

Evaluation of Micro-bubble Flotation for Treating Ultra-fine Particles and Improvement by Applying Ultrasonic Irradiation

**SDIMI 2013@Miros Island
July 1st, 2013**

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Background

Further Treatment of Mineral Resources

Lack of high grade ores → **Low grade and complex** ore treatment and/or Reuse of **old (rich) tailings** → (Ultra-) Fine grinding → **Fine (nano) particles** treatment

Wastewater Treatment

Solid/liquid separation and/or **mutual separation** of **precipitates** to remove or recover specific components

Management of Hazardous Elements

Hazardous elements are often concentrated into fine (nano) fractions and necessary to be removed

Flotation probability

Total Flotation Probability: $P_{\text{flot}} = P_c * P_a * (1 - P_d)$

P_c : Collision of particles and bubbles

P_a : Adhesion of particles to bubbles

$(1 - P_d)$: Non-detachment of particles from bubbles

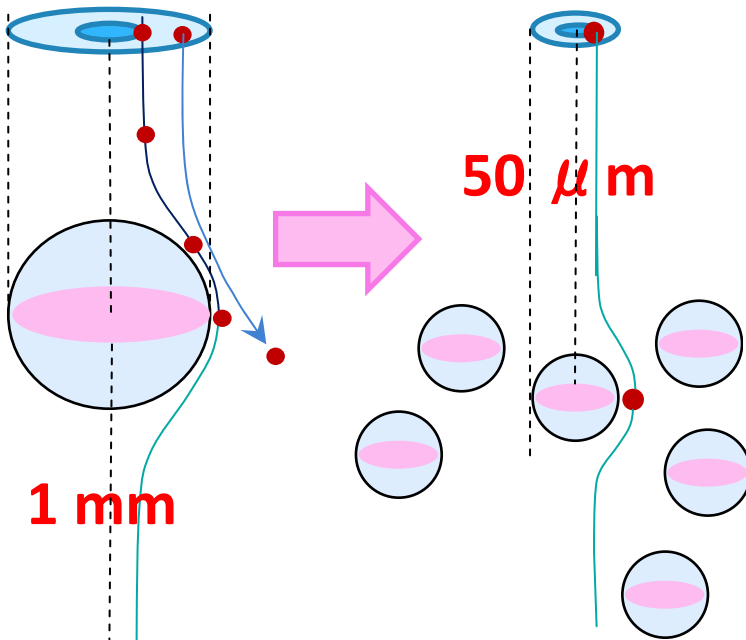
Assumptions

1. Homogeneity of particles
 2. No interaction of particles
 3. No interaction of various flotation phenomena.
- * Argument: Flotation follows 1st order kinetics.
 - * Weight floated dw in the time dt is proportional to the product of residual particle weight and dw .

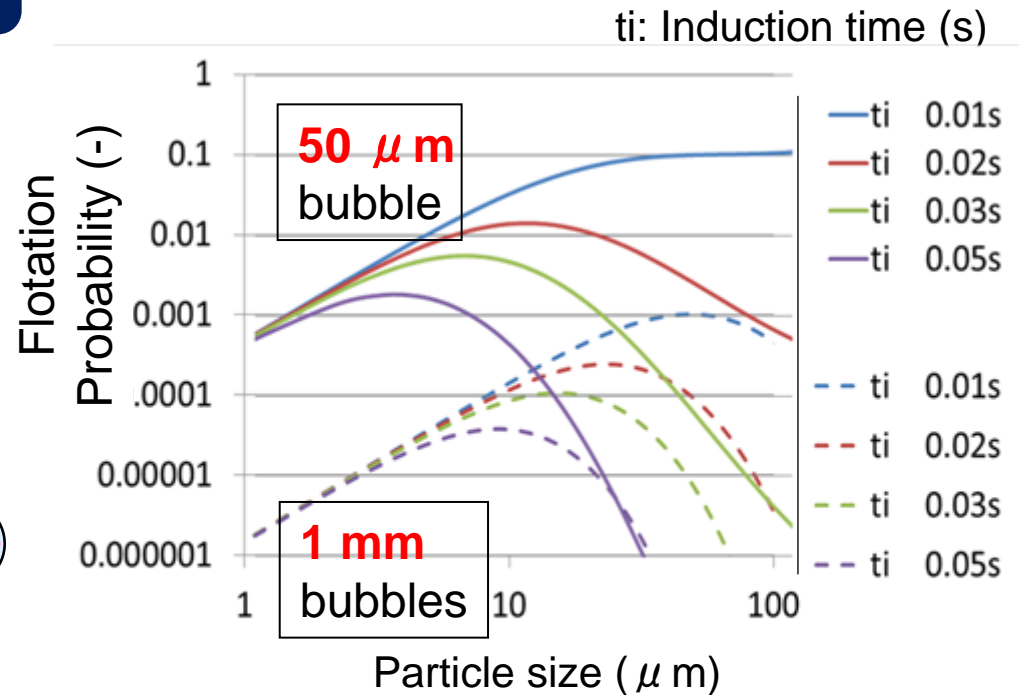
Necessity of **Micro**-bubble Flotation

LOW Collision Probability

HIGH Collision Probability



20 times Sectional Area and Higher collision probability



Relation between particle size and flotation probability

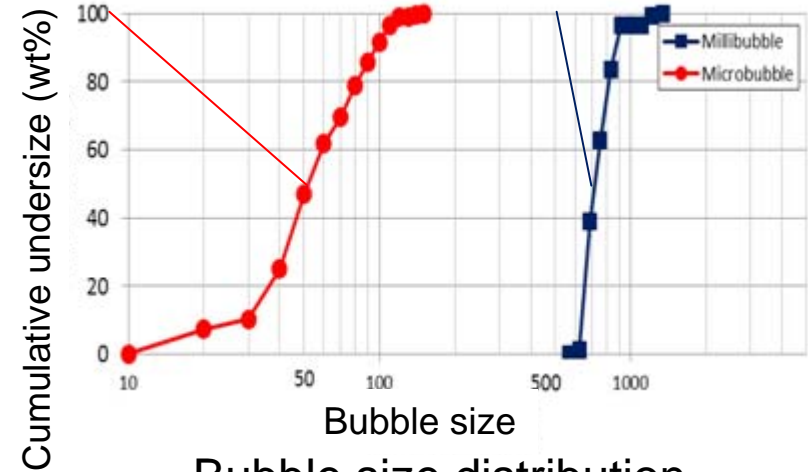
Problems in **Micro-bubble Flotation**

1. **Rising velocity is low** because of small bubble size, then, flotation capacity is low.
 2. Although the effectiveness of micro-bubble flotation to improve collision probability is clear but **NOT** **adhesion and non-detachment probabilities**, and **little experimental validation**.
 3. Air-pressure and/or pulp-circulation types of micro-bubble generators are **difficult to control bubble size and flow rate**.
- **Detailed theoretical and experimental comparison of Micro- and Milli-bubble flotation**
- **“Ultrasonic Irradiation”** to air bubbles in order to solve the above problems and improve the effectiveness

Detailed comparison of Micro- and Milli-Bubble Flotation

Experimental

Micro-bubble 52 μm of 50% size Milli-bubble 708 μm of 50% size



Bubble size distribution at pH6, SDS 1.0×10^{-4} M

Pulp of hematite fines
(0.45 wt% PD, 220 mL)

← 0.002 M with KNO_3

← pH adjustment with HNO_3 or KOH

← SDS addition (1.0×10^{-4} M)

← pH adjustment with HNO_3 or KOH

10 min conditioning

← 33 μL of MIBC

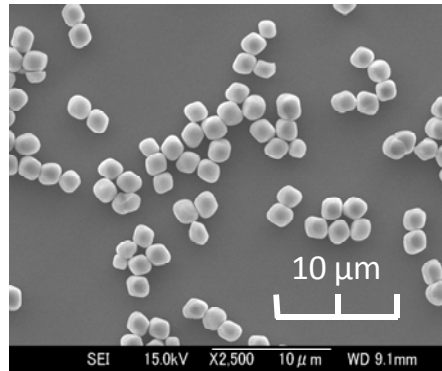
Air bubble introduction

10 min Flotation

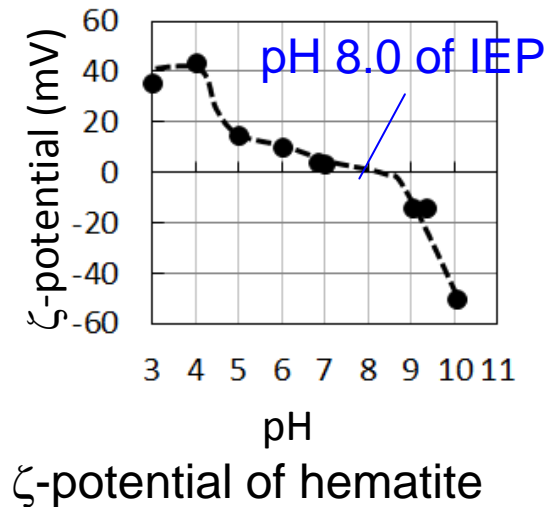
Froth

Tailin

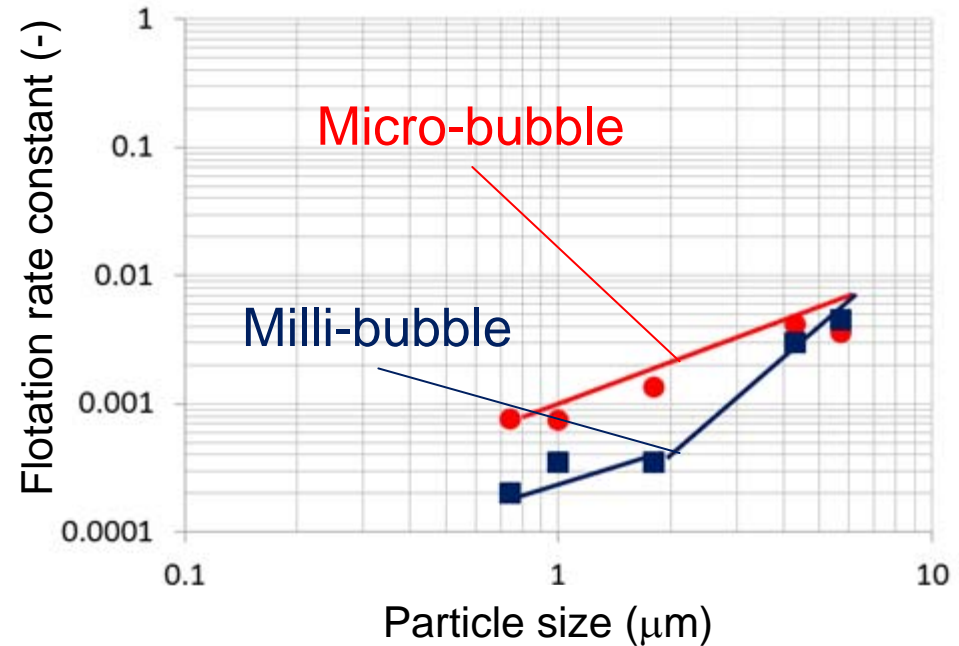
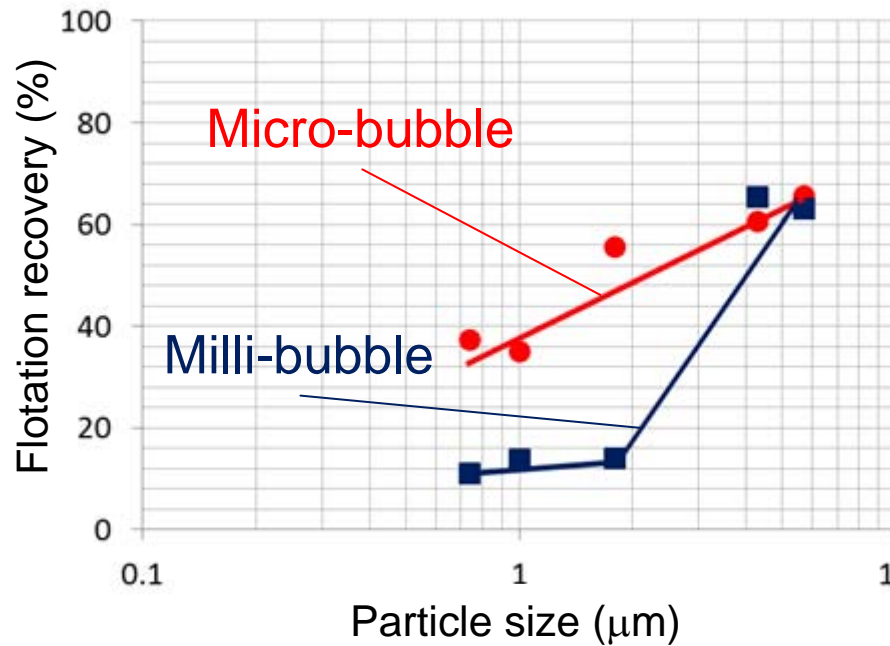
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Hematite fines
Synthesized
by gel-sol method



Flotation results for Hematite fines



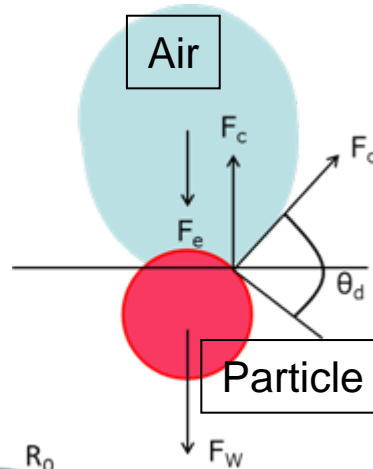
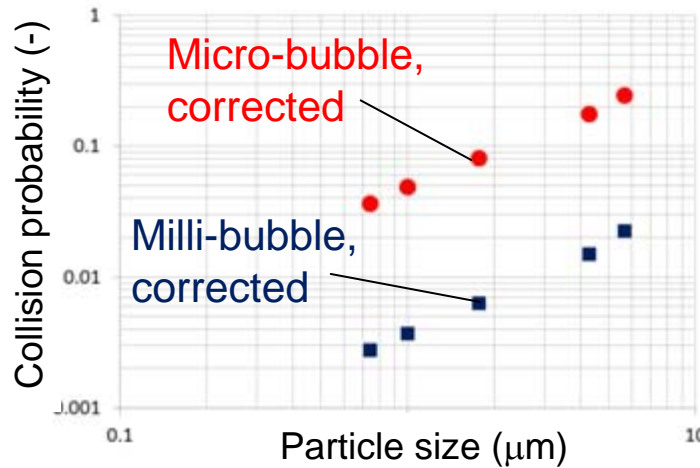
Relation between particle size and flotation recovery / flotation rate constant

- It was confirmed that micro-bubble flotation has an advantage to milli-bubble flotation in flotation recovery and the rate constant, especially in finer size ranges.
- It is also demonstrated that flotation recovery and the rate constant becomes lower in finer size ranges with both flotation methods.

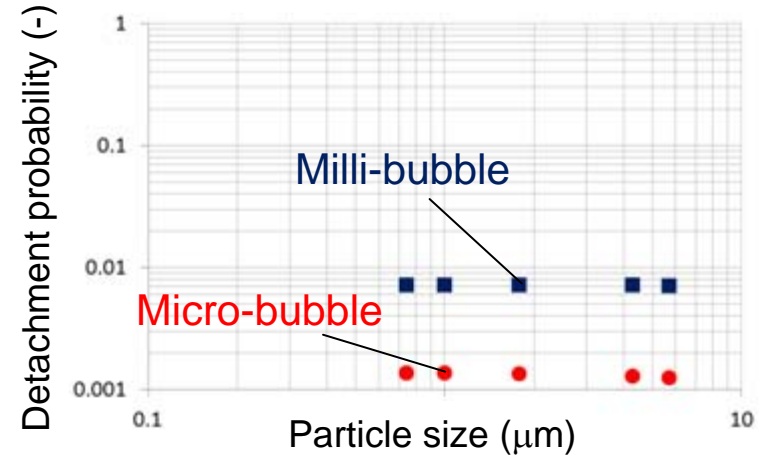
Collision & Detachment Probability

$$P = P_c \times P_a \times (1 - P_d)$$

Heindel Collision Model, P_c



Drzymala Detachment Model, P_d



$$P_d = \frac{1}{1 + F_{at}/F_{de}}$$

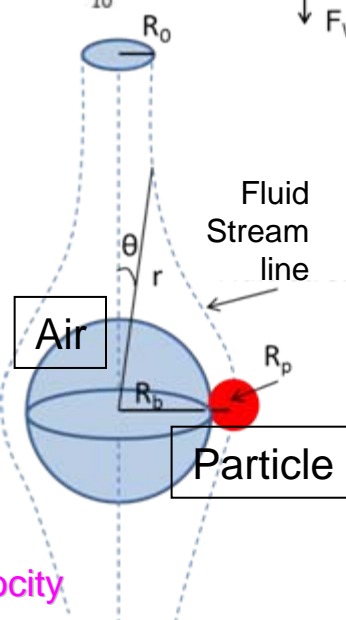
Detachment force: $F_{de} = F_w + F_d$

Apparent gravity of particle
Drag of particle

Attachment force: $F_{at} = F_c + F_e$

Vertical comp. interface force
Excess force

$$P_c = \frac{1}{1 + |G|} \left[\frac{1}{2(R_p + R_b)^3} \{ 2R_p^3 + 3R_p^2 R_b \} + \frac{2Re_b^{0.72}}{15(R_p + R_b)^4} \{ R_b R_p^3 + 2R_b^2 R_p^2 \} \right] + \frac{|G|}{1 + |G|}$$

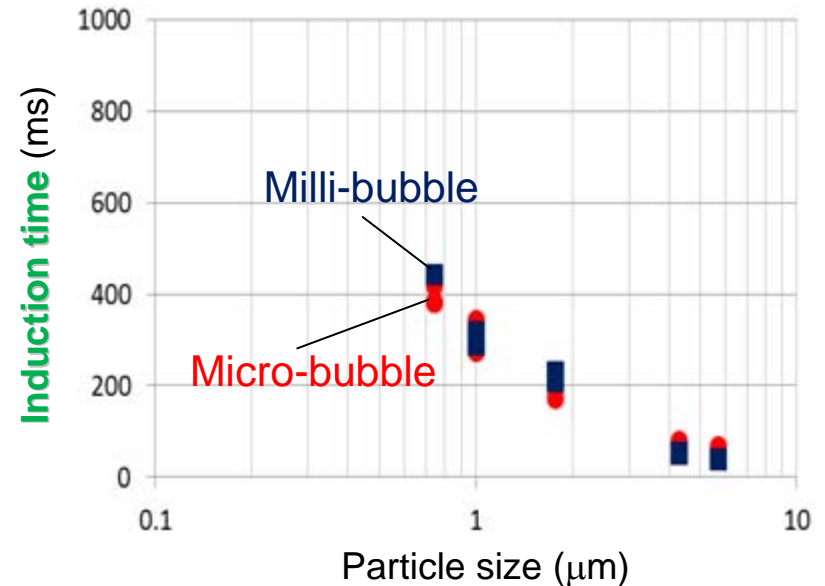
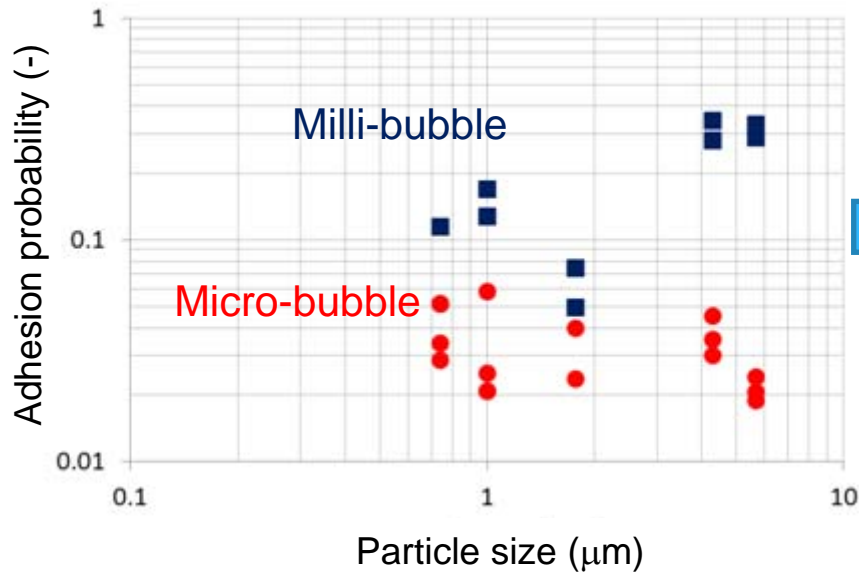


* Considering particle size and velocity

Adhesion Probability

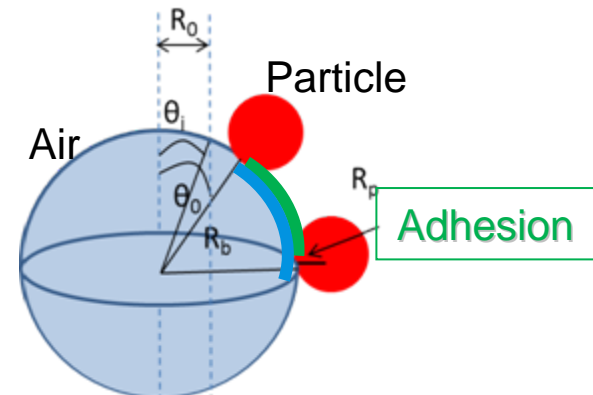
$$P = P_c \times P_a \times (1 - P_d)$$

Yoon Adhesion Model

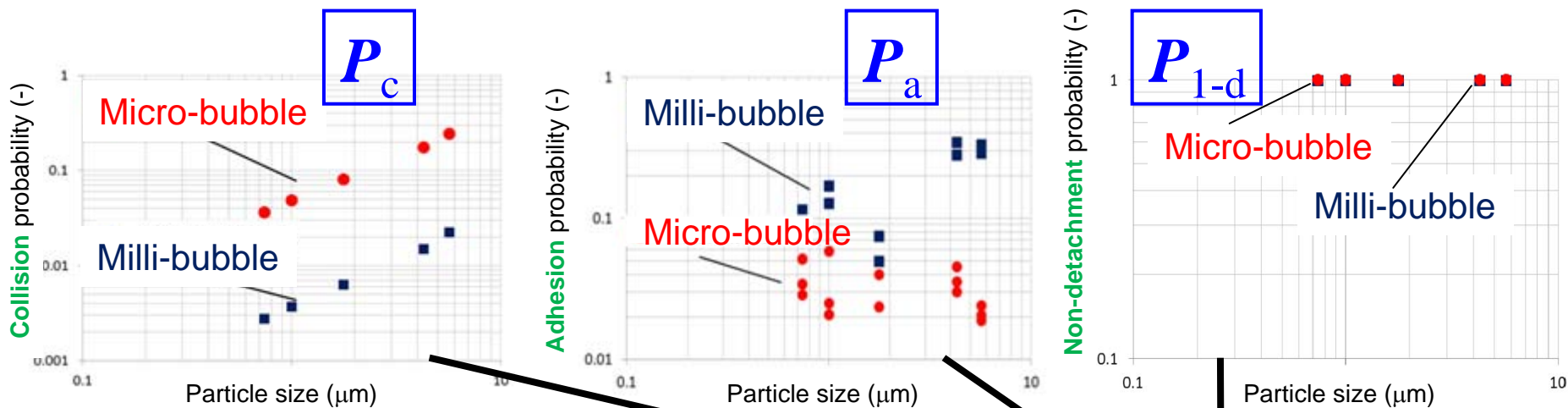


$$P_a = \sin^2 \left[2 \arctan \exp \left\{ \frac{-(45 + 8 \text{Re}^{0.72}) \mu_b t_i}{30 R_b (R_b / R_p + 1)} \right\} \right]$$

* **Induction time**: must be shorter than **slipping time** for adhesion

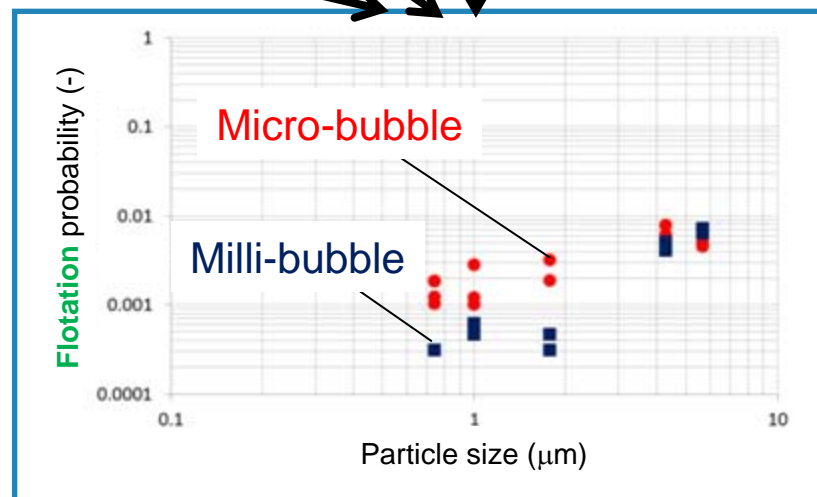


Comparison of **Micro**-bubble Flotation with **Milli**-bubble Flotation



Property of **Micro**-bubble flotation compared with **Milli**-bubble flotation

Probability	Comparison
Collision	Much higher
Adhesion	Lower
Non-detachment	Fair
Total flotation	Higher

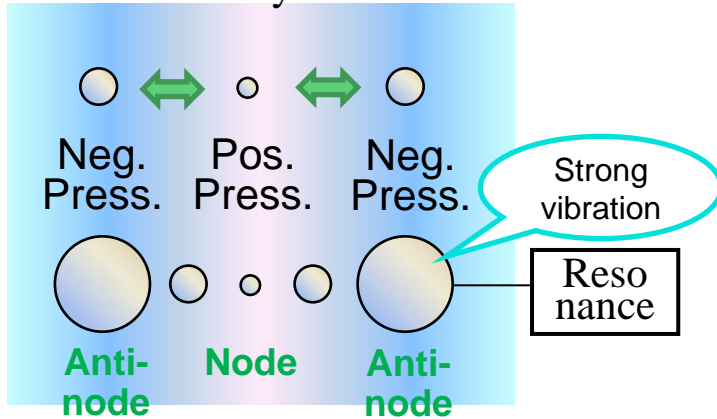


**Improvement of Micro-bubble
Flotation by Applying
Ultrasonic Irradiation**

Ultrasonic Irradiation to Air Bubbles

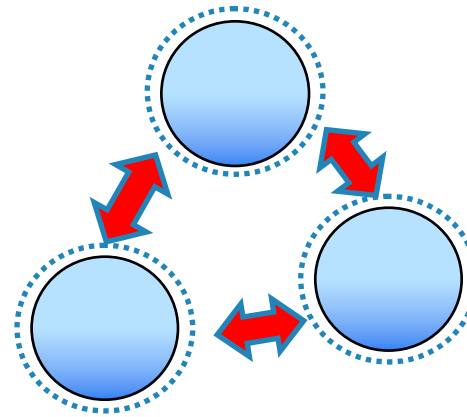
Primary Bjerknes Force:

Change in bubble volume
in the stationary wave

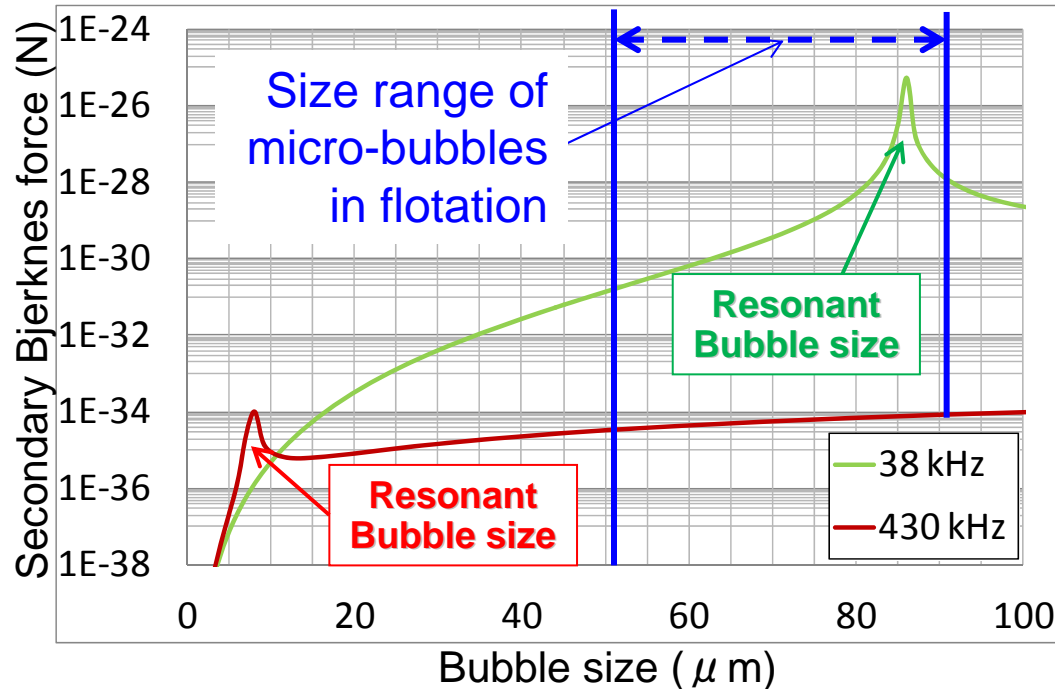


Secondary Bjerknes force:

Interaction of bubbles



Secondary ultrasonic vibration is generated from the bubbles

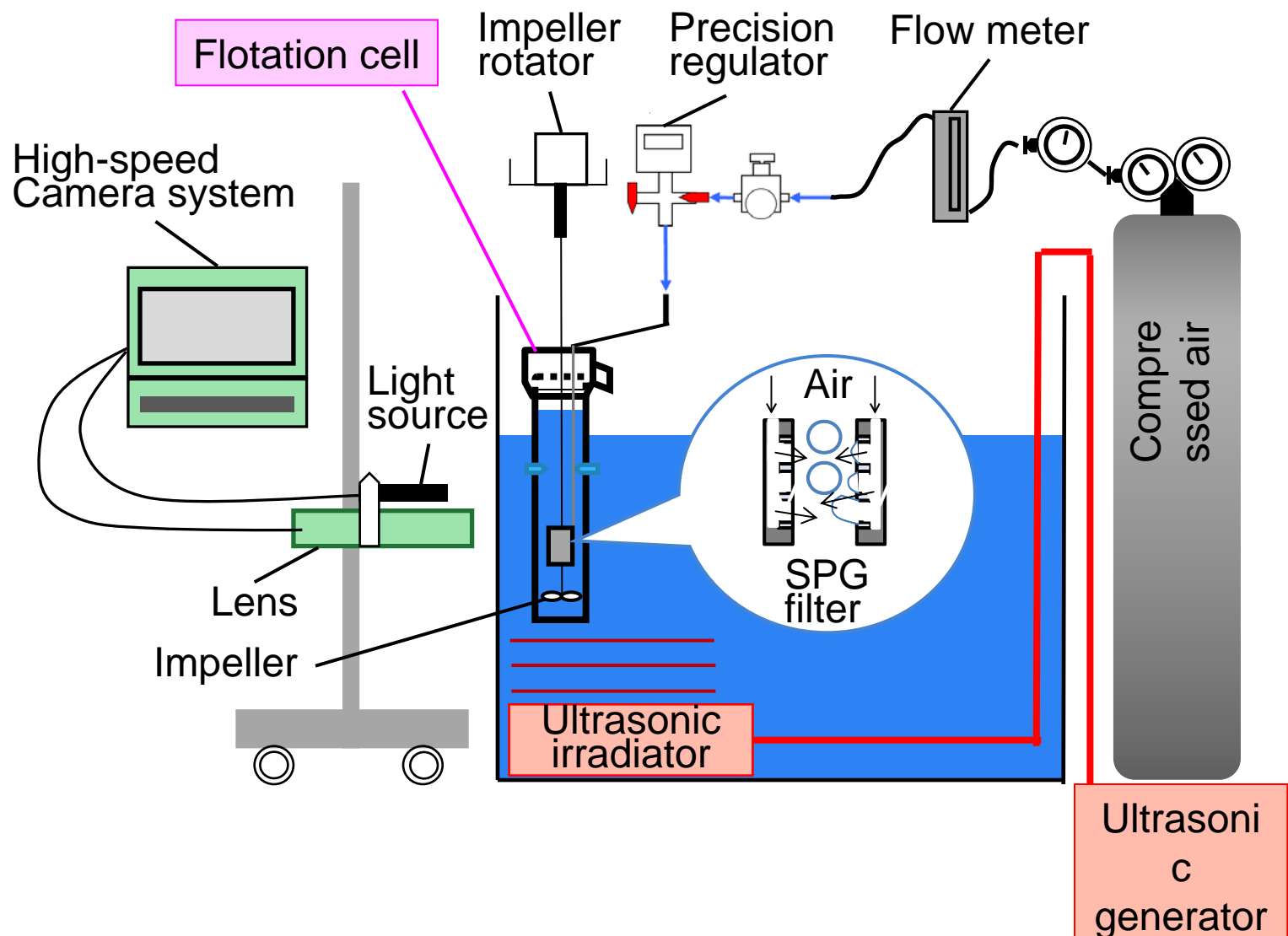


$$F_{B2} = \frac{2\pi |A|^2 \omega^2 R_{10} R_{20}}{\rho L^2 (\omega_1^2 - \omega^2)(\omega_2^2 - \omega^2)}$$

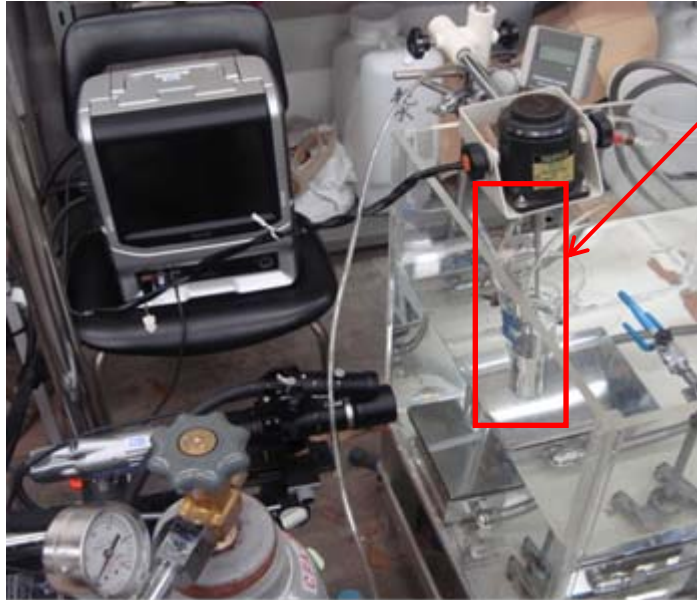
A : Amplitude of stationary wave
 ω : Frequency, R_{10} & R_{20} : Bubble size,
 ρ : Liquid density
 L : Distance between bubbles,
 ω_1 & ω_2 : Resonance frequency of bubbles

$F > 0$: Attractive \rightarrow Coagulation and incorporation of bubbles
 $F < 0$: Repulsive \rightarrow Dispersion of bubbles

Experimental of Flotation with Ultrasonic Irradiation



Experimental of Bubbles Observation



Flotation cell

Measurement of bubble size distribution
by high-speed camera

Conditions:

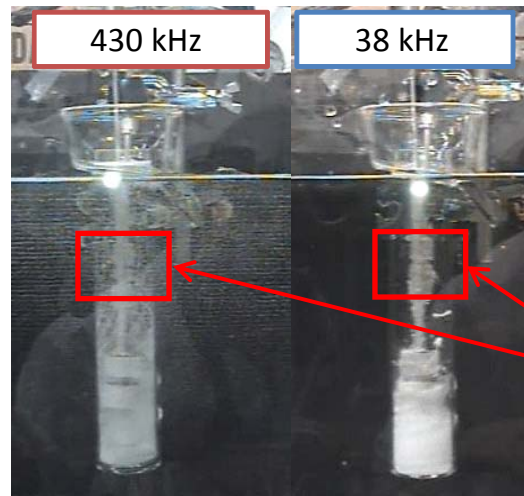
SDS conc.: 1.0×10^{-3} , 1.0×10^{-4} , 1.0×10^{-5} M

MIBC: 150 μ L/L

pH: 3.0, 7.0, 11.0

Ionic strength: 4.0×10^{-3} M

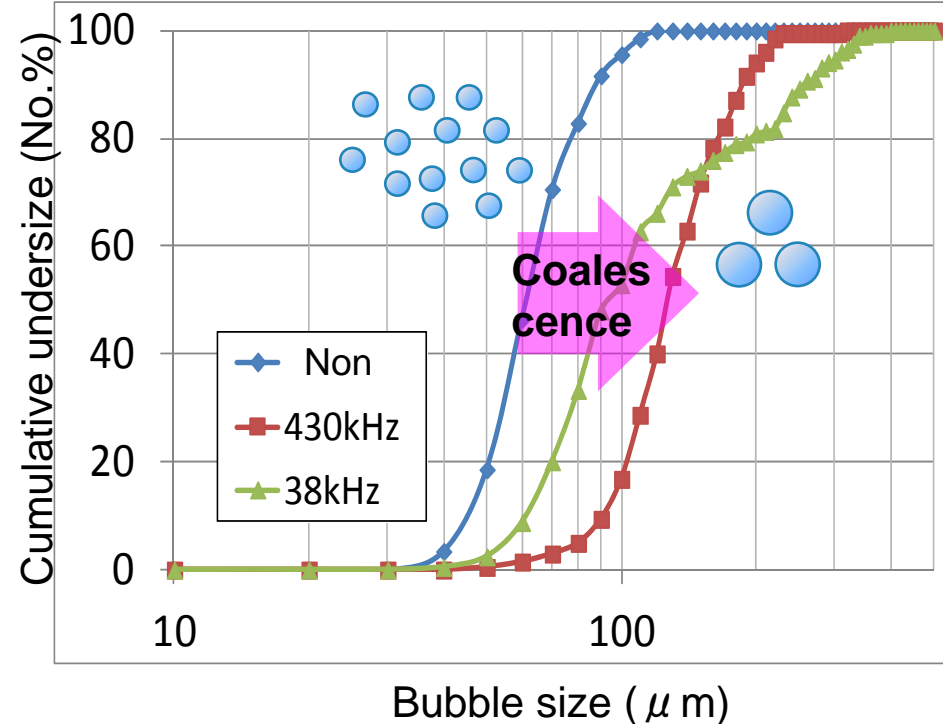
No. bubbles counted with high speed camera:
200 for single bubbles
50 for coagulated bubbles



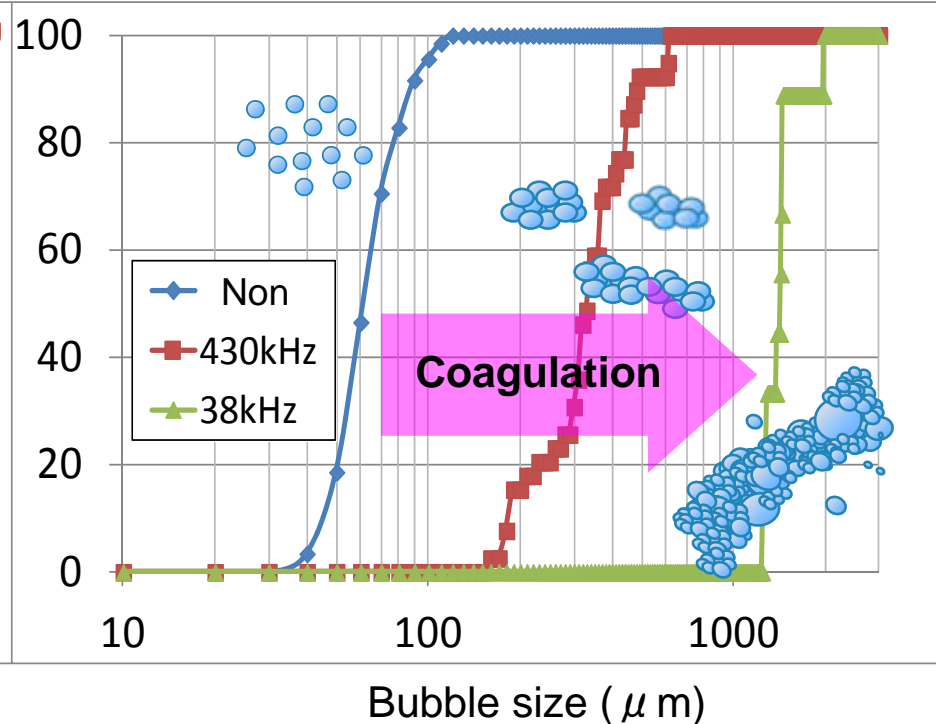
Bubbles
Observation area

Bubble Size Distribution

Single bubbles

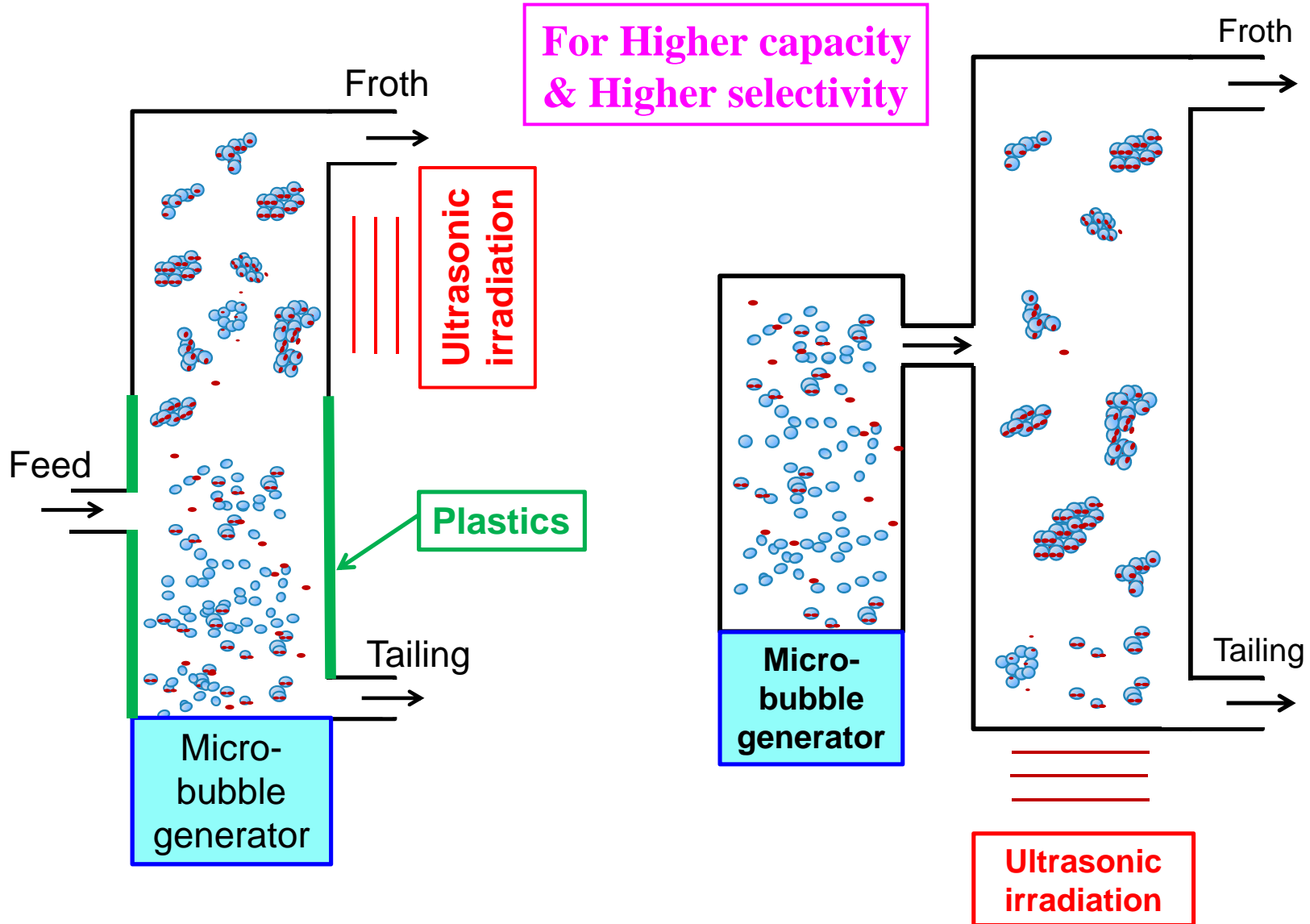


Coagulated bubbles

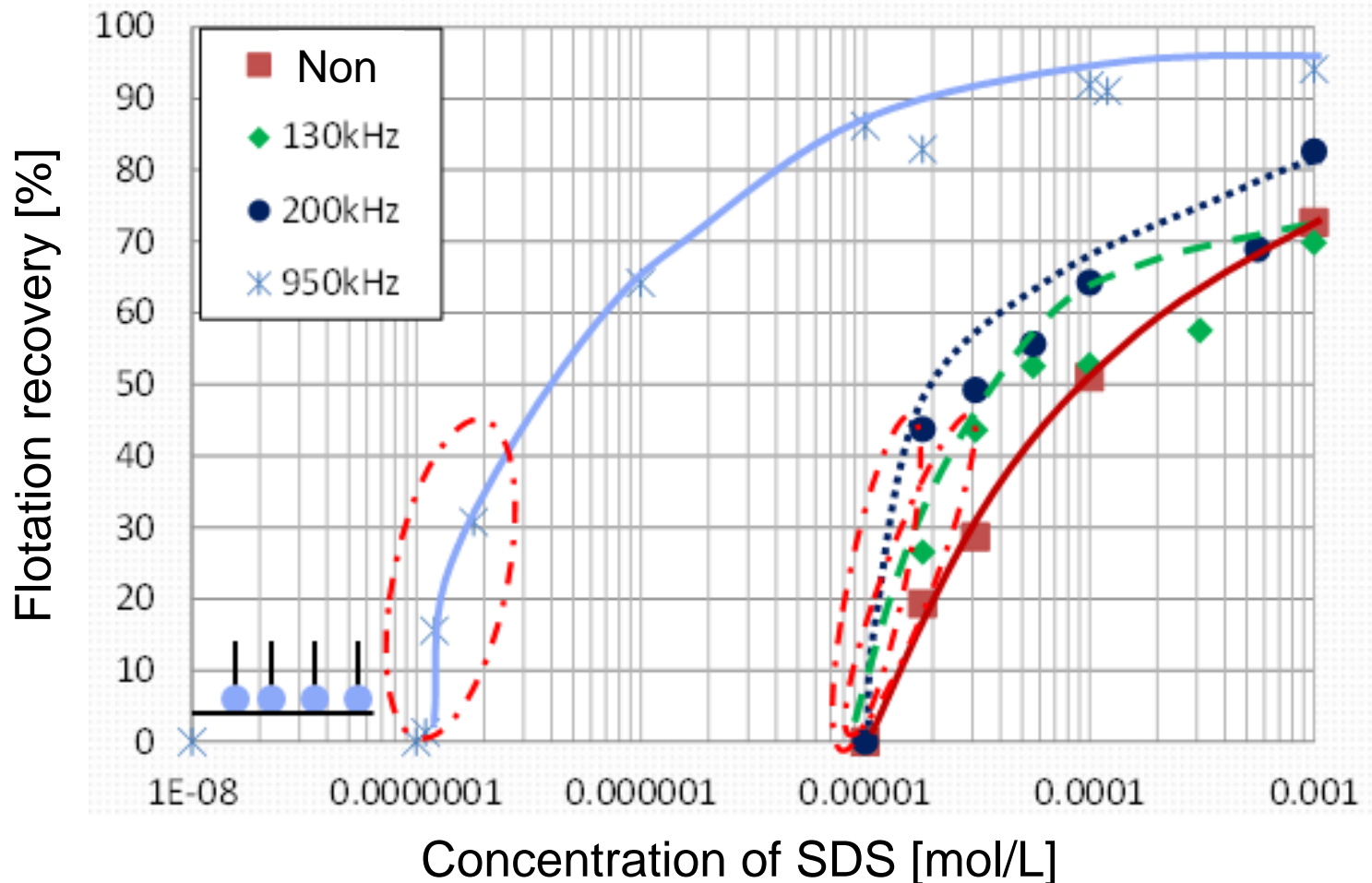


- **Coalescence of bubbles** could lead to the **higher selectivity** of mixed components.
- **Increase in bubble size** could lead to the **increase in flotation rate**.

Nobel Micro-bubble Flotation System

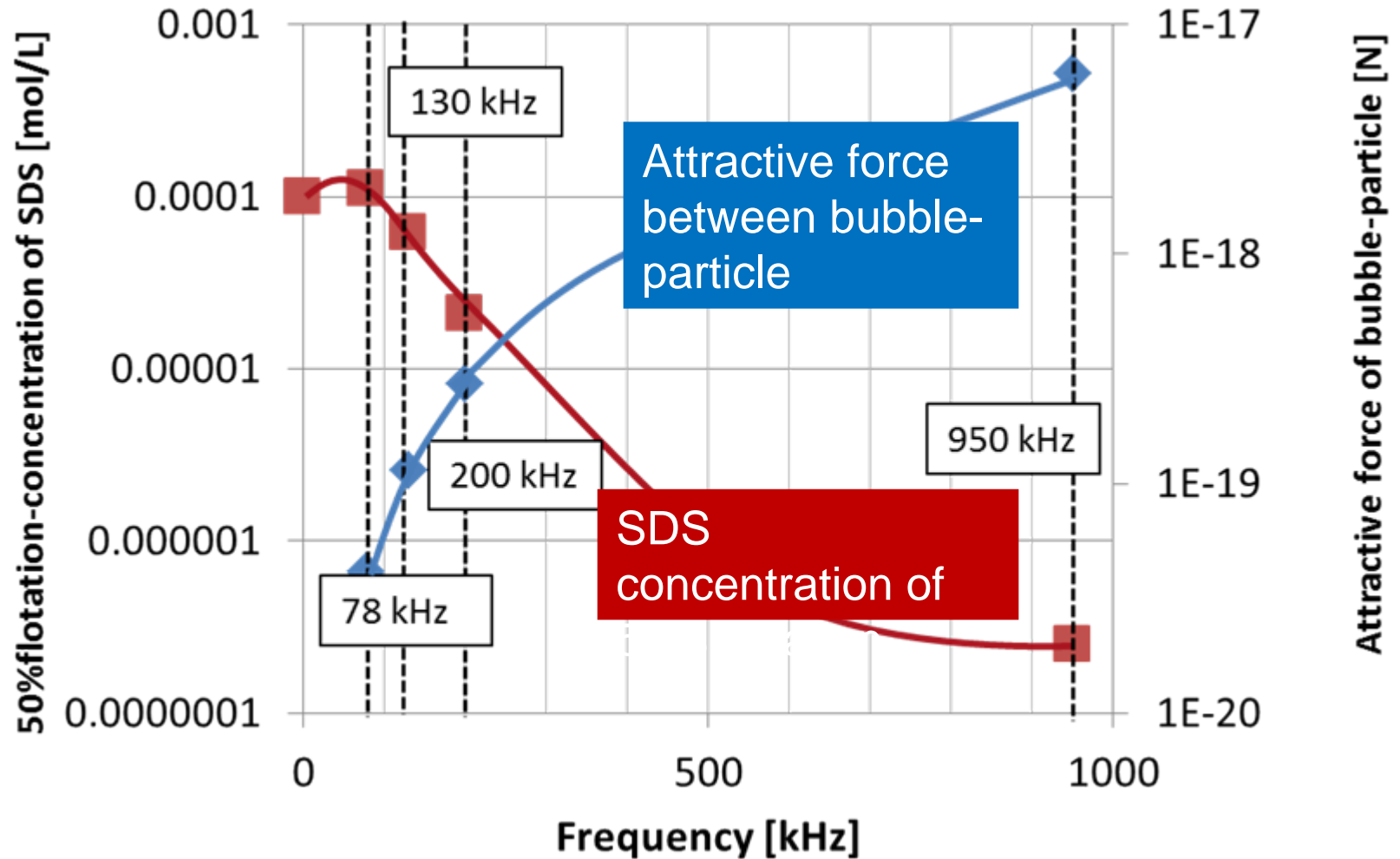


Change in Flotation Recovery with Ultrasonic Irradiation



Dramatic decrease of apparent CMC with ultrasonic irradiation
⇒ It might be suggested that **the increase in hydrophobic interaction** among surfactant molecules can be achieved.

Change in the SDS Concentration of 50% flotation and Bubble-Particle Attractive Force



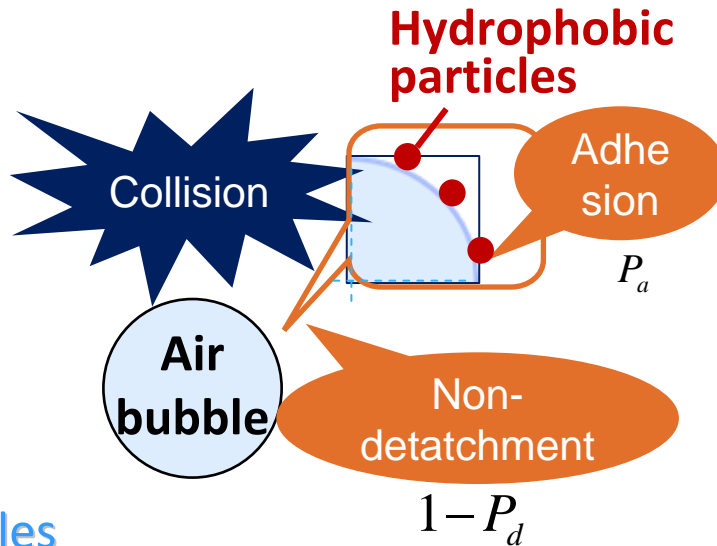
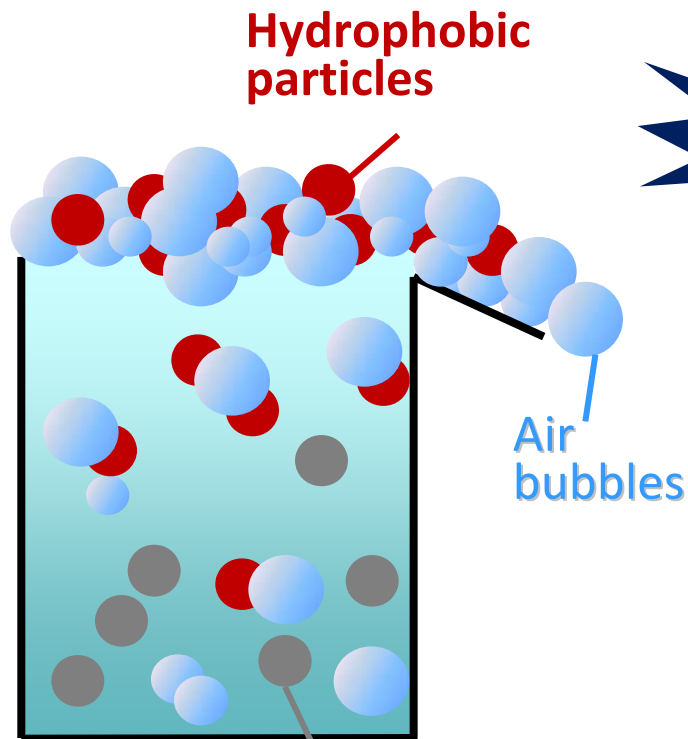
⇒ Flotation recovery can be achieved with much lower SDS concentration in case of higher ultra-sonic frequency.

Conclusion

1. Flotation recovery, rate constant, and the probability were higher in Micro-bubble flotation than in Milli-bubble flotation.
2. We modified Yoon flotation model and Heindel collision model by considering the bubbles and particles rising spaces and particle size.
3. Adhesion probability of particles to bubbles, which was obtained by combining experimental flotation probability, Heindel model and Drzymala model, were lower in Micro-bubble flotation than in Milli-bubble flotation.
4. Induction time, calculated from the adhesion probability, was increased by decreasing particle size both in Micro- and Milli-bubble flotation, which indicated that the energy to break bubble surface by particle attachment was smaller in the case of finer particles.
5. Bubbles were coalesced and/or coagulated by the secondary Bjerkness force generated by ultrasonic irradiation. Ultrasonic wave whose frequency is closer to the resonance frequency had a higher effect.
6. We demonstrated two kinds of Micro-bubble flotation systems with ultrasonic irradiation in order to increase the capacity and selectivity.
7. It might be suggested that ultrasonic irradiation of higher frequency increased the flotation recovery with much lower collector concentration.



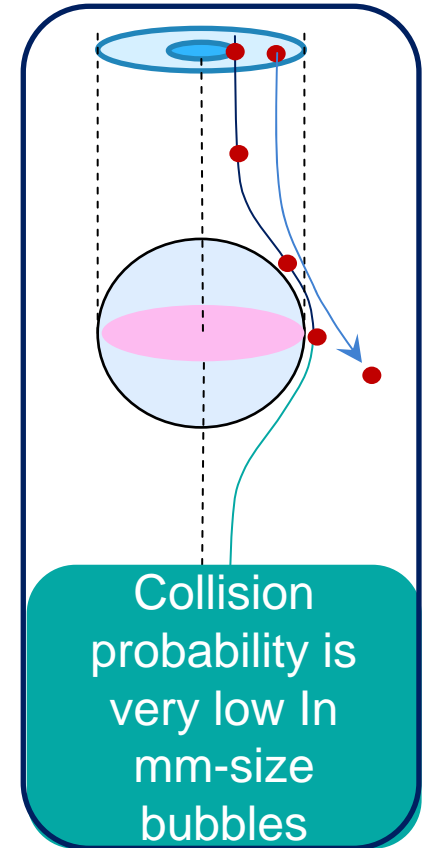
Problem in Milli-bubble Flotation: Low Collision Probability



$$P = P_c \times P_a \times (1 - P_d)$$

Collision Probability

**Difficulty in
fines flotation**



Effect of Ultrasonic Irradiation to Bubbles Behavior

Bubbles coalescence ratio

430kHz	9.63	38kHz	14.6
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Decrease in Specific Surface Area

Non irradiation	81 m^{-1}
430kHz irradiation	15 m^{-1}
38kHz irradiation	3.3 m^{-1}

Effect of ultrasonic frequency to flotation behavior

	Flotation rate	Grade	Recovery
430kHz	Fair	Fair	Fair
38kHz	Excellent	Excellent	Low