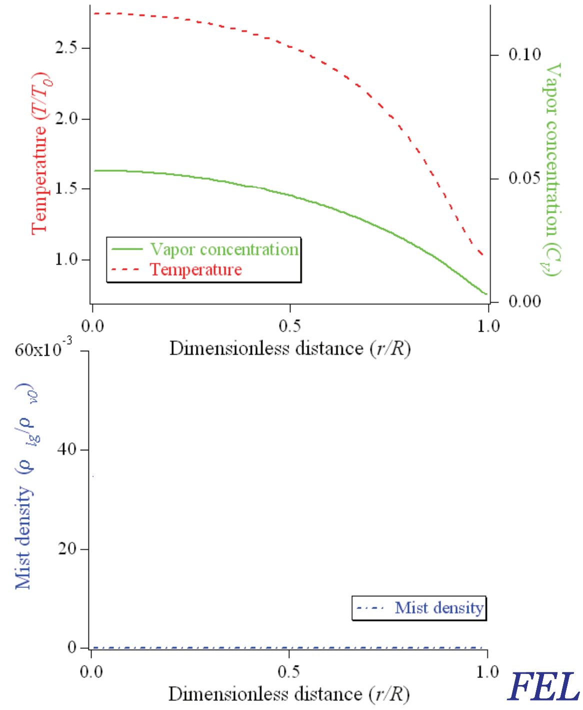
$p_0 = 100\ \mathrm{kPa}$

$\Delta p = 50\ \mathrm{kPa}$

FEL

Distributions of temperature, vapor concentration and mist density





E

R_0 = 13 μm

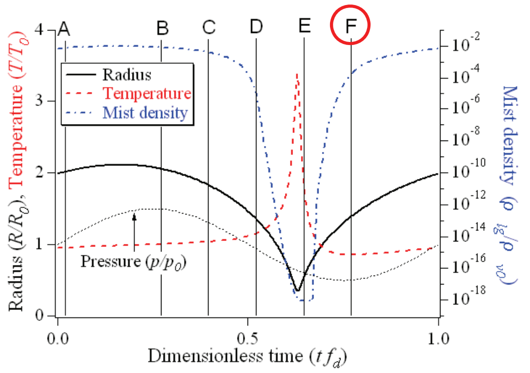
f_d = 0.2 MHz

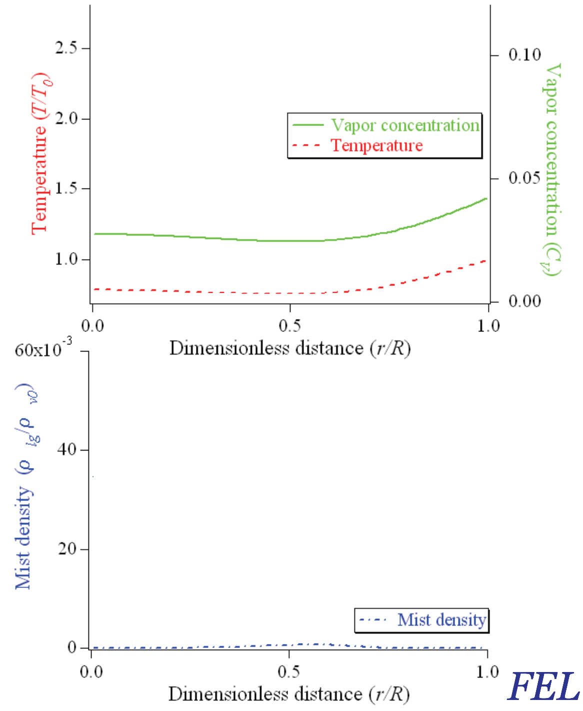
p_0 = 100 kPa

Δp = 50 kPa

FEL

Distributions of temperature, vapor concentration and mist density





F

R_0 = 13 μm

f_d = 0.2 MHz

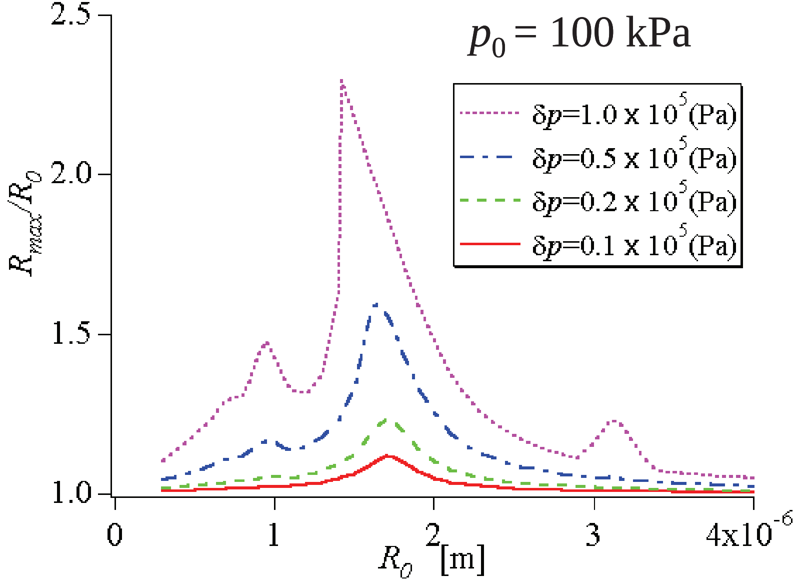
p_0 = 100 kPa

Δp = 50 kPa

FEL

Maximum bubble radius

$R_0 = 0.3 \sim 4\ \mu\text{m}$
$f_d = 2\ \text{MHz}$
$p_0 = 100\ \text{kPa}$



FEL

Spherical bubble model

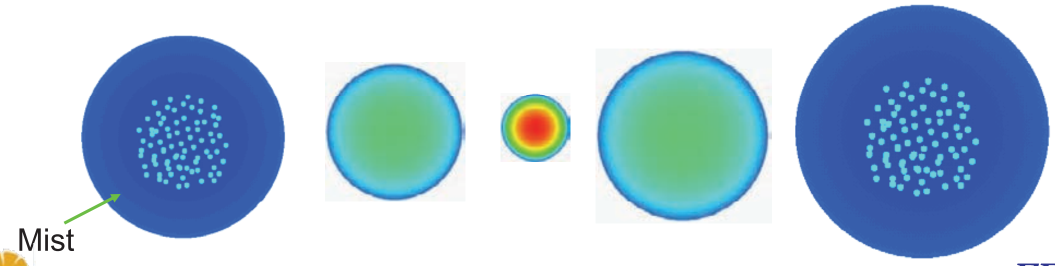
Internal thermal phenomena are considered

- Mass and heat transfer through the bubble wall
- Phase change at the bubble wall
- Counter diffusion of vapor and non-condensable gas
- Mist condensation and evaporation

Matsumoto, *Trans. of JSME*, 1986.

- Temperature gradient model at the bubble wall

Preston et al., *CAV2003*, 2003.



FEL

Governing equations

The motion of the bubble wall (Fujikawa & Akamatsu equation)

$$R\ddot{R}\left(1-2\frac{\dot{R}}{c}+\frac{\dot{m}}{\rho_l c}\right)+\frac{3}{2}\dot{R}^2\left(1+\frac{4}{3}\frac{\dot{m}}{\rho_l c}-\frac{4}{3}\frac{\dot{R}}{c}\right)$$

$$-\frac{\ddot{m}R}{\rho_l}\left(1-2\frac{\dot{R}}{c}+\frac{\dot{m}}{\rho_l c}\right)-\frac{\dot{m}}{\rho_l}\left(\dot{R}+\frac{\dot{m}}{2\rho_l}\right)+\frac{p_\infty - p_{l,r=R}}{\rho_l}-\frac{R\dot{p}_{l,r=R}}{\rho_l c}=0$$

$$p_{l,r=R}=p_v+p_g-\frac{\dot{m}^2\left(\rho_{vi}+\rho_{gi}-\rho_l\right)}{\rho_l\left(\rho_{vi}+\rho_{gi}\right)}-2\frac{\sigma}{R_b}-4\frac{\mu_l}{R}\left(\dot{R}-\frac{\dot{m}}{\rho_l}\right)$$

The energy conservation equation in gas phase with mist

$$\left(C_{vg}M_g+C_{vv}M_v+C_{vl}M_c\right)\frac{d\overline{T}}{dt}-\frac{p_gM_g}{{\rho_g}^2}\frac{d\rho_g}{dt}-\frac{p_vM_v}{{\rho_v}^2}\frac{d\rho_v}{dt}$$

$$-L\frac{dM_c}{dt}-S\lambda\left.\frac{\partial T}{\partial r}\right|_{r=R}+\Delta h_g\frac{dM_g}{dt}+\Delta h_v\left(\frac{dM_v}{dt}+\frac{dM_c}{dt}\right)+\Delta h_l\frac{dM_c}{dt}=0$$

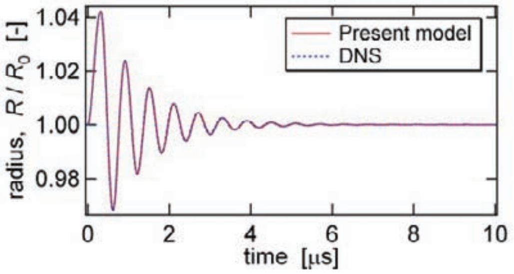
The energy conservation equation in liquid phase
The diffusion equation of non-condensable gas in liquid
The nucleation rate equation of mist

FEL

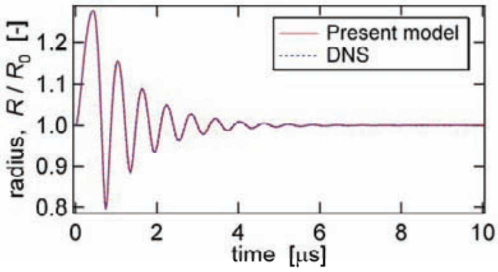
Present model vs. DNS

Internal gas: nitrogen
Initial bubble radius: 2 μm
Initial pressure: 100 kPa
Initial temperature: 293 K

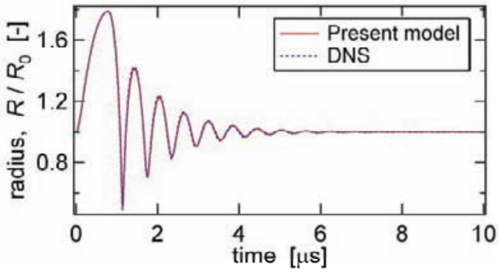
DNS: Takemura and Matsumoto, *JSME Int. J.*, 1994.



100 kPa → 90 kPa → 100 kPa



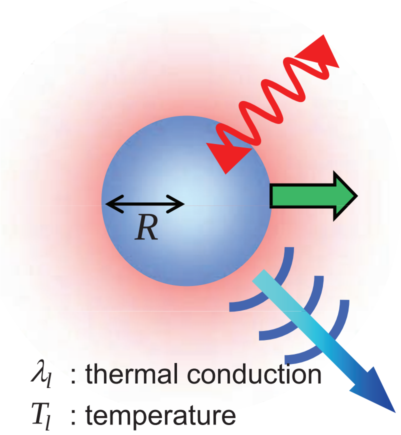
100 kPa → 50 kPa → 100 kPa



100 kPa → 10 kPa → 100 kPa

FEL

Heating Mechanism of Microbubbles



Energy affecting the heat near the bubble

Heat deposition

$$W_T = -\lambda_l \frac{\partial T_l}{\partial r} \cdot 4\pi R^2$$

Viscous dissipation

$$W_V = 4\mu_l \frac{\dot{R}}{R} \cdot \dot{R} \cdot 4\pi R^2$$

Acoustic emission

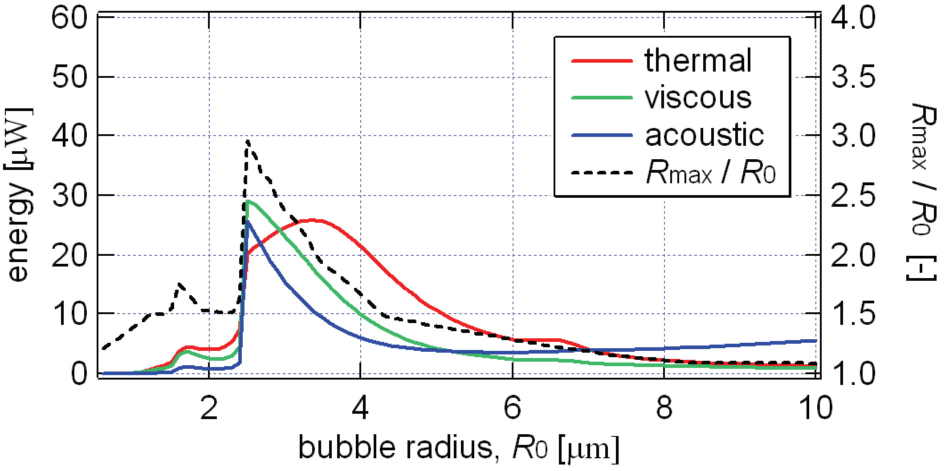
$$W_A = \rho_l \frac{\left(R\ddot{R} + 2\dot{R}^2\right)^2}{c_l} \cdot 4\pi R^2$$

Energy escaping to large distances

λ_l : thermal conduction
T_l : temperature
μ_l : viscosity
ρ_l : density
c_l : sound speed

FEL

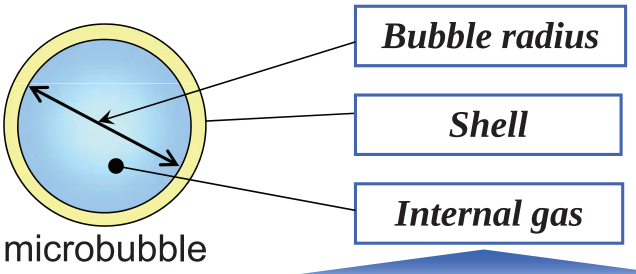
Energy Radiation



Frequency : 1.0 MHz
Amplitude : 100 kPa
Initial radius : 1 - 10 μm
Internal gas : air

FEL

Properties of Microbubbles



Bubble radius （～ 10μm）

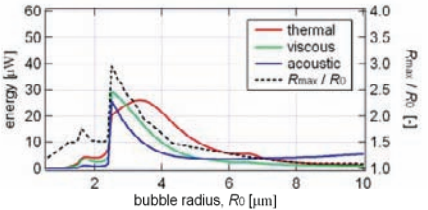
Shell （material, thickness …）

Internal gas

	Specific heat ratio [-]	Gas constant [J / kg･K]	Heat conductivity [mW /m･K]
Argon (Ar)	1.67	208.1	18.2
air	1.40	287.0	26.9
Sulfur Hexafluoride (SF_6)	1.09	56.9	14.8

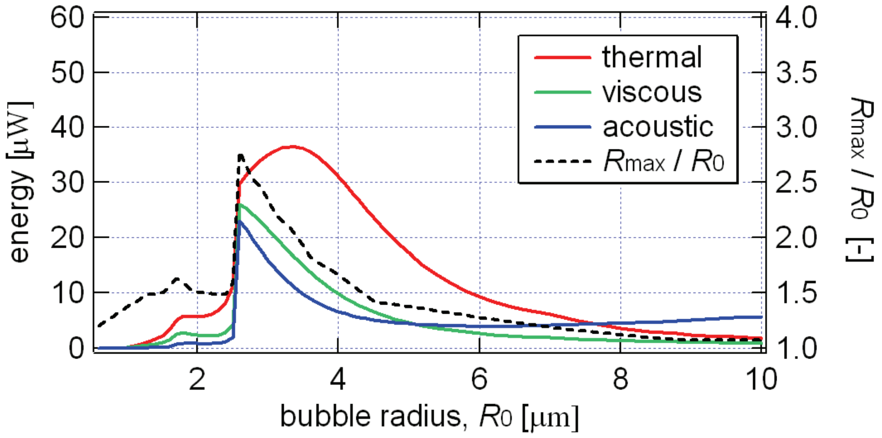
FEL

Ar bubble



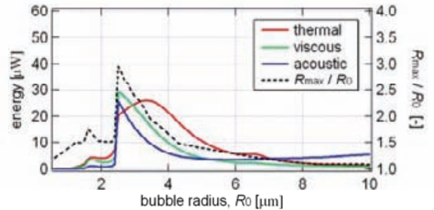
(Air bubble)

Frequency　: 1.0 MHz
Amplitude　: 100 kPa
Initial radius : 1 - 10 μm
Internal gas　:　Ar



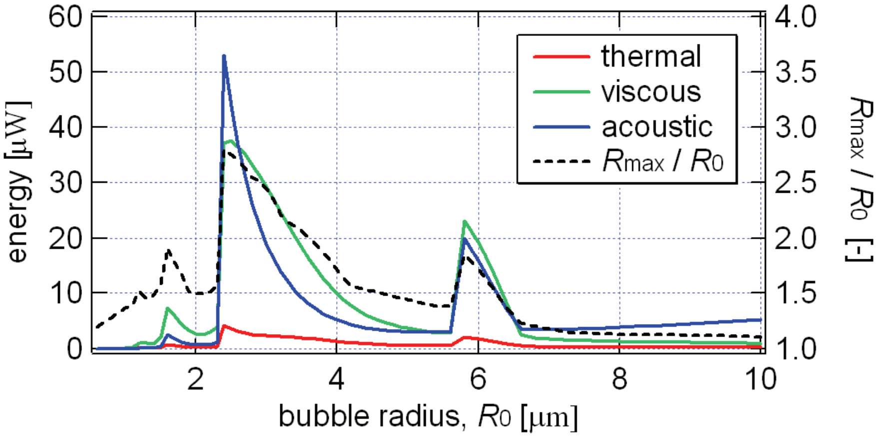
FEL

SF6 Bubble



(Air bubble)

Frequency　: 1.0 MHz
Amplitude　: 100 kPa
Initial radius : 1 - 10 μm
Internal gas　:　Ar



FEL

Acoustic emission from a microbubble

Acoustic velocity of water

$$c_\infty = \sqrt{\frac{n(p_L + B)}{\rho_L}} \quad = 1.478 \times 10^3 (\mathrm{m/s})$$

$$n = 7.15,\ B = 3.049 \times 10^8 (\mathrm{Pa})$$

Emitted acoustic pressure from micro bubble in far field

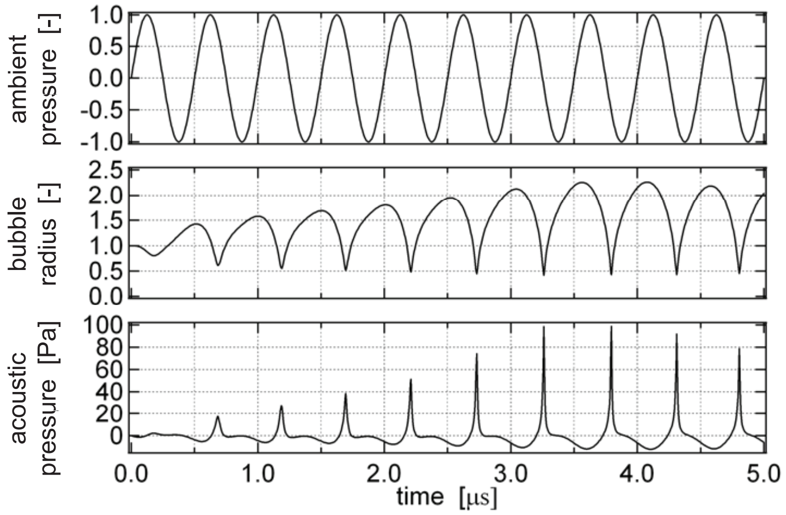
（Fujikawa, 1979）

$$\begin{aligned} p_a = \frac{\rho_L}{r} \Big[& 2R\dot{R}^2 + R^2\ddot{R} \\ & - \frac{1}{c_\infty}\left(R^3\dddot{R} + 6R^2\ddot{R}\dot{R} + 2R\dot{R}^3\right)\Big] + o(c_\infty^{-1}) \end{aligned}$$

FEL

Nonlinear oscillation of a microbubble

R_0 = 1.5 μm, p_0 = 101.3 kPa, f_0 = 2 MHz, Δp = 100 kPa

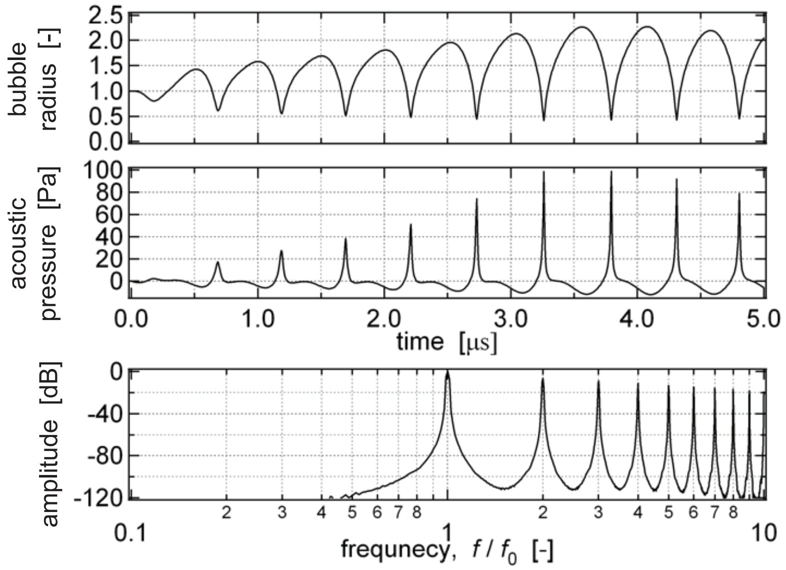


Time history of ambient pressure, bubble radius
and acoustic pressure from the bubble

FEL

Nonlinear oscillation of a microbubble

R_0 = 1.5 μm, p_0 = 101.3 kPa, f_0 = 2 MHz, Δp = 100 kPa



Time history of bubble radius and acoustic
pressure, and spectrum of the acoustic pressure

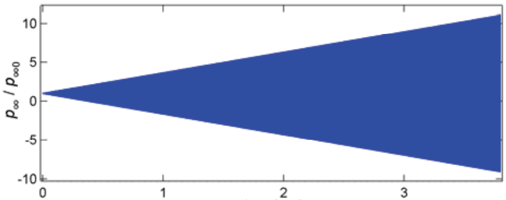
FEL

Calculation Conditions

Initial Bubble Radius, R_{b0}	2.0 [μm]
Initial Ambient Pressure, $p_{\infty 0}$	101.3 [kPa]
Initial Temperature	293 [K]
Waveform of Ambient Pressure	sinus
Ultrasound Frequency, f_0	1.34 [MHz]
Amplitude of Ambient Pressure	0 [kPa] ~ 1 [MPa]

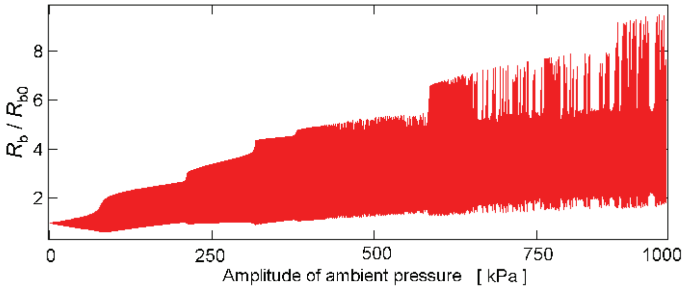
Formula of ambient ultrasound pressure

$$p_\infty = \frac{f_0 t}{500} A\sin(2\pi f_0 t) \times 10^5 + p_{\infty 0}$$

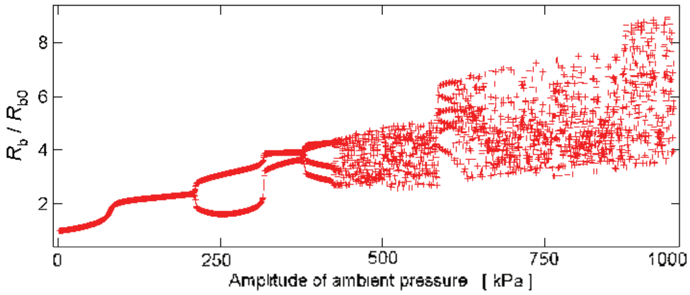


FEL

Bubble Radius



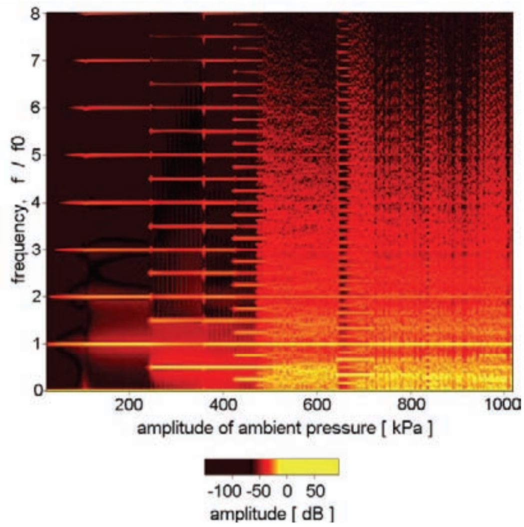
Time history of bubble radius



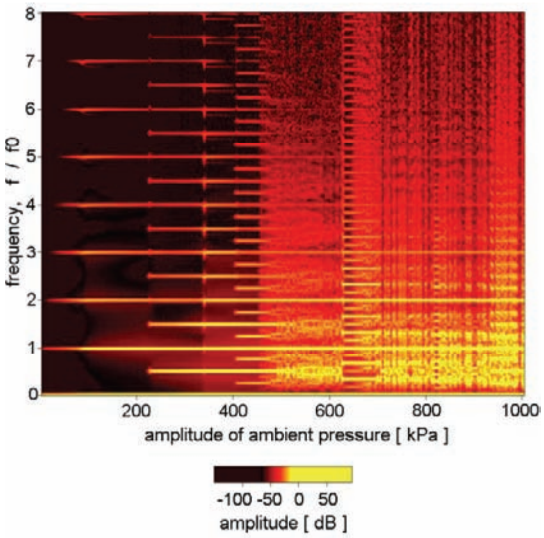
Bifurcation diagram of bubble radius

FEL

Acoustic Turbulence



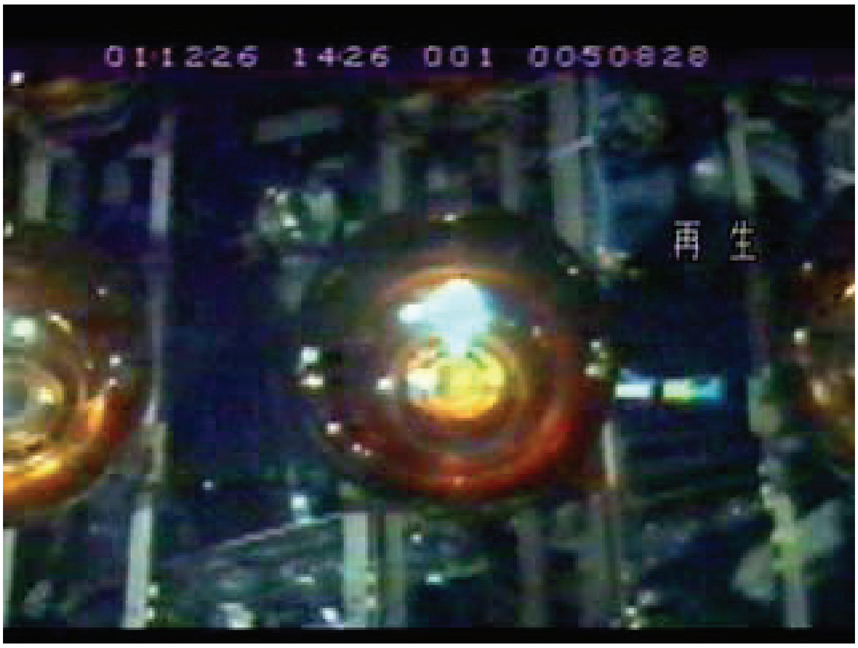
Power spectrum of bubble radius



Power spectrum of acoustic pressure

FEL

Experiment of PMs in Water (Depth = 30 m)



FEL

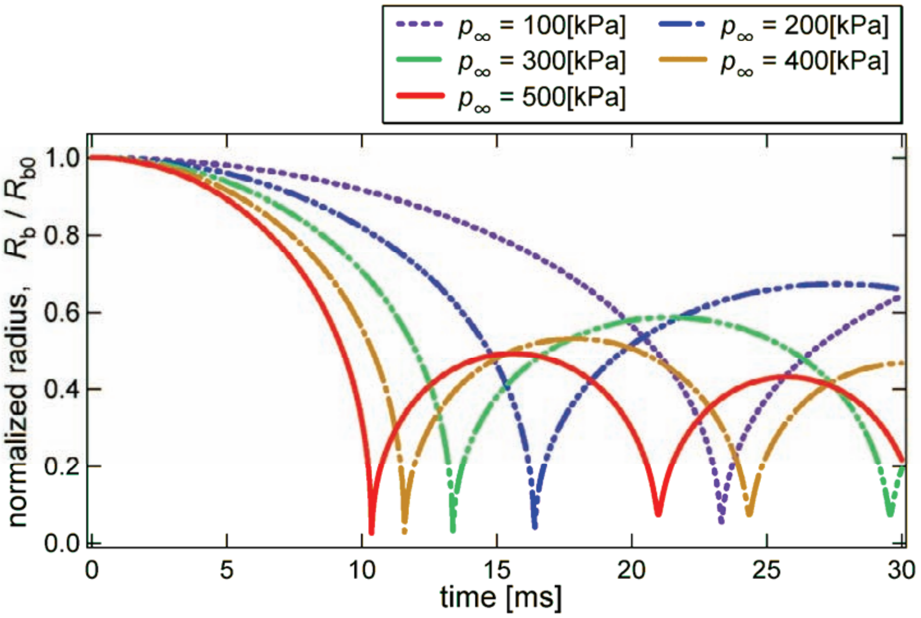
Simulation Model

- Assumption

(1) Gases inside the bubble and the surrounding liquid move maintaining spherical symmetry.
(2) Pressure and temperature inside the bubble are uniform except the thin boundary layer near the bubble wall.
(3) Non-condensable gas obeys Henry's law at the bubble wall.
(4) Viscosity of the liquid is ignored except at the bubble wall.

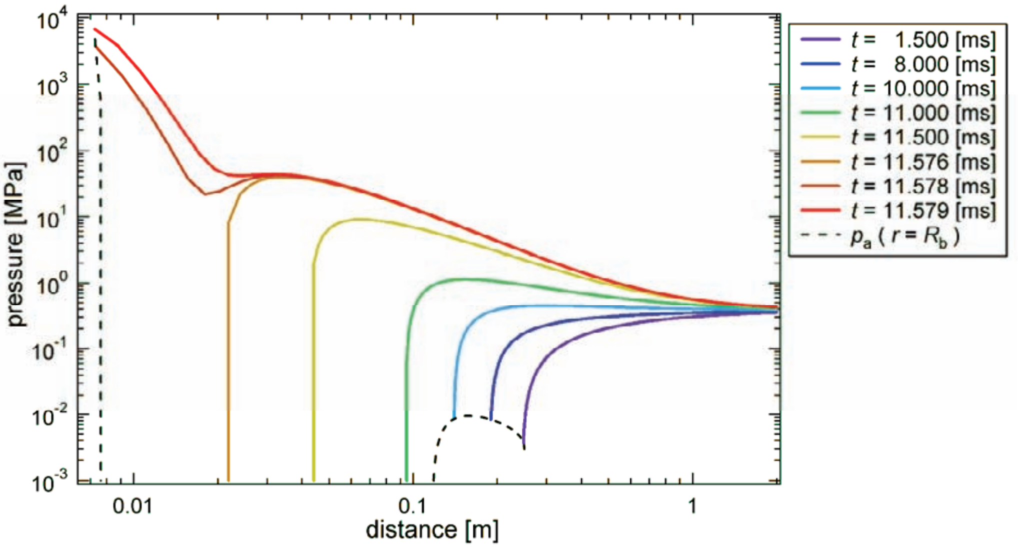
FEL

Time History of Bubble Radius



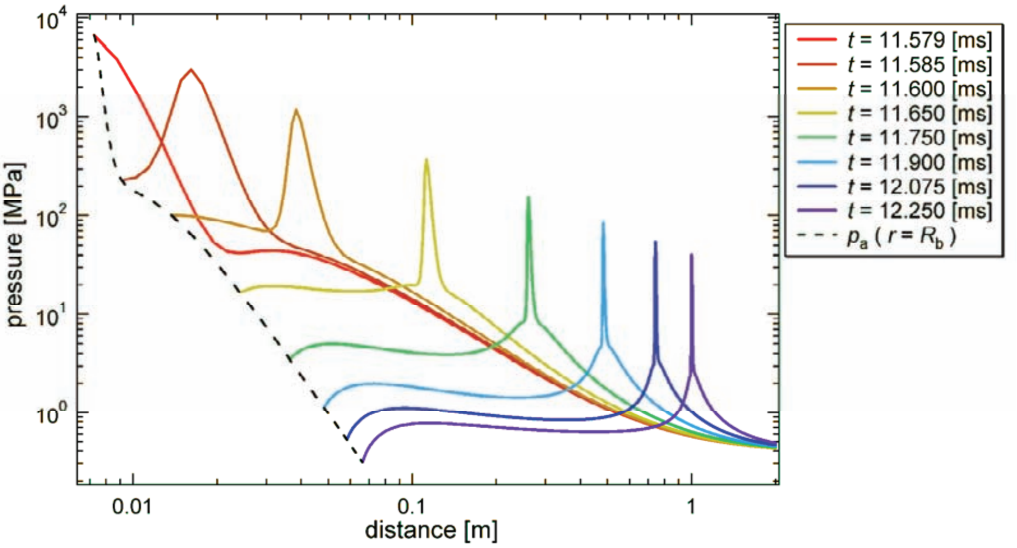
FEL

Time History of Pressure Distribution (p∞=400kPa)



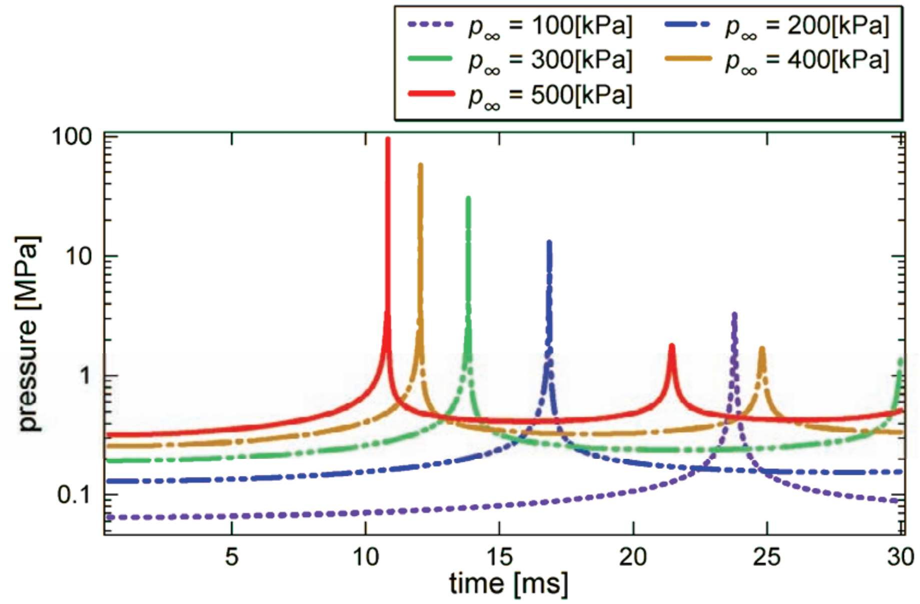
FEL

Time History of Pressure Distribution (p∞=400kPa)



FEL

Time History of Emitted Pressure at 0.7 m



FEL

Bubble Collapse and Shock Wave Formation

FEL

目次

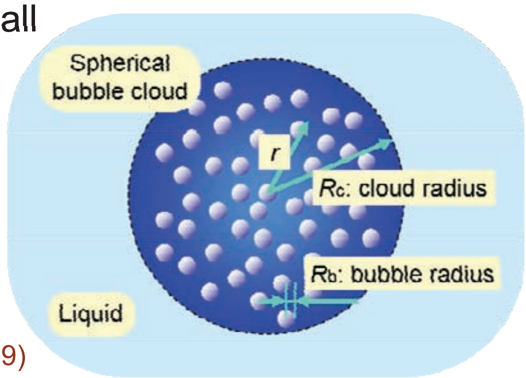
- はじめに
- 単一気泡の挙動
- **気泡クラウドの挙動**
- 流体機械のキャビテーションエロージョン
- おわりに

FEL

Model of a bubble cloud

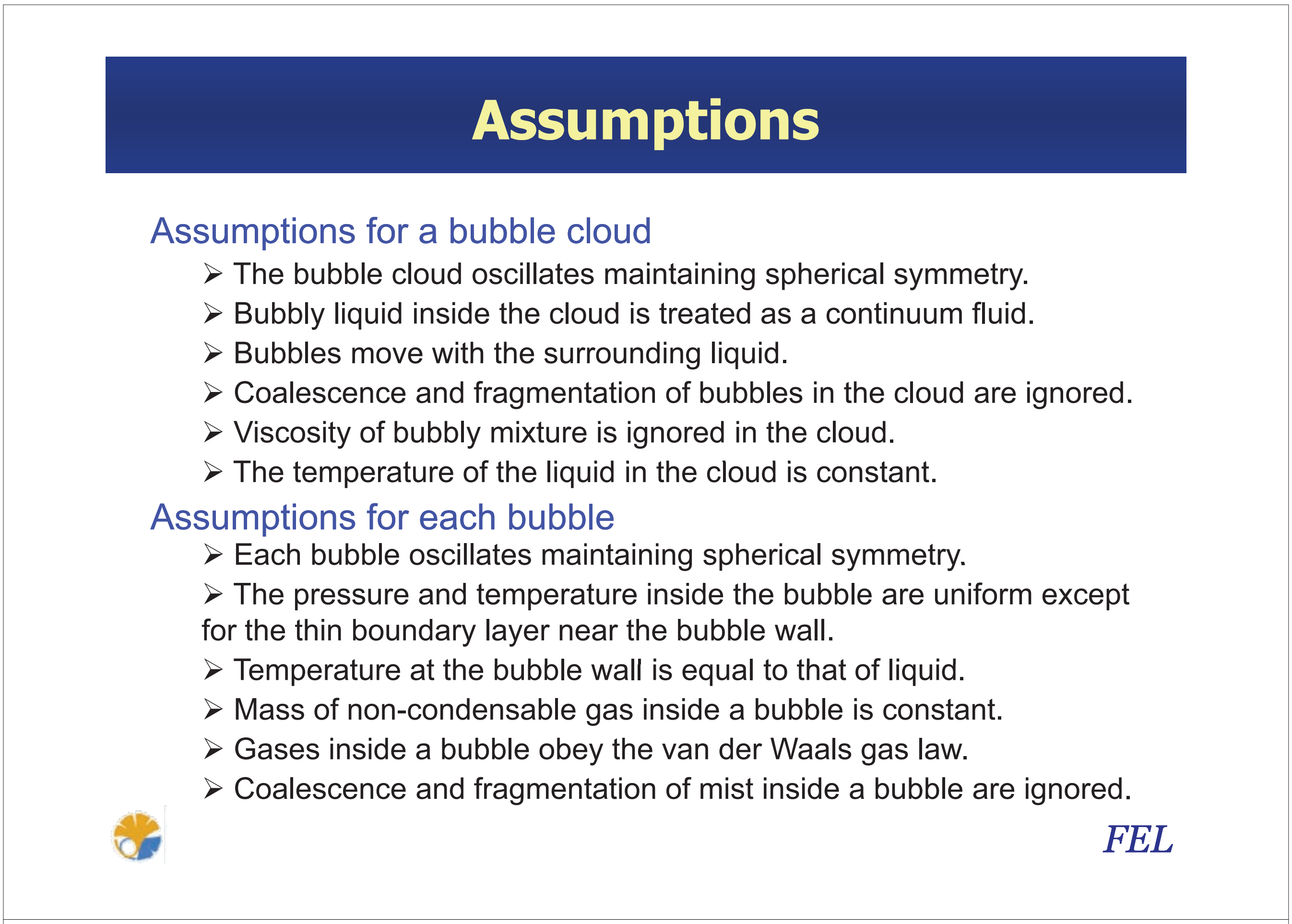
The following phenomena are considered.

- ➢ Compressibility of the liquid
- ➢ Evaporation and condensation of the liquid at the bubble wall
- ➢ Evaporation and condensation of the mist inside the bubble
- ➢ Heat transfer through the bubble wall



Shimada, Kobayashi and Matsumoto (1999)

FEL



Assumptions

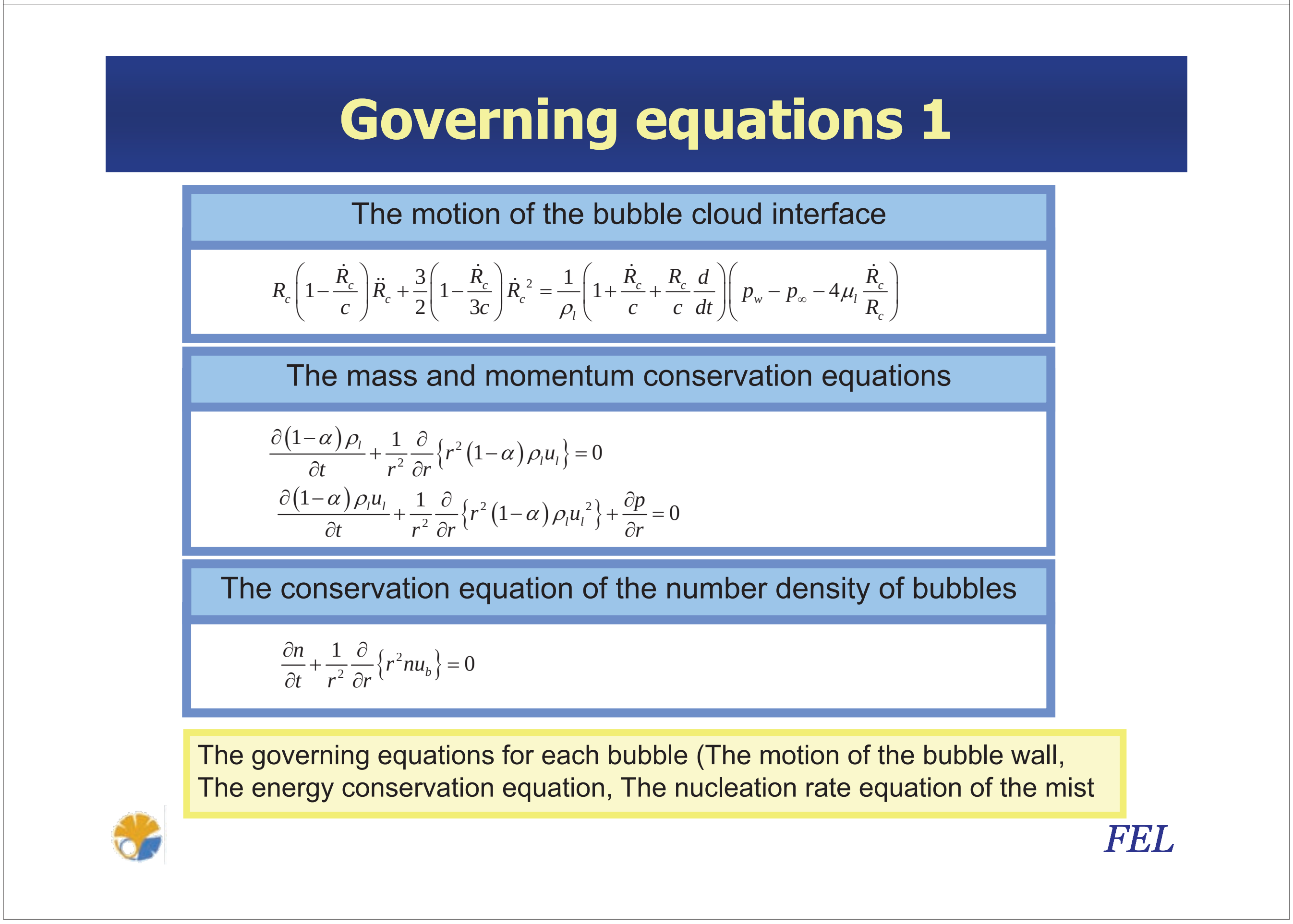
Assumptions for a bubble cloud

- The bubble cloud oscillates maintaining spherical symmetry.
- Bubbly liquid inside the cloud is treated as a continuum fluid.
- Bubbles move with the surrounding liquid.
- Coalescence and fragmentation of bubbles in the cloud are ignored.
- Viscosity of bubbly mixture is ignored in the cloud.
- The temperature of the liquid in the cloud is constant.

Assumptions for each bubble

- Each bubble oscillates maintaining spherical symmetry.
- The pressure and temperature inside the bubble are uniform except for the thin boundary layer near the bubble wall.
- Temperature at the bubble wall is equal to that of liquid.
- Mass of non-condensable gas inside a bubble is constant.
- Gases inside a bubble obey the van der Waals gas law.
- Coalescence and fragmentation of mist inside a bubble are ignored.

FEL



Governing equations 1

The motion of the bubble cloud interface

$$R_c\left(1-\frac{\dot{R}_c}{c}\right)\ddot{R}_c+\frac{3}{2}\left(1-\frac{\dot{R}_c}{3c}\right)\dot{R}_c^{\,2}=\frac{1}{\rho_l}\left(1+\frac{\dot{R}_c}{c}+\frac{R_c}{c}\frac{d}{dt}\right)\left(p_w-p_\infty-4\mu_l\frac{\dot{R}_c}{R_c}\right)$$

The mass and momentum conservation equations

$$\frac{\partial(1-\alpha)\rho_l}{\partial t}+\frac{1}{r^2}\frac{\partial}{\partial r}\left\{r^2(1-\alpha)\rho_l u_l\right\}=0$$

$$\frac{\partial(1-\alpha)\rho_l u_l}{\partial t}+\frac{1}{r^2}\frac{\partial}{\partial r}\left\{r^2(1-\alpha)\rho_l u_l^{\,2}\right\}+\frac{\partial p}{\partial r}=0$$

The conservation equation of the number density of bubbles

$$\frac{\partial n}{\partial t}+\frac{1}{r^2}\frac{\partial}{\partial r}\left\{r^2 n u_b\right\}=0$$

The governing equations for each bubble (The motion of the bubble wall, The energy conservation equation, The nucleation rate equation of the mist

FEL

Governing equations 2

The motion of the bubble wall (Fujikawa & Akamatsu equation)

$$R\ddot{R}\left(1-2\frac{\dot{R}}{c}+\frac{\dot{m}}{\rho_l c}\right)+\frac{3}{2}\dot{R}^2\left(1+\frac{4}{3}\frac{\dot{m}}{\rho_l c}-\frac{4}{3}\frac{\dot{R}}{c}\right)$$

$$-\frac{\ddot{m}R}{\rho_l}\left(1-2\frac{\dot{R}}{c}+\frac{\dot{m}}{\rho_l c}\right)-\frac{\dot{m}}{\rho_l}\left(\dot{R}+\frac{\dot{m}}{2\rho_l}\right)+\frac{p_\infty - p_{l,r=R}}{\rho_l}-\frac{R\dot{p}_{l,r=R}}{\rho_l c}=0$$

$$p_{l,r=R} = p_v + p_g - \frac{\dot{m}^2\left(\rho_{vi}+\rho_{gi}-\rho_l\right)}{\rho_l\left(\rho_{vi}+\rho_{gi}\right)}-2\frac{\sigma}{R_b}-4\frac{\mu_l}{R}\left(\dot{R}-\frac{\dot{m}}{\rho_l}\right)$$

The energy conservation equation in gas phase with mist

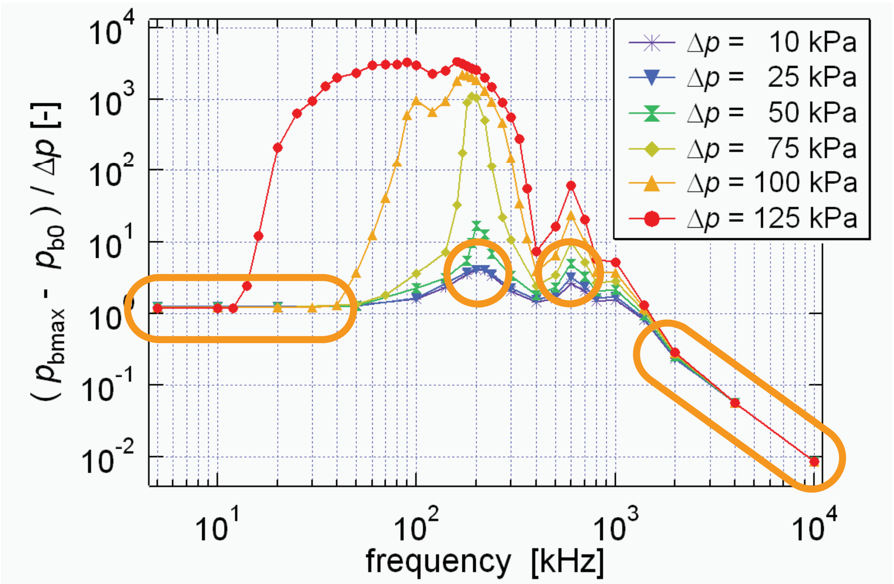
$$\left(C_{vg}M_g + C_{vv}M_v + C_{vl}M_c\right)\frac{d\bar{T}}{dt}-\frac{p_g M_g}{\rho_g{}^2}\frac{d\rho_g}{dt}-\frac{p_v M_v}{\rho_v{}^2}\frac{d\rho_v}{dt}$$

$$-L\frac{dM_c}{dt}-S\lambda\left.\frac{\partial T}{\partial r}\right|_{r=R}+\Delta h_v\left(\frac{dM_v}{dt}+\frac{dM_c}{dt}\right)+\Delta h_l\frac{dM_c}{dt}=0$$

The nucleation rate equation of mist

FEL

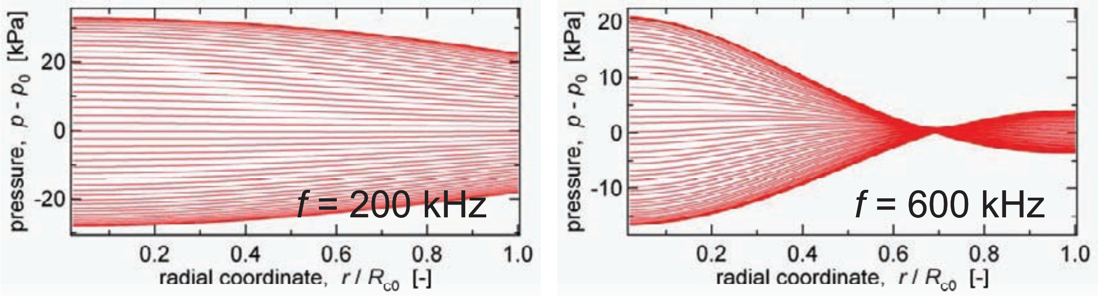
Frequency response of a bubble cloud



Maximum pressure inside the bubbles in the cloud

FEL

Natural modes (Δp = 10 kPa)

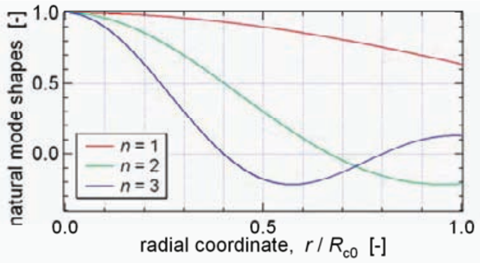


Water pressure inside the bubble cloud

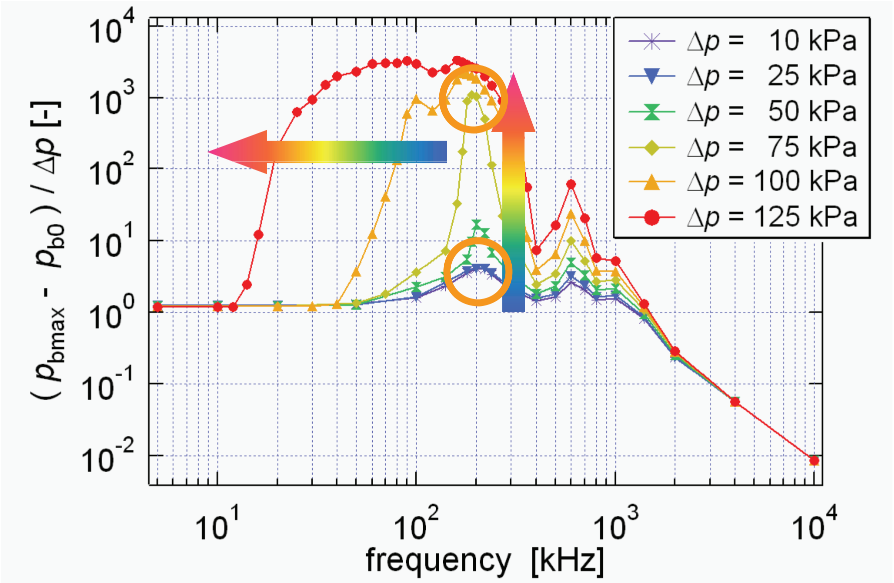
Natural mode shapes

Linearized analysis of a spherical bubble cloud (d'Agostino & Brennen, 1989)

- Continuity equation
- Momentum equation
- Rayleigh-Plesset equation

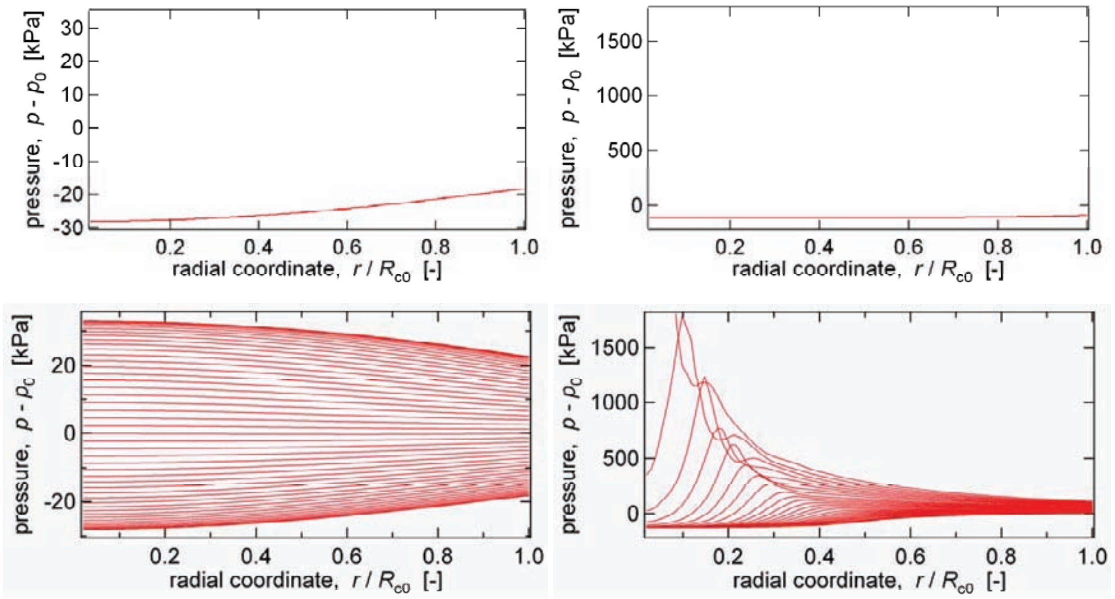


Frequency response of a bubble cloud



Maximum pressure inside the bubbles in the cloud

Pressure wave in the bubble cloud

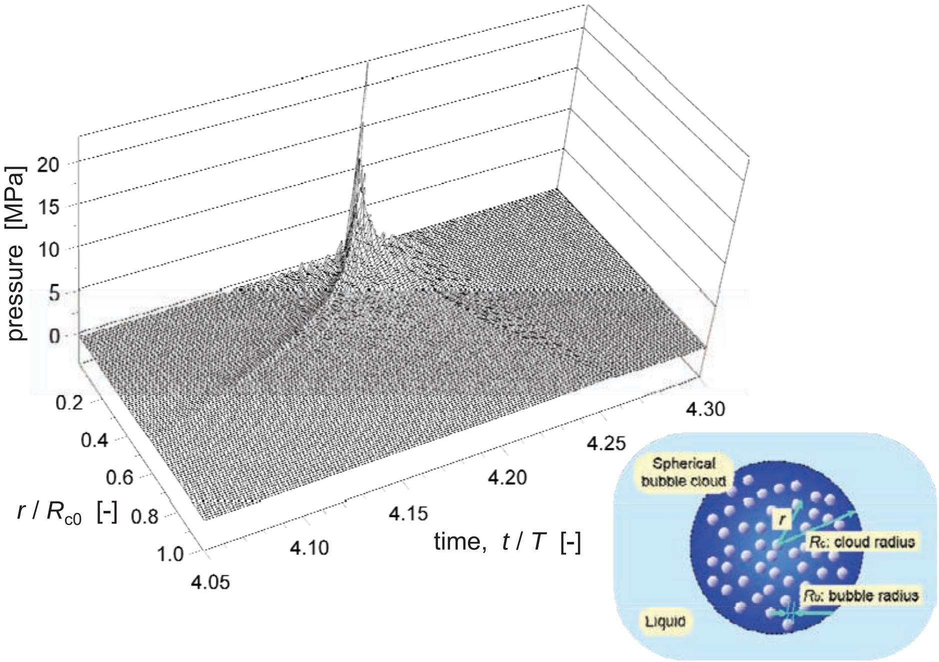


Δp = 10 kPa, 200 kHz

Δp = 75 kPa, 190 kHz

FEL

Collapse of the cloud (Δp = 125 kPa, 160 kHz)



Water pressure inside the bubble cloud

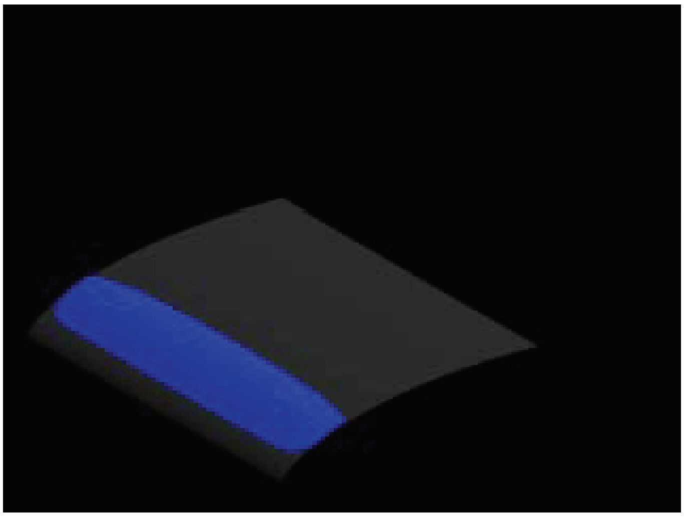
FEL

目次

- はじめに
- 単一気泡の挙動
- 気泡クラウドの挙動
- **流体機械のキャビテーションエロージョン**
- おわりに

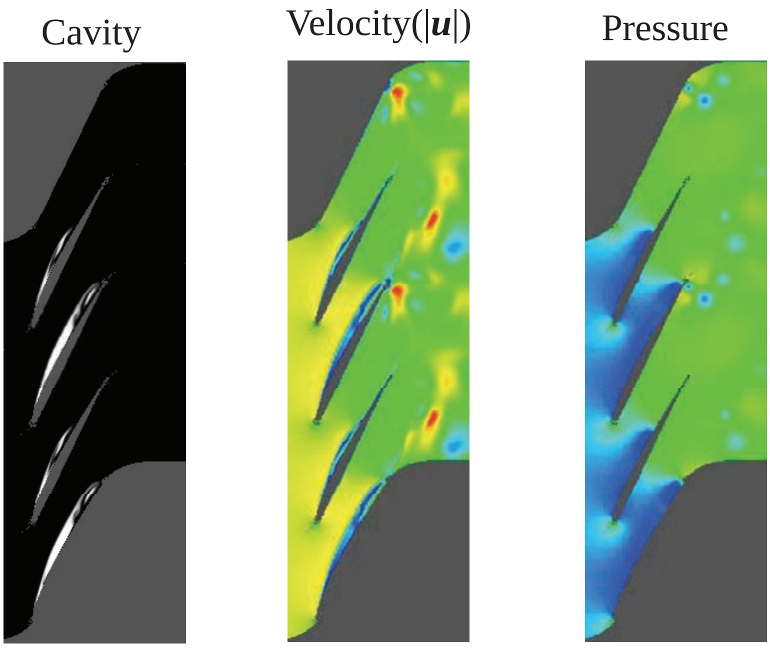
FEL

クラウドキャビテーションの渦放出



FEL

翼列キャビテーションの時間発展



$\alpha_\infty = 6\mathrm{deg},\ \sigma = 0.6$

FEL

背　景

ポンプの生産コスト低減　→　小型化

⇩ 高速（高回転）化

キャビテーションエロージョン

エロージョン予測：　従来は実験的な手法が主流

⇩

CFDの有効活用　　→　試験の省力化による開発期間短縮

エロージョン予測法の一例：

キャビテーション長さ

⇩ 実験式

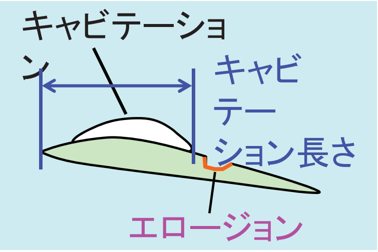
エロージョン速度を予測

⇔

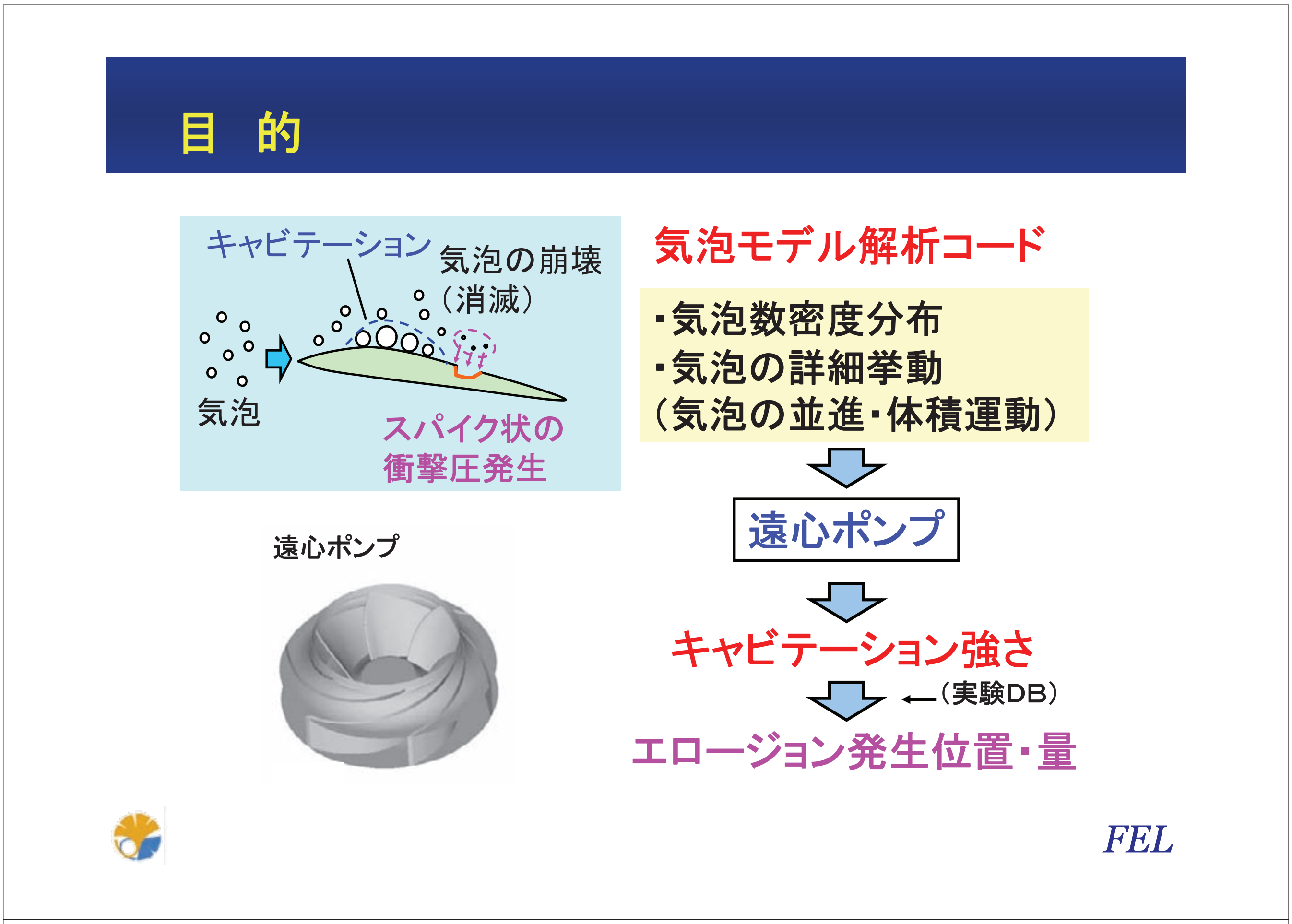
可視化計測

⇩

CFD予測



FEL



目　的

キャビテーション
気泡の崩壊（消滅）
気泡
スパイク状の衝撃圧発生

遠心ポンプ

気泡モデル解析コード

- ・気泡数密度分布
- ・気泡の詳細挙動（気泡の並進・体積運動）

↓

遠心ポンプ

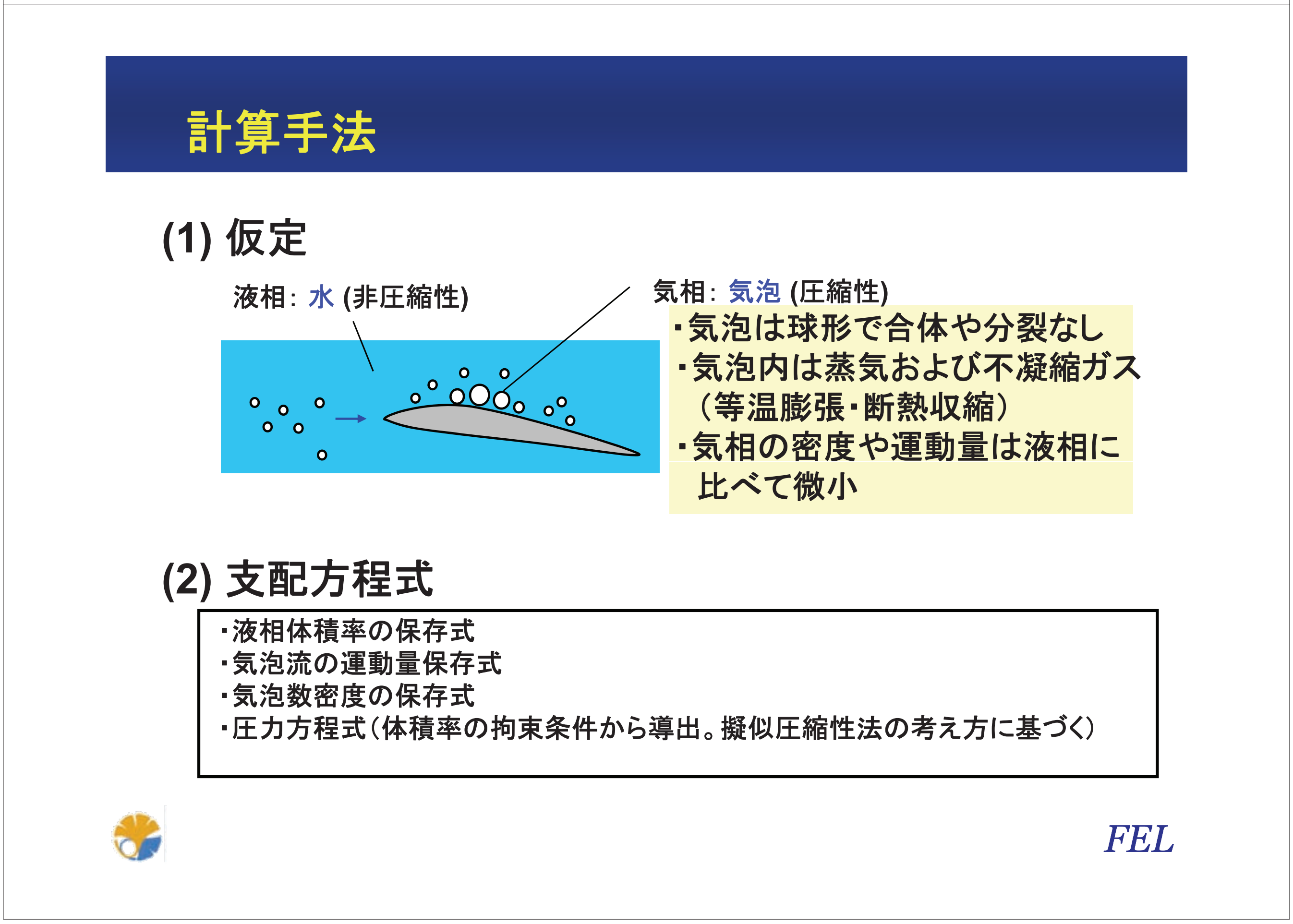
↓

キャビテーション強さ

↓ ←（実験DB）

エロージョン発生位置・量

FEL



計算手法

(1) 仮定

液相：水 (非圧縮性)

気相：気泡 (圧縮性)

- ・気泡は球形で合体や分裂なし
- ・気泡内は蒸気および不凝縮ガス（等温膨張・断熱収縮）
- ・気相の密度や運動量は液相に比べて微小

(2) 支配方程式

- ・液相体積率の保存式
- ・気泡流の運動量保存式
- ・気泡数密度の保存式
- ・圧力方程式（体積率の拘束条件から導出。擬似圧縮性法の考え方に基づく）

FEL

支配方程式-1

$$\frac{\partial \hat{Q}}{\partial t}+\frac{\partial \hat{E}}{\partial \xi}+\frac{\partial \hat{F}}{\partial \eta}+\frac{\partial \hat{G}}{\partial \zeta}=\frac{\partial \hat{E}_v}{\partial \xi}+\frac{\partial \hat{F}_v}{\partial \eta}+\frac{\partial \hat{G}_v}{\partial \zeta}+\hat{H} \quad \text{--- (1)}$$

$$\hat{Q}=\begin{bmatrix} f_L \\ \rho_L f_L u_L \\ \rho_L f_L v_L \\ \rho_L f_L w_L \\ p \\ n_G \end{bmatrix} / J \qquad \hat{E}=\begin{bmatrix} f_L U_L \\ \rho_L f_L u_L U_L+\xi_x p \\ \rho_L f_L v_L U_L+\xi_y p \\ \rho_L f_L w_L U_L+\xi_z p \\ c^2 \rho_L f_L U_L+c^2 \rho_L f_G U_G \\ n_G U_G \end{bmatrix} / J \qquad \hat{E}_v=\mu\begin{bmatrix} 0 \\ \xi_x \tau_{xx}+\xi_y \tau_{xy}+\xi_z \tau_{xz} \\ \xi_x \tau_{yx}+\xi_y \tau_{yy}+\xi_z \tau_{yz} \\ \xi_x \tau_{zx}+\xi_y \tau_{zy}+\xi_z \tau_{zz} \\ 0 \\ 0 \end{bmatrix} / J$$

$$\hat{H}=\begin{bmatrix} 0 \\ \rho_L \Omega v_L \\ -\rho_L \Omega u_L \\ 0 \\ 4c^2 \rho_L \pi r_G{}^2 n_G \dfrac{D_G r_G}{D_G t} \\ 0 \end{bmatrix} / J$$

回転直交座標系における絶対速度成分

⇩

外力項にコリオリカ

FEL

支配方程式-2

気泡の体積運動

Rayleigh-Plesset 式

※市販コード等では左辺第1項を省略し、簡易式を解く（気泡挙動の概略を解く）ものがある。

$$r_G \frac{D^2 r_G}{Dt^2}+\frac{3}{2}\left(\frac{Dr_G}{Dt}\right)^2=\frac{p_B-p_L}{\rho_L}+\frac{1}{4}(u_{Li}-u_{Gi})(u_{Li}-u_{Gi}) \quad \text{--- (2)}$$

気泡径

$$p_B=p_G+p_v-\frac{2T}{r_G}-4\mu\frac{1}{r_G}\frac{Dr_G}{Dt} \quad \text{--- (3)}$$

気泡内圧力

ボイド率

$$f_G=\frac{4}{3}\pi r_G{}^3 n_G \quad \text{--- (4)}$$

気泡数密度

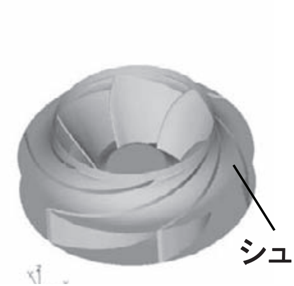
気泡の並進運動

$$F_{Ai}+F_{pi}+F_{Di}+F_{Li}+F_{Ci}=0 \quad \text{--- (5)}$$

F_{Ai} : 付加慣性力
F_{pi} : 周囲流体の加速による力
F_{Di} , F_{Li} ：抗力および揚力
F_{Ci} : コリオリカ

FEL

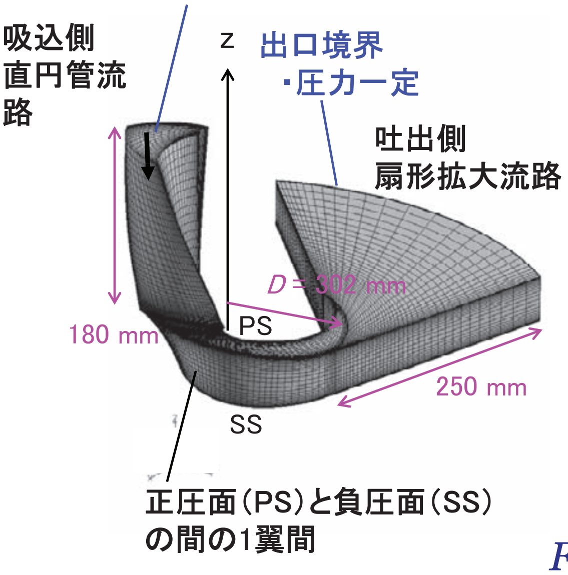
）解析領域と境界条件



- ・シュラウドあり
- ・羽根枚数6枚

入口境界
・流速、気泡径、気泡数密度等の一様流入

出口境界
・圧力一定



- ・解析格子数 約 220,000
- ・初期条件
  - ボイド率：0.001 (= 0.1%)
  - 気泡径 ：1.0×10^{-5} m (= 10 μm)

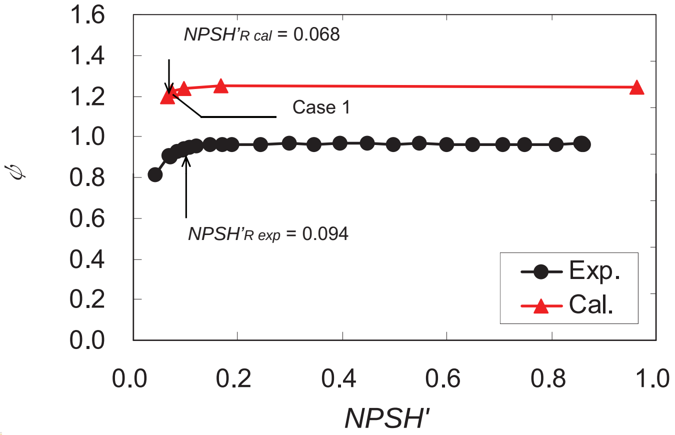
FEL

解析結果および考察 1

4.1 キャビテーション性能

解析結果は、ポンプの一般的なキャビテーション性能と定性的に一致

部分負荷条件 (Q/Q_d = 0.6)



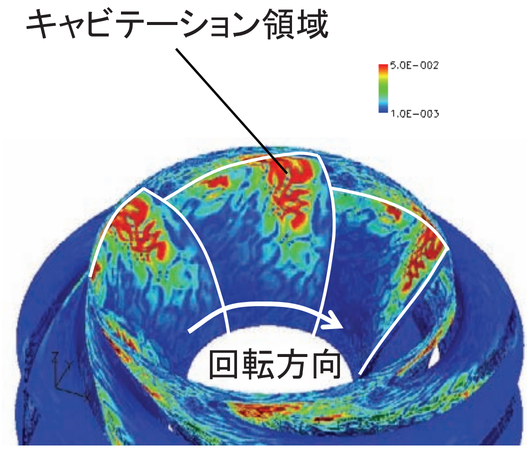
$\psi = H / (U_t^2/2g)$
$NPSH' = NPSH / (U_t^2/2g)$

FEL

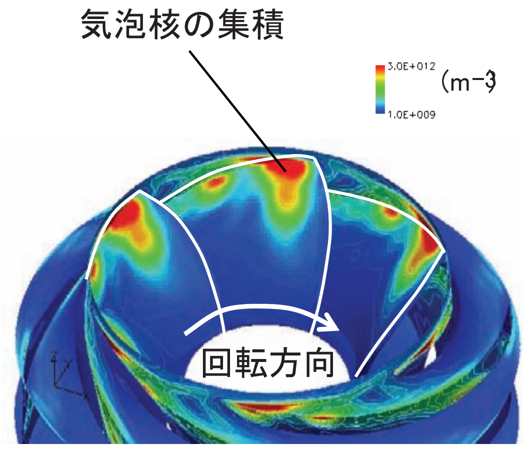
解析結果および考察　２

ボイド率と気泡数密度

Rayleigh−Plesset 式中の $\mu = \mu_L = 1.0 \times 10^{-3}$ (Pa s) を仮定



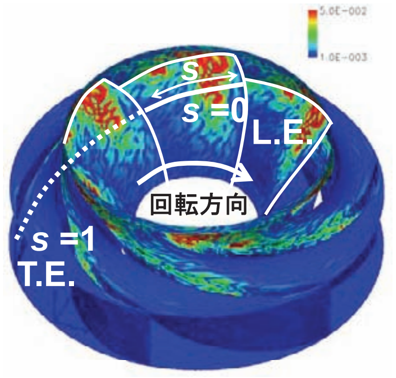
ボイド率



気泡数密度

FEL

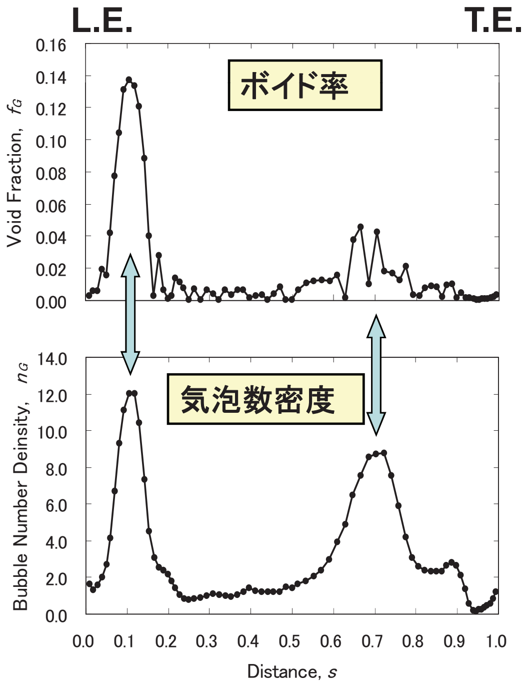
解析結果および考察　３



羽根負圧面に沿った
羽根前縁からの距離*s*

$$f_G = \frac{4}{3}\pi r_G{}^3 n_G$$

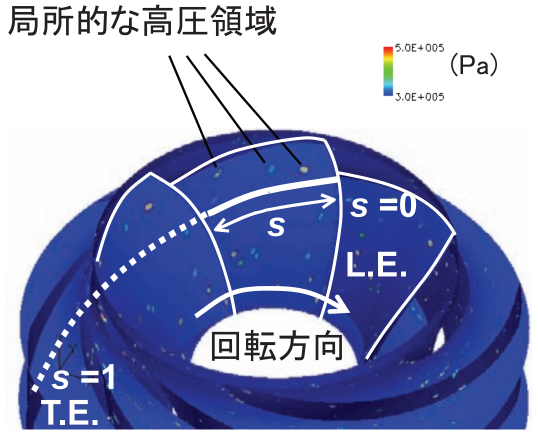
ボイド率　　気泡数密度

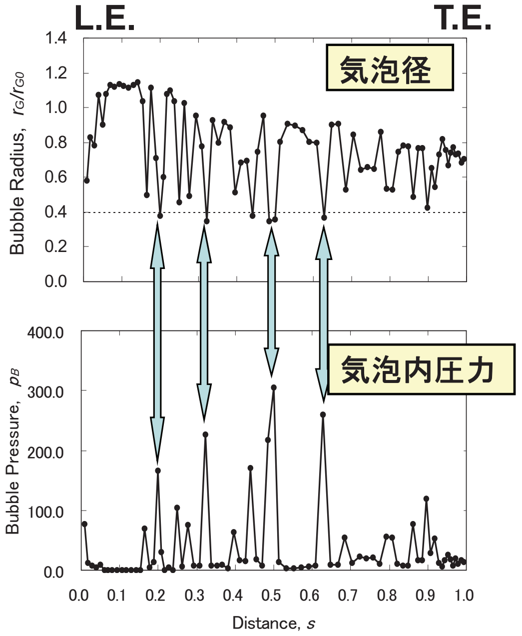


FEL

解析結果および考察　4

気泡径と気泡内圧力

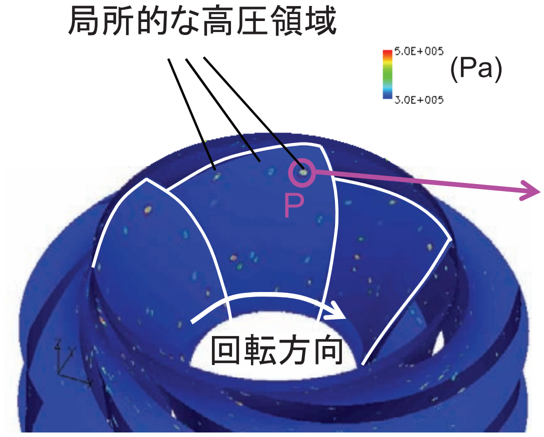




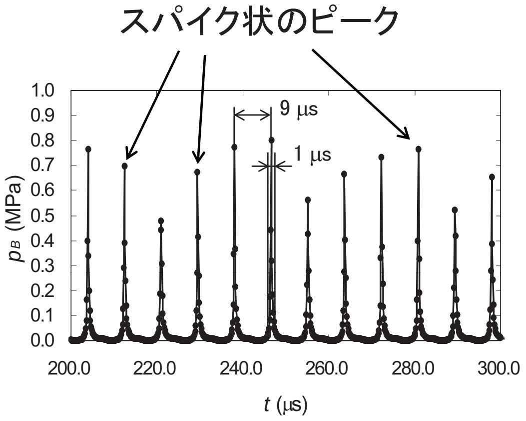
FEL

解析結果および考察　5

気泡内圧力の時間変化



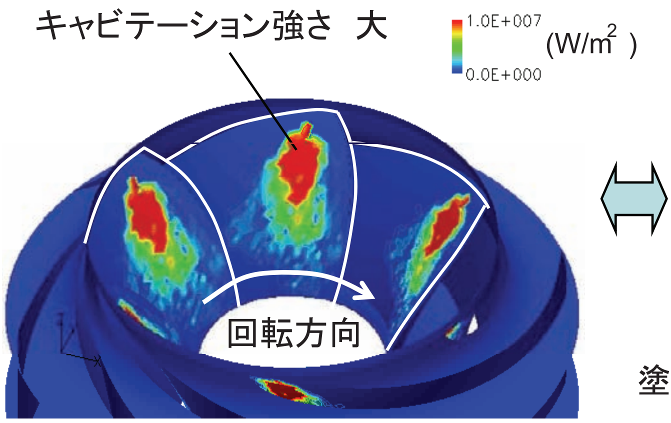
気泡内圧力

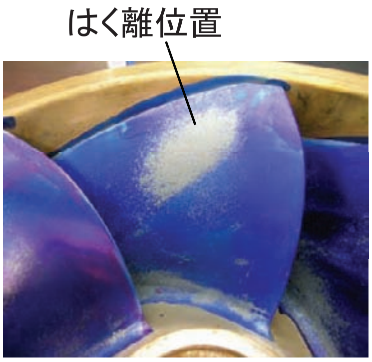


気泡内圧力の時間変化

FEL

キャビテーション強さとエロージョン発生位置





塗料試験結果（NPSHR付近）

気泡内圧力　　気泡数密度

キャビテーション強さ：
$$I = \sum_{p_{Bth}} \frac{p_B^{\,2}\, n_G\, \Delta V \Delta t}{2\rho_L C} \Big/ \Delta T$$
$p_B > p_{B\,th}$ (=0.75 MPa)

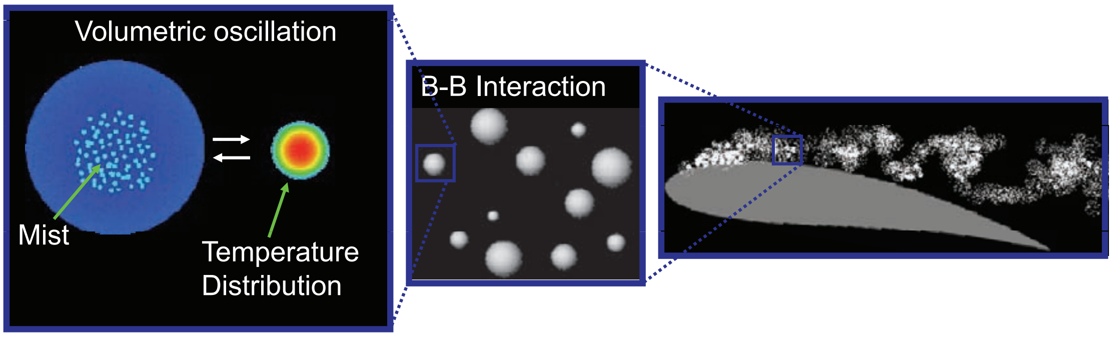
FEL

目次

- はじめに
- 単一気泡の挙動
- 気泡クラウドの挙動
- 流体機械のキャビテーションエロージョン
- **おわりに**

FEL

キャビテーションにおけるマルチスケールダイナミックス



Internal Phenomena of a Cavitation Bubble

Bubble Cloud

Cavitating Flow around a Hydrofoil

Micro

Mezzo

Macro

FEL

おわりに

- キャビテーション流れは，様々な時間空間スケールが重畳した現象であり，それらのスケールを合理的に繋いで解析することが重要となる
- 気泡流モデルでキャビテーション流れ解析を用い，羽根車のエロージョン発生位置予測を試みた
- その結果，キャビテーションの発生に伴って変化する羽根車内の液相圧力や流速の空間分布，ボイド率，気泡数密度，気泡径，気泡内圧力等の空間分布や時間変化が，合理的に予測可能となった
- キャビテーション強さ評価法を用いたエロージョン発生位置予測の有効性が示された

FEL