Influence of Surfactant Concentration on the Critical Current Density

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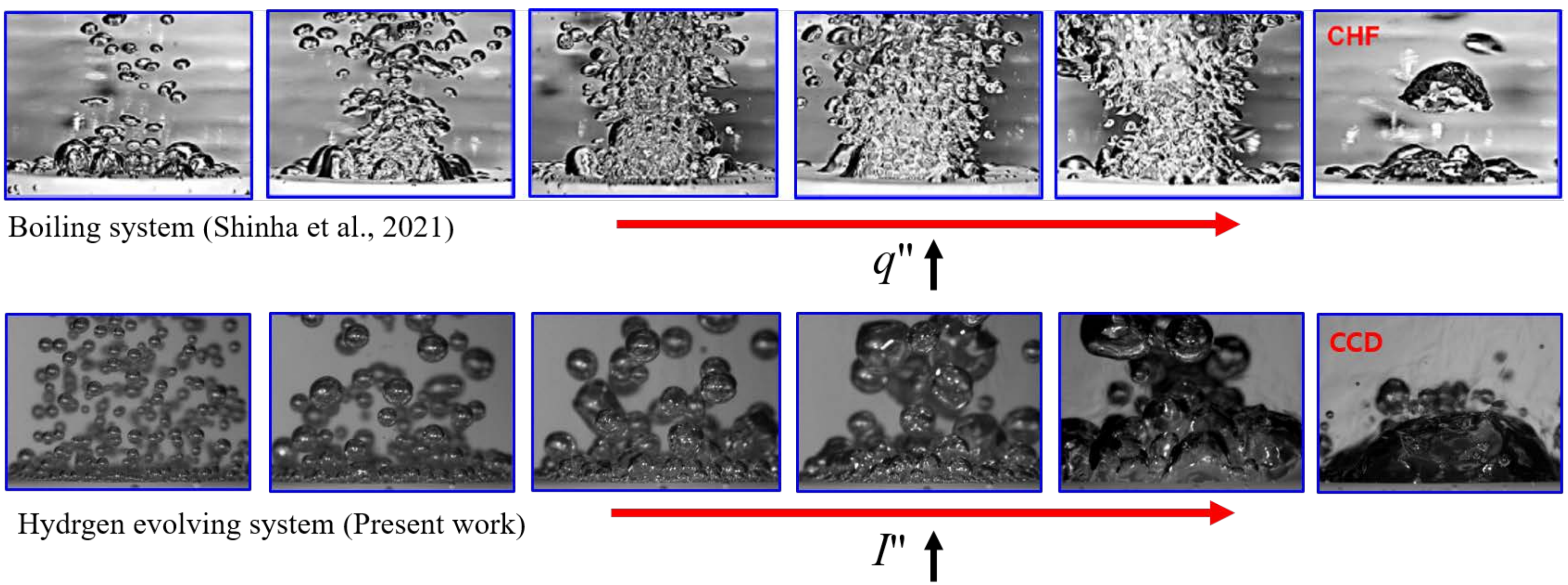
Introduction

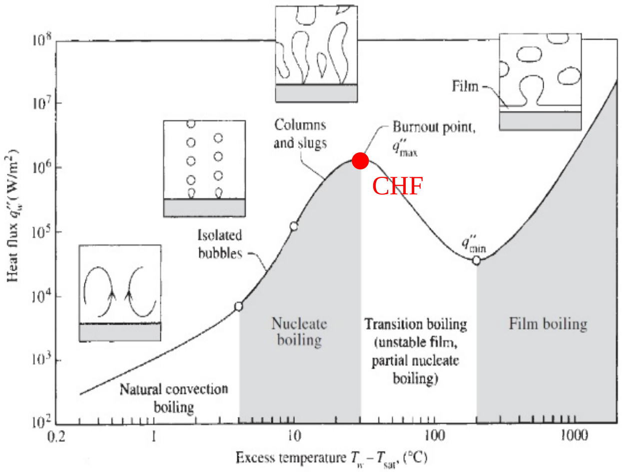
- Investigation on the CHF phenomenon is one of prime issue in the nuclear engineering
- Experimental hardness reaching on the CHF condition
  - Failure of test section and instrument devices
- Similar to the CHF ⟶ Critical Current Density (CCD) in hydrogen evolving system
  - Simple experimental setup and efficient experiment time



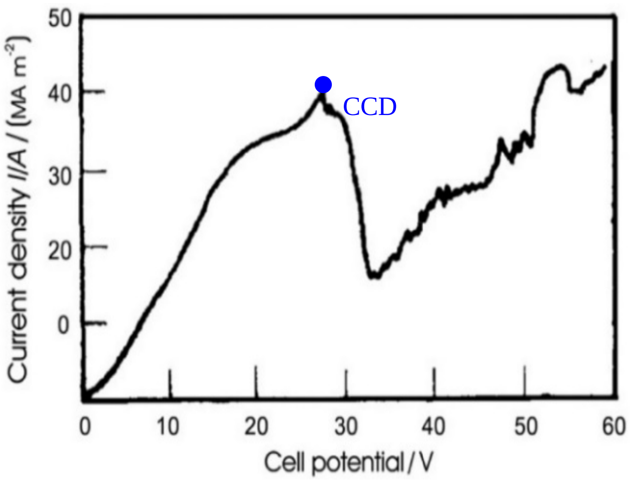
Motivation

Boiling (Heat transfer)
Heat flux
Wall superheat
Critical Heat Flux (CHF)

Hydrogen reduction (Mass transfer)
Current density
Cell potential difference
Critical Current Density (CCD)



Boiling curve (Bejan, 2013)



E-I curve (Sillen et al., 1982)

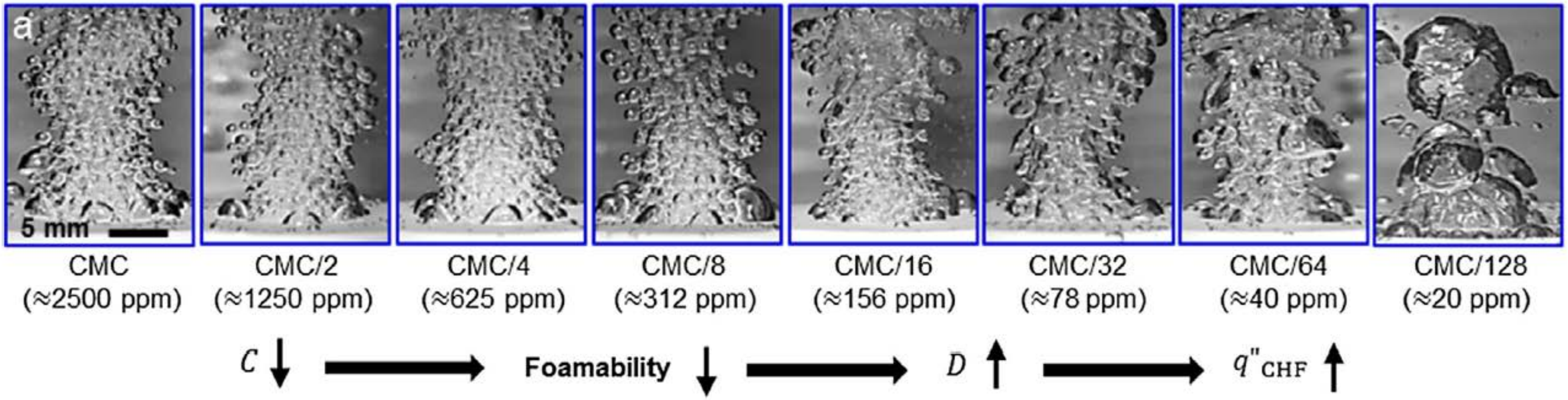
Basic idea

- Same gas generation mechanism: Heterogeneous nucleation
- Gas generation is limited by the thermal reistance and electric resistance

Object of study

- The CHF depends strongly on the surface tension
  - Use of the surfactant can manipulate the surface tension independently

- Raza et al., (2017) performed the CHF experiments varying the surfacntant concentation



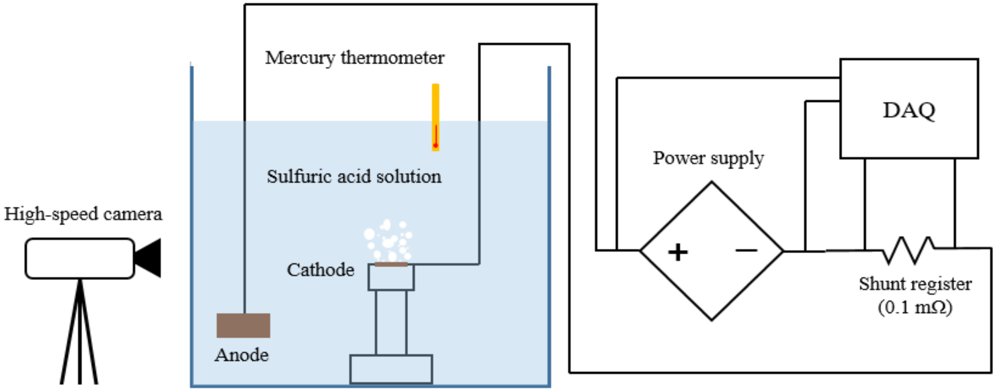
- By analyzing the effect of surface tension on CCD, we aim to improve the analogous relationship between the CHF and the CCD

Experimental setup

- 1.5 M of H_2SO_4 solution was used as working fluid
- CTAB was used as surfactant
  - The experiments were carried out near the CMC (298 ppm at CTAB)
- Copper was used as cathode simulating heater surfaces
  - Roughness average (R_a) is 0.168 μm (Bare surface)

Test matrix

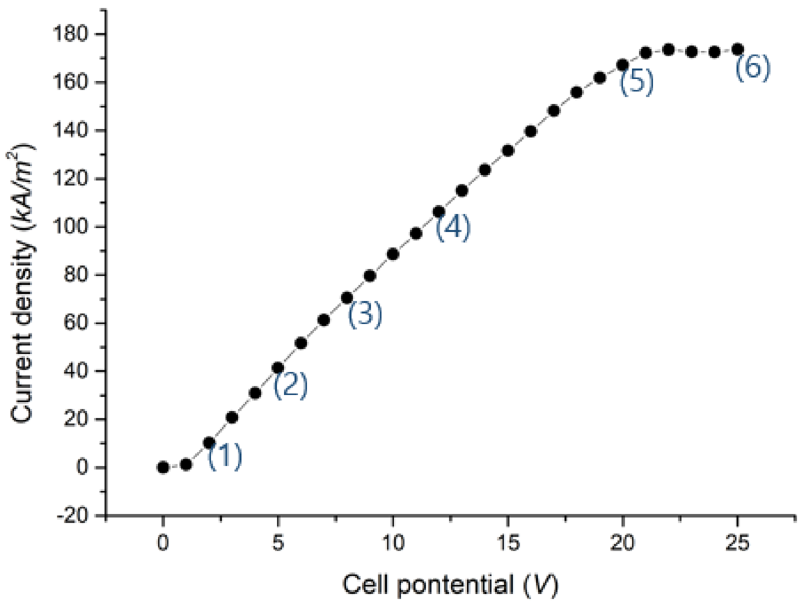
CTAB concentration (ppm)	Surface tension (mN/m)	Contact angle (degree)
0	74. 50	73.89
4	73.22	73.49
11	66.50	73.09
54	60.81	68.82
72	35.17	64.59
145	36.80	64.59
220	35.58	54.17
291	35.11	53.62

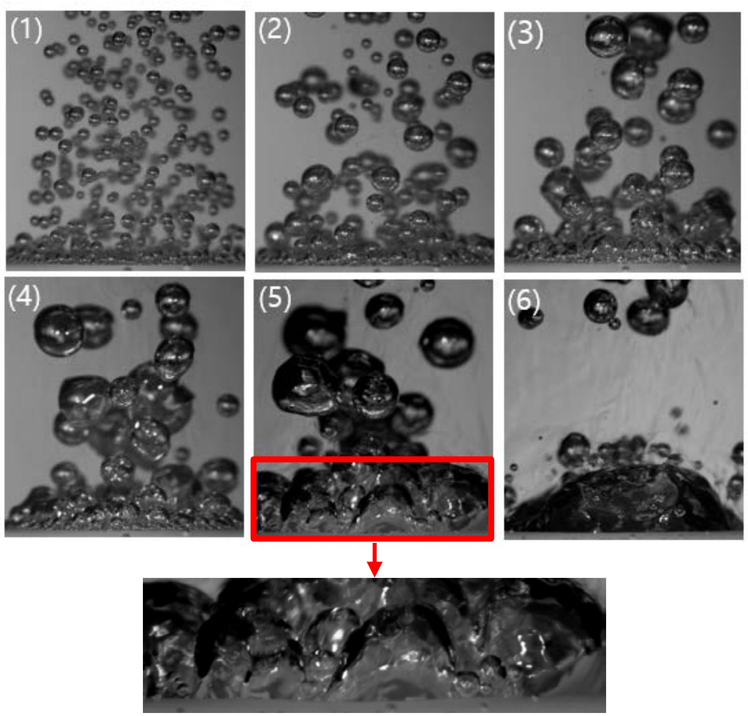


Experimental apparatus and test section

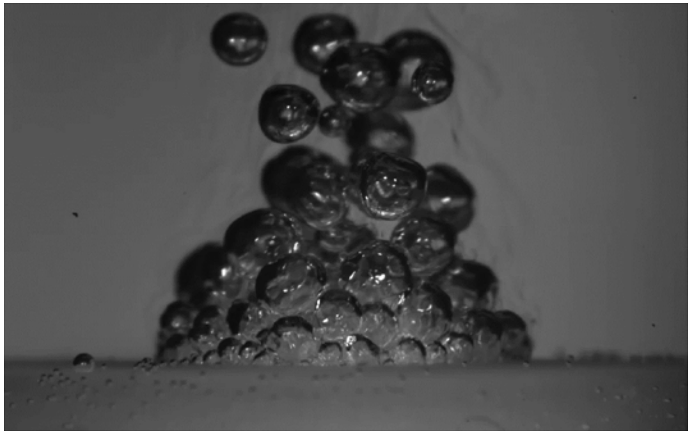
Hydrogen bubble behavior according to the E-I curve

- Current density ↑ ⟶ Size of bubble ↑
- At a certain high current density ⟶ Partial hydrogen film ⟶ CCD
- After the CCD point ⟶ Stable hydrogen film

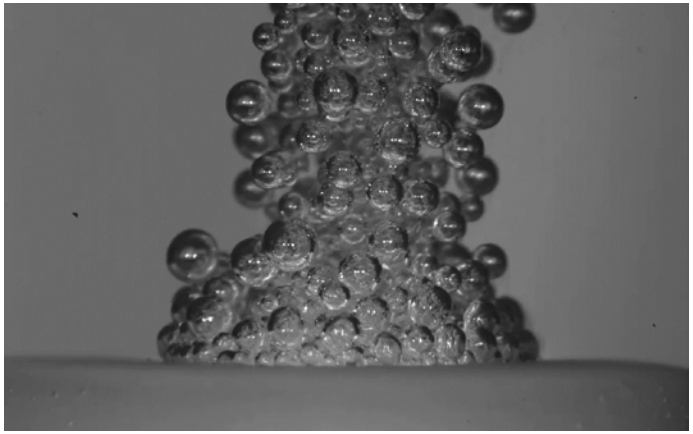




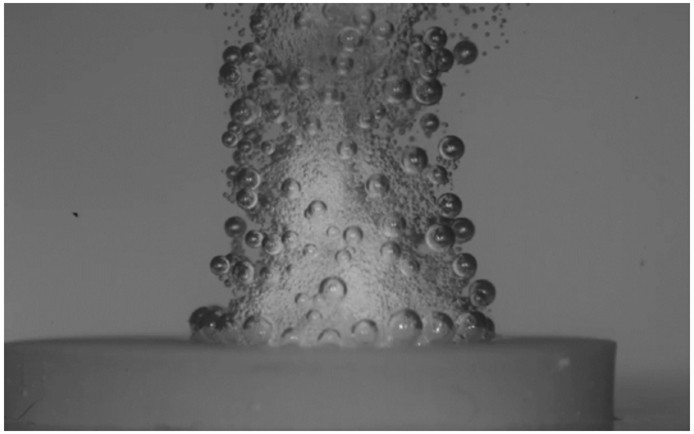
Bubble behaviors according to the surfactant concentration



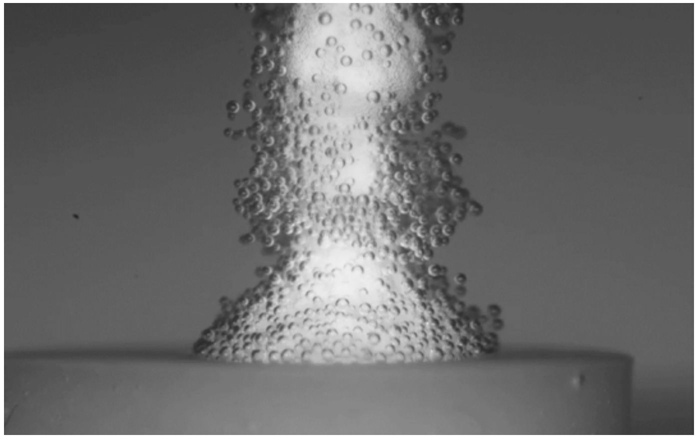
0 ppm



54 ppm



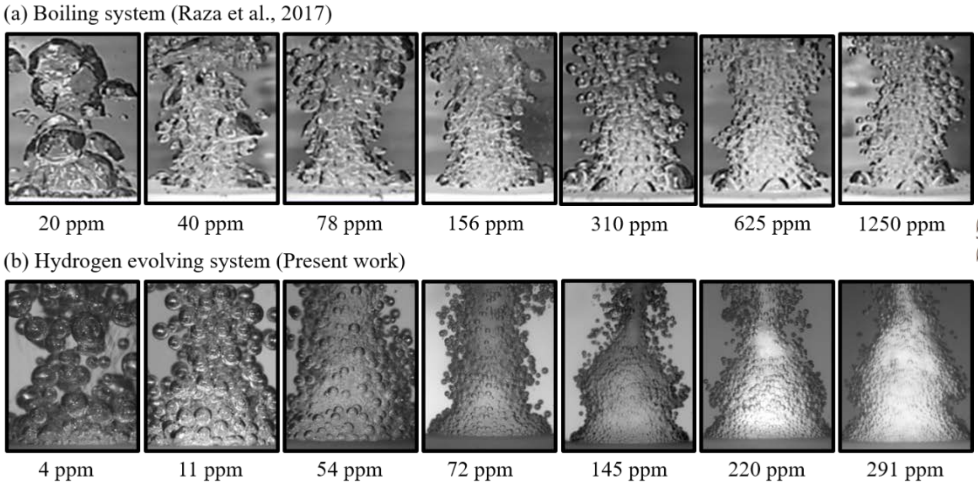
145 ppm

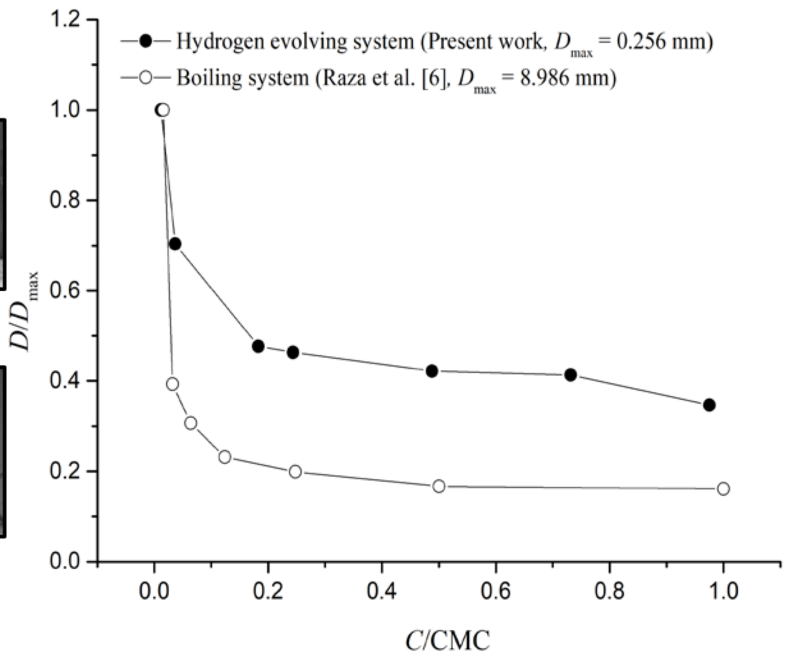


291 ppm

Bubble behaviors according to the surfactant concentration

- Surfactant concentration ↑ ⟶ Surface tension ↓ ⟶ Bubble diameter ↓





Effect of surfactant concentration on bubble diameter

Influence of bubble behavior on CCD

- To analyze the influence of surface tension on the CCD, we borrowed Raza et al.'s analytic process

$$q''_{CHF} = h_{lv}\rho_g v_s \quad (1)$$

- The critical gas velocity (v_g) at the CHF can be expressed considering the gas area fraction (A_R)

$$v_s = v_g \frac{A_b}{A_{hex}} = v_g A_R \quad (2)$$

↓ Combining the Eq. (1)

$$q''_{CHF} = h_{lv}\rho_g v_g A_R \quad (3)$$

Influence of bubble behavior on CCD

- By Faraday law, the CCD can be expressed by analogous relation

$$q''_{CHF} = h_{lv}\rho_g v_g A_R \qquad \approx \qquad I''_{CCD} = \frac{nF}{m}\rho_g v_g A_R \tag{4}$$

- The velocity of bubble can be calculated using the force balance between the buoyancy and drag force

$$(\rho_l - \rho_g) g \frac{1}{6}\pi D^3 = \frac{1}{2} C_d \rho_l \frac{\pi}{4} D^2 v^2 \tag{5}$$

or

$$v = \sqrt{4/(3C_d)}\sqrt{(\rho_l - \rho_g) g D / \rho_l} \tag{6}$$

Influence of bubble behavior on CCD

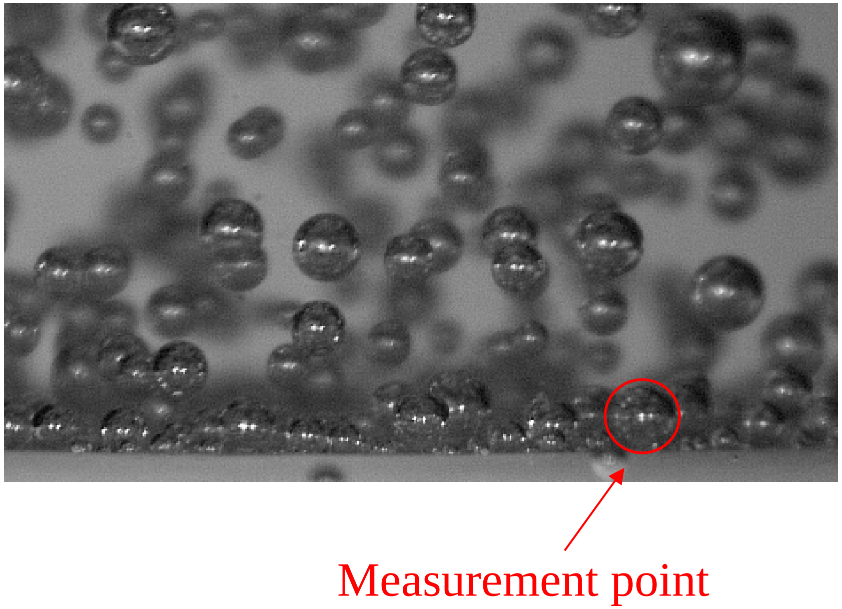
- Combining the Eq. (4) and Eq. (6)

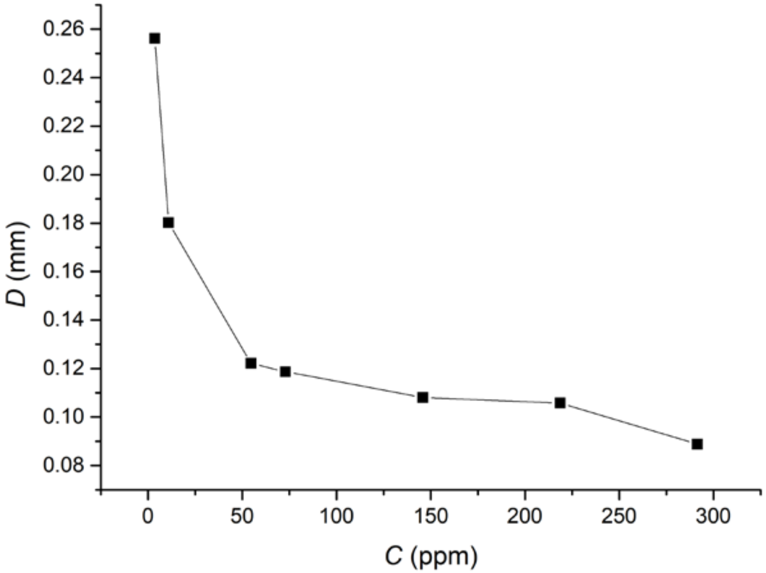
$$I''_{CCD} = \left[\frac{nF}{m} \rho_g \sqrt{\frac{4(\rho_l - \rho_v)g}{3\rho_l}} \right] \frac{A_R \sqrt{D}}{\sqrt{C_d}} \qquad (7)$$

- As a result, the CCD is determined by the D, A_R and C_d
  - D : Mesure just before the CCD
  - A_R : Hexagonal close packing
  - C_d : Regrssion analysis

Evaluation of the *D*

- The *D* just before the CCD
  - 10 samples was measured according to the CTAB concentration
  - Averaged standard deivation is 0.017 mm

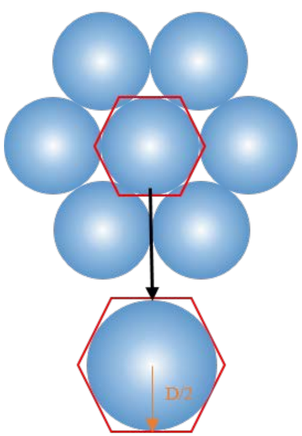




Evaluation of the A_R

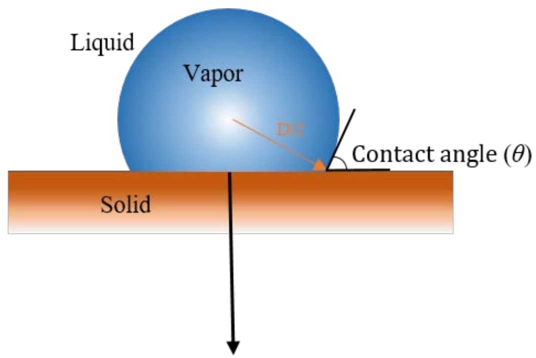
- We assumed that, the bubbles have a hexagonal packing structure

Top view

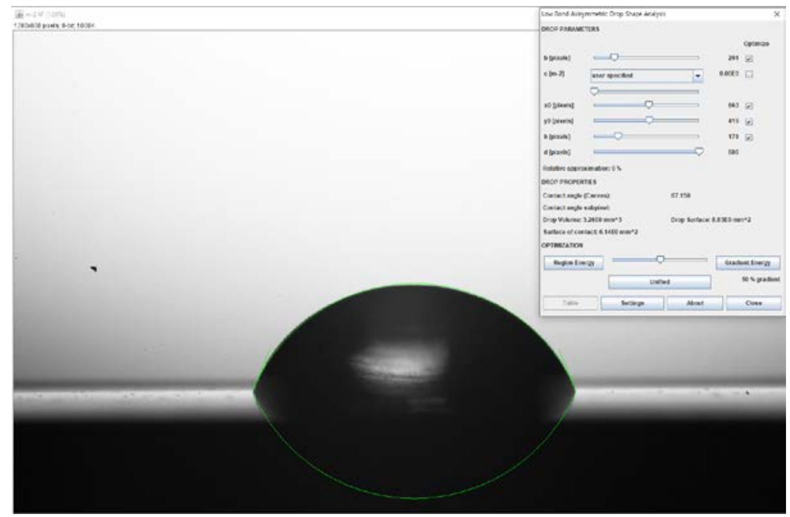


$A_{hex} = \sqrt{3}\, D^2/2$

Side view



$A_b = \pi D^2 sin^2\theta/4$



LB-ADSA method

$$A_R = \frac{A_b}{A_{hex}} = \frac{\pi \sin^2\theta}{2\sqrt{3}} \qquad (8)$$

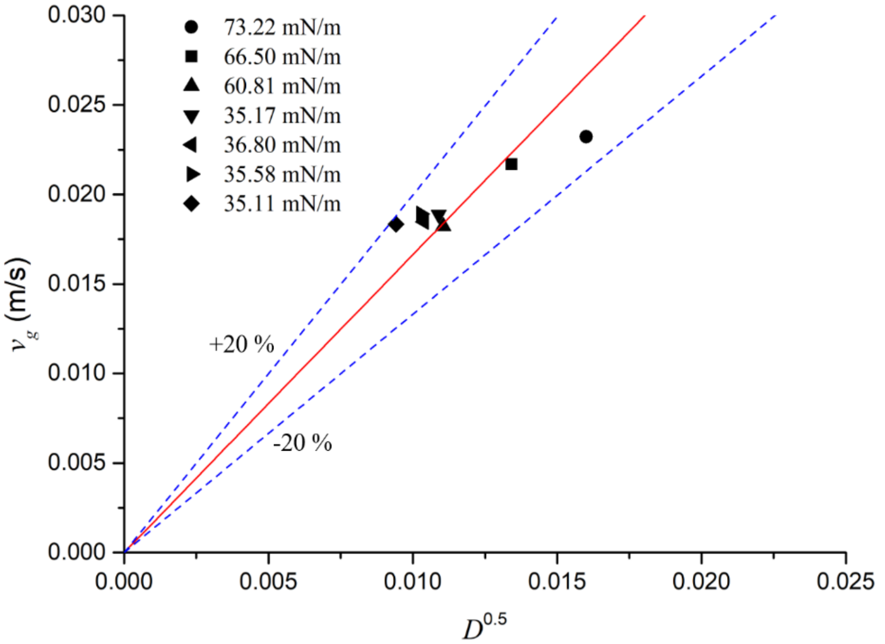
Evaluation of the C_d

- Based on the fact that the cross sectional area is identical to the cathode surface, the C_d can be regarded as a constant independent to the D
  - If the C_d is constant, the velocity is proportional to $D^{0.5}$

$$v = \sqrt{4/(3C_d)}\sqrt{(\rho_l - \rho_v)gD/\rho_l}$$

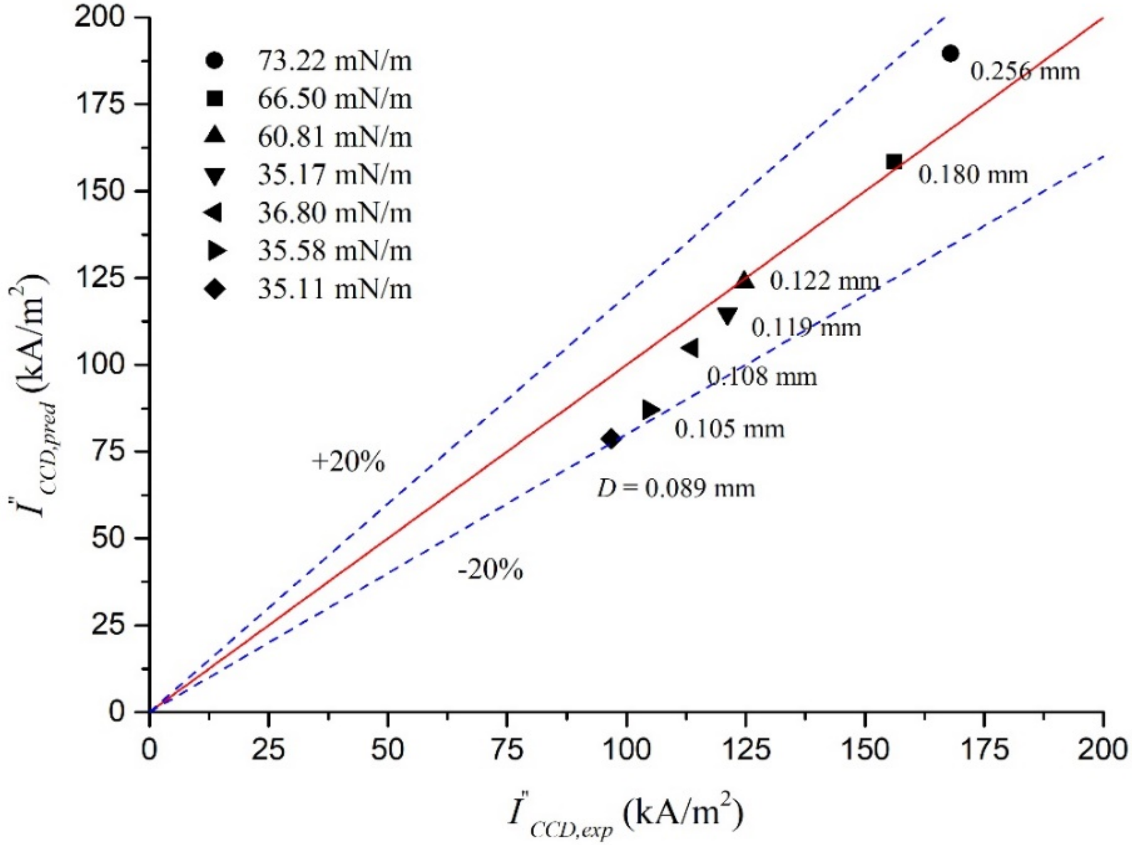
$$I''_{CCD} = \frac{nF}{m}\rho_g v_g A_R$$

$$v_g = \frac{mI''_{CCD}}{nF\rho_g A_R} \qquad (9)$$



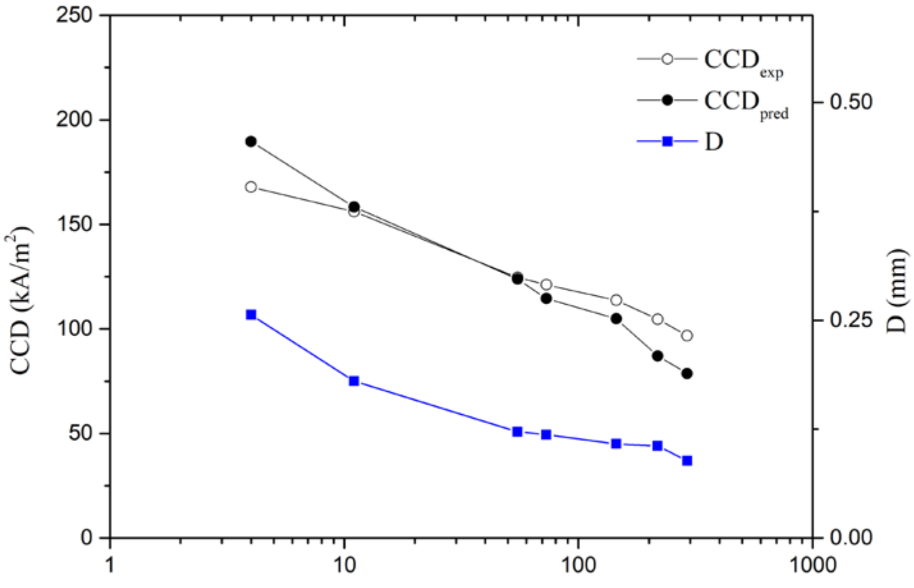
- By regression analysis, C_d = 4.87

Prediction of CCD using D, A_R and C_d

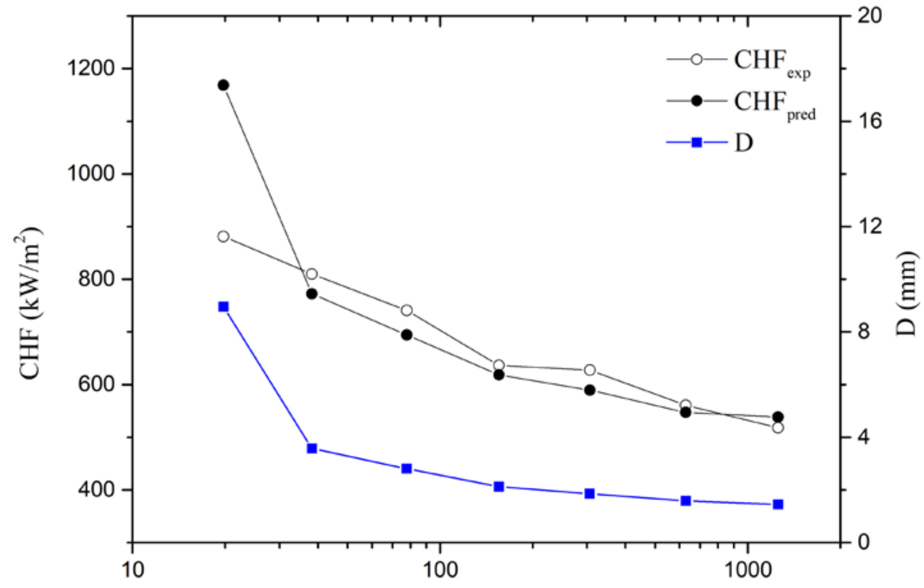


- CCD is well predicted using D, A_R and C_d

Comparison of the CCD and CHF



Present work



Raza et al., 2017

- It is concluded that the influence of surface tension on the CCD showed similar tendency with the CHF.

Conclusions

- Influence of the surface tension on the bubble behavior and CHF were simulated by the hydrogen evolving system

- As the surfactant concentration increased, the surface tension was decreased
  - Decrease of the surface tension decreases the bubble diameter and the CCD/CHF

- The relationship between the bubble behavior and the CCD was analyzed
  - Equation for the CCD prediction as a function of bubble velocity is derived
  - The CCD is predicted using the bubble parameters D, A_R, C_d
  - The similar trend was showed in the CHF

- It is concluded that the CCD is significantly affected by surface tesnion, similar to the CHF

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Appendix

Verification of the C_d

- By regression analysis, C_d = 4.87
- C_d of Single bubble can be calculated

$$C_d = \frac{16}{Re}\left\{1+\left[\frac{8}{Re}+\frac{1}{2}\left(1+3.315Re^{-0.5}\right)\right]^{-1}\right\} \qquad (10)$$

- Using the Eq. (10), C_d = 9.42
- Yang et al., (2018) and Tao et al., (2019) repoted that when the bubble form the column with the large gas fraction the C_d is decreased