CFD Simulations and Experimental Verification on Nucleate Pool Boiling of Liquid Nitrogen

XIONG Wei

K. Tang, Chen Jianye, Wang Yuchen, Zhang Xiaobin*

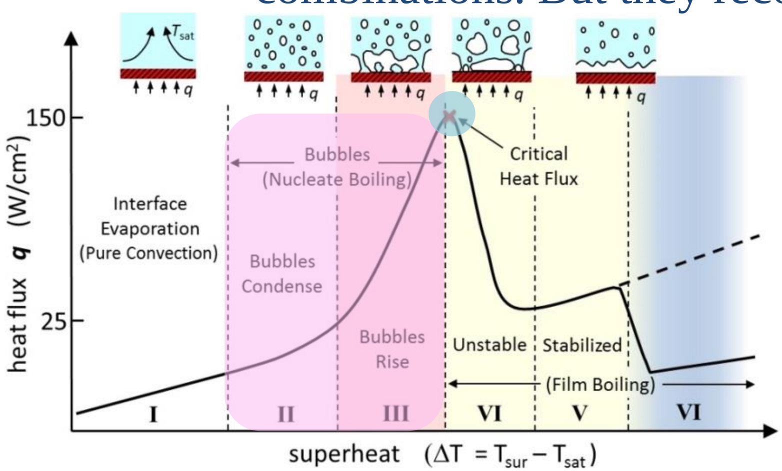
Institute of Refrigeration and Cryogenics, Zhejiang University,

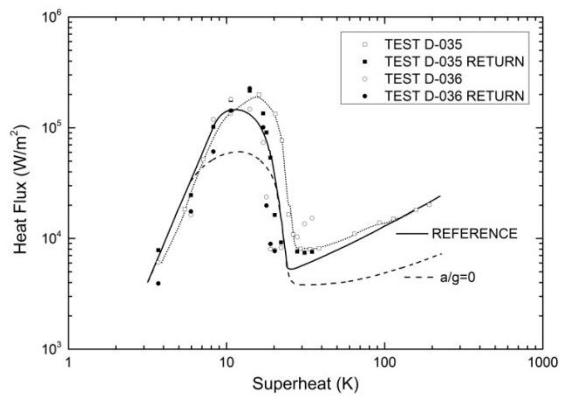
Hangzhou, 310027, China

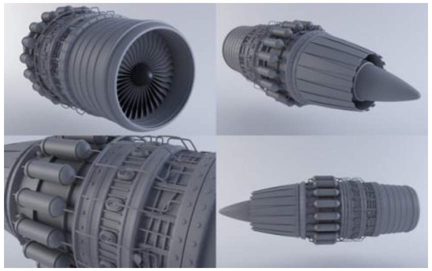
Supported by
National High-Tech Research & Development
Program of China (863 Program) (SS2013AA050503)

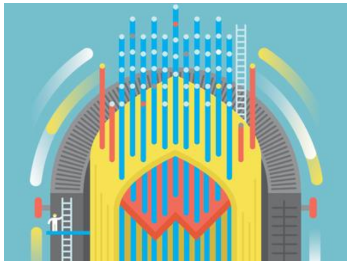
Stories of Boiling

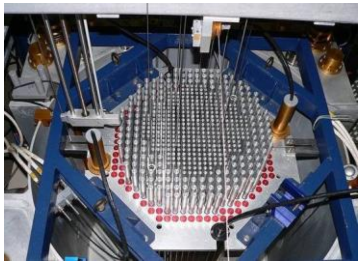
- Nucleate boiling is a useful and common way of heat transfer in mechanical industry.
- Bubbles **generated, merged, and coalesced** in the nucleate boiling region, leading to a complicated temperature and pressure field distribution.
- Experiments using cryogenic fluids are much more intricate and complicated than experiments conducted with common fluids.
- The UMich and NASA have already conducted profound boiling researches on LH_2 & LN_2 in 1970[1].They have formulated boiling curves under various boiling combinations. But they recorded **no photographs or micro bubble analysis.**

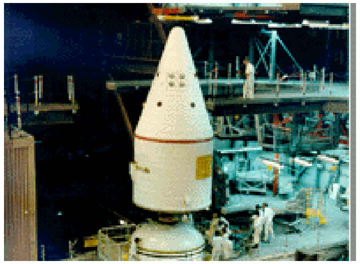






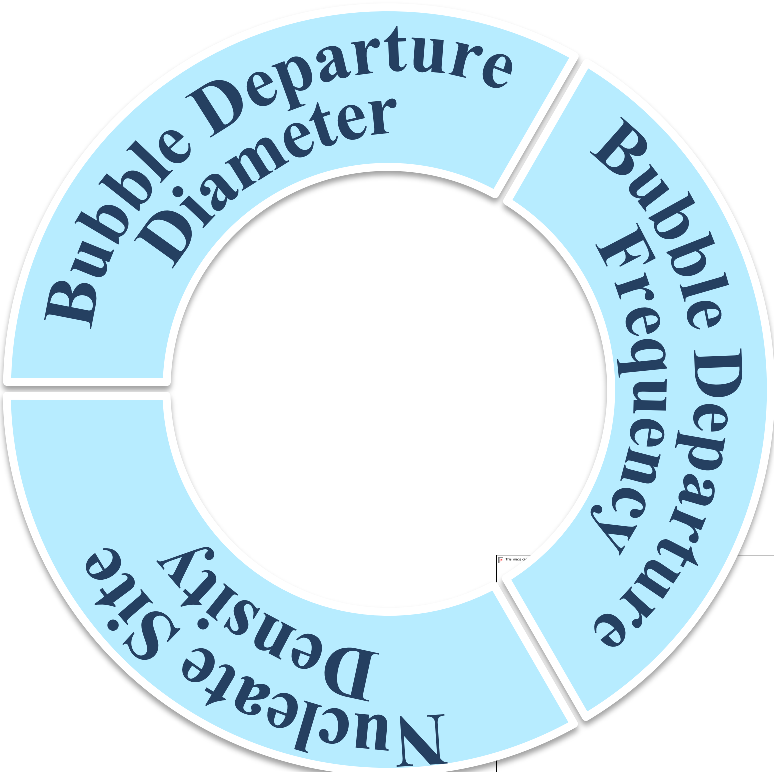






[1] Merte H, Laboratory. U O M H. Incipient and steady boiling of liquid nitrogen and liquid hydrogen under reduced gravity[EB/OL]. Heat Transfer Laboratory, University of Michigan, 1970.

State-of-the-art CORRELATIONS



[1] Carey V P. Liquid-vapor phase-change phenomena : an introduction to the thermophysics of vaporization and condensation processes in heat transfer equipment[M]. Washington, D.C.:

State-of-the-art CORRELATIONS

Bubble Departure Frequency

Contributors	Correlations
Cole	$f=\left[\frac{4g(\rho_l-\rho_g)}{3D_b\rho_l}\right]^{0.5}$
Zuber	$f=\frac{0.59}{D_b}\left[\frac{\sigma g(\rho_l-\rho_g)}{{\rho_l}^2}\right]^{0.25}$
Kocamustafaogullari and Ishii	$f=\frac{1.18}{D_b}\left[\frac{\sigma g(\rho_l-\rho_g)}{{\rho_l}^2}\right]^{0.25}$
Hatton and Hall	$f=\frac{3}{\pi\eta_l}\left[\frac{16k_l\sigma T_{sat}}{(h_{fg}\rho_g)^2 D_b D_c}\right]^2$
Ivey	$f=0.9\left(\frac{g}{D_b}\right)^{0.5}$ for hydrodynamic region
	$f=0.44\left(\frac{g}{D_b^3}\right)^{0.25}$ for transition region
	$f=\frac{C}{D_b^2}$ for thermodynamic region
Stephan	$f=\frac{1}{\pi}\sqrt{\frac{g}{2D_b}}\left[1+\frac{4\sigma}{D_b^2\rho_g g}\right]^{0.5}$

[1] Carey V P. Liquid-vapor phase-change phenomena : an introduction to the thermophysics of vaporization and condensation processes in heat transfer equipment[M]. Washington, D.C.:

State-of-the-art CORRELATIONS

Bubble Departure Diameter

Contributors	Correlations
Fritz	$D_b(D_{bF}) = 0.0208\varphi\left[\frac{\sigma}{g(\rho_l-\rho_g)}\right]^{0.5}$
Zuber	$D_b = \left[\frac{6\sigma}{g(\rho_l-\rho_g)}\frac{k\Delta T_{sup}}{Q_w}\right]^{1/3}$
Han and Griffith	$D_b = 0.843\varphi\left[\frac{2\sigma}{g(\rho_l-\rho_g)}\right]^{0.5}$
Cole and Shulman	$D_b = \left[\frac{\sigma}{g(\rho_l-\rho_g)}\right]^{0.5} P^{-1}$
Cole	$D_b = \varphi\left[\frac{\sigma}{g(\rho_l-\rho_g)}\right]^{0.5}\frac{\rho_l C_{p,l}\Delta T_{sup}}{\rho_g h_{fg}}$
Cole and Rohsenow	$D_b = 1.5 \times 10^{-4}\left[\frac{\sigma}{g(\rho_l-\rho_g)}\right]^{0.5}\left(\frac{\rho_l C_{p,l} T_{sat}}{\rho_g h_{fg}}\right)^{1.25}$
Tolubinskiy and Kostanchuk	$D_b = D_{ref}\exp\left(-\frac{\Delta T_{sub}}{\Delta T_{refd}}\right)$
Ünal	$D_b = \frac{2.42\times 10^{-5} P^{0.709} a}{\sqrt{b\phi}}$ $a = \frac{(Q_w - h_l\Delta T_{sub})^{1/3} k_l}{2C^{1/3} h_{fg}\sqrt{\pi k_l/\rho_l C_{p,l}\rho_g}}\sqrt{\frac{k_w\rho_w C_{p,w}}{k_l\rho_l C_{p,l}}}$, $C = \frac{h_{fg}\mu_l\left[C_{p,l}/(0.013 h_{fg} Pr^{1.7})\right]^3}{\left[\sigma/(\rho_l-\rho_g)g\right]^{0.5}}$, $b = \Delta T_{sub}/2(1-\rho_g/\rho_l)$, $\phi = \begin{cases}\left(\frac{u_l}{0.61}\right)^{0.47} & for\ u_l \geq 0.61\ m/s \\ 1.0 & for\ u_l < 0.61\ m/s\end{cases}$
Kocamustafaogullari and Ishii	$D_b = 0.0012\left(\frac{\rho_l-\rho_g}{\rho_l}\right)^{0.9} D_{bF}$
Lee, et al	$\mathrm{D_d} = 8437.5\frac{\alpha_l^2\rho_l}{\sigma}\mathrm{Ja}^2$
Kim	$\sqrt{\frac{(\rho_l-\rho_v)}{\sigma}}\ \mathrm{D_d} = 0.1649\mathrm{Ja}^{0.7}$

[1] Carey V P. Liquid-vapor phase-change phenomena : an introduction to the thermophysics of vaporization and condensation processes in heat transfer equipment[M]. Washington, D.C.:

State-of-the-art CORRELATIONS

Nucleate Site Density

Contributors	Correlations	
Cornwel and Brown	$N_a \sim T_{sup}^{m}$	m = 4.5
Lemmert and Chawla	$N_a = \left[n \Delta T_{sup} \right]^{m}$	
Koncar et al.		n = 185 , m = 1.805
Kurul and Podowski		n = 210 , m = 1.805
Krepper et al.	$N_a = n \left[\frac{\Delta T_{sup}}{\Delta T_{refN}} \right]^{m}$	n = 0.8 × 10^6, ΔT_{refN} =10 K (Bartolomej et al. [31]) n = 3 × 10^7 (DEBORA 1-2 [33]) n = 5 × 10^6 (DEBORA 3-7 [33])
Kirichenko	$N_a = n \left[\frac{\rho_g h_{fg} \Delta T_{sup}}{\sigma T_{sat}} \right]^{m}$	n = 1×10^{-7} , m = 2, $P/P_{cr} \geq 0.04$ n = 6.25×10^{-6} , m = 3, $P/P_{cr} < 0.04$

[1] Carey V P. Liquid-vapor phase-change phenomena : an introduction to the thermophysics of vaporization and condensation processes in heat transfer equipment[M]. Washington, D.C.:

State-of-the-art CORRELATIONS

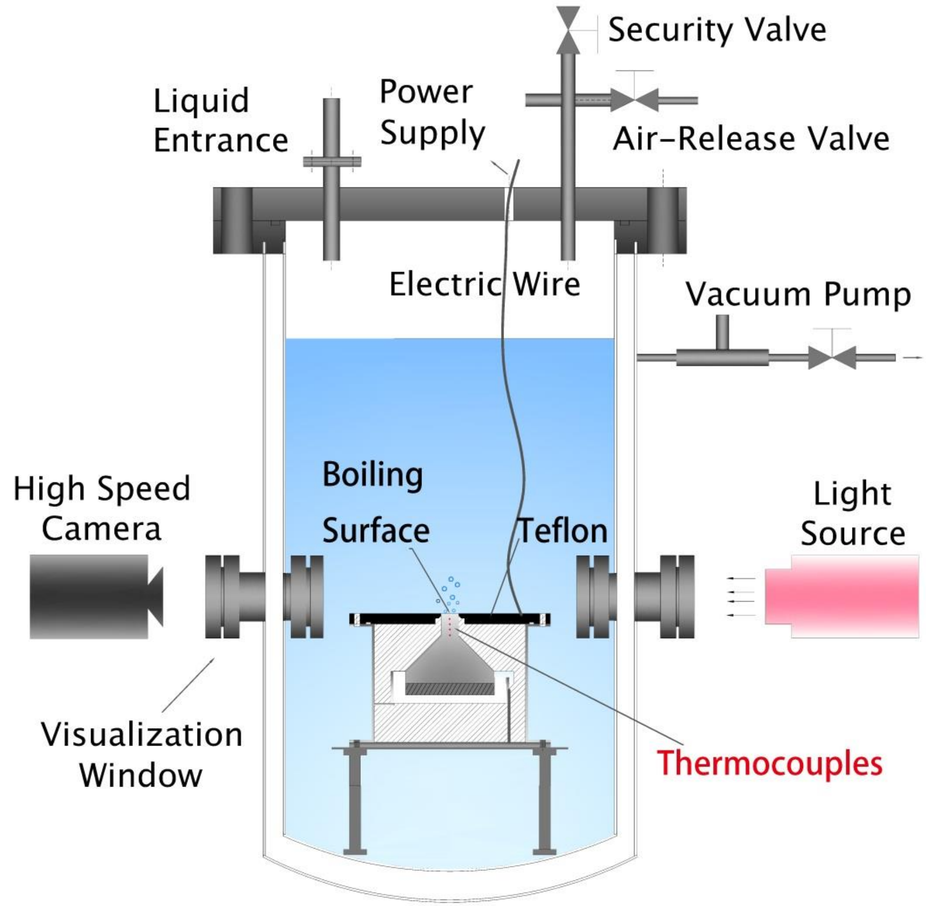
Nucleate Site Density

Contributors	Correlations	
Cornwel and Brown	$N_a \sim T_{sup}^m$	m = 4.5
Lemmert and Chawla	$N_a = [n\Delta T_{sup}]^m$	
Koncar et al.		n = 185 , m = 1.805
Kurul and Podowski		n = 210 , m = 1.805
Krepper et al.	$N_a = n\left[\frac{\Delta T_{sup}}{\Delta T_{refN}}\right]^m$	n = 0.8 × 10^6, ΔT_{refN} =10 K (Bartolomej et al. [31]) n = 3 × 10^7 (DEBORA 1-2 [33]) n = 5 × 10^6 (DEBORA 3-7 [33])
Kirichenko	$N_a = n\left[\frac{\rho_g h_{fg}\Delta T_{sup}}{\sigma T_{sat}}\right]^m$	n = 1×10^{-7} , m = 2, $P/P_{cr} \geq 0.04$ n = 6.25×10^{-6} , m = 3, $P/P_{cr} < 0.04$

- Mostly applied to water, organic fluids, and some common fluids only[1];
- Researches concerning cryogenic fluids such as He3, H2, and N2 lack enough experimental comparisons and verifications, accuracy can't be guaranteed;
- Researches on nucleate boiling of LN2 mainly focused on flow boiling in micro tube. It still remains blank in researches on bubble departure frequency and diameter.

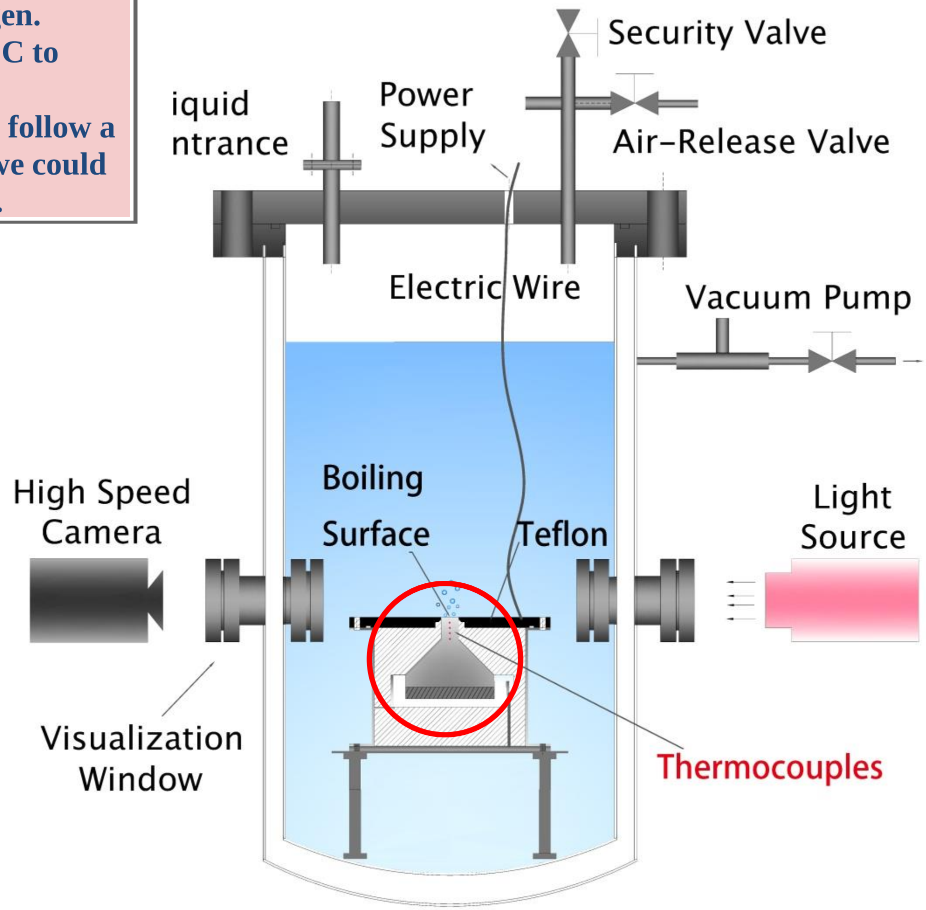
[1] Carey V P. Liquid-vapor phase-change phenomena : an introduction to the thermophysics of vaporization and condensation processes in heat transfer equipment[M]. Washington, D.C.:

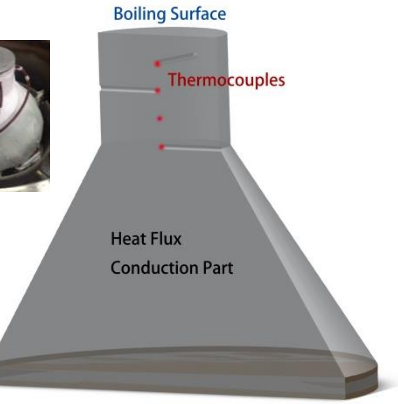
Experimental Setup

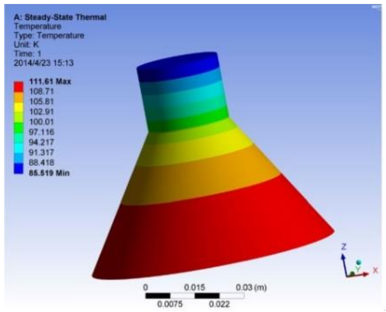


Experimental Setup

- 4 thermocouples are set in the cone, another thermocouple measures the temperature of liquid nitrogen.
- Using Keithley 2700 and HSC to acquire the measured data.
- The 4 points are expected to follow a linear pattern, from which we could derive the wall temperature.

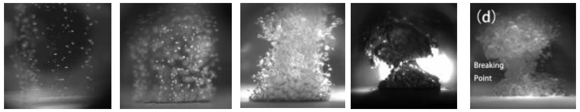


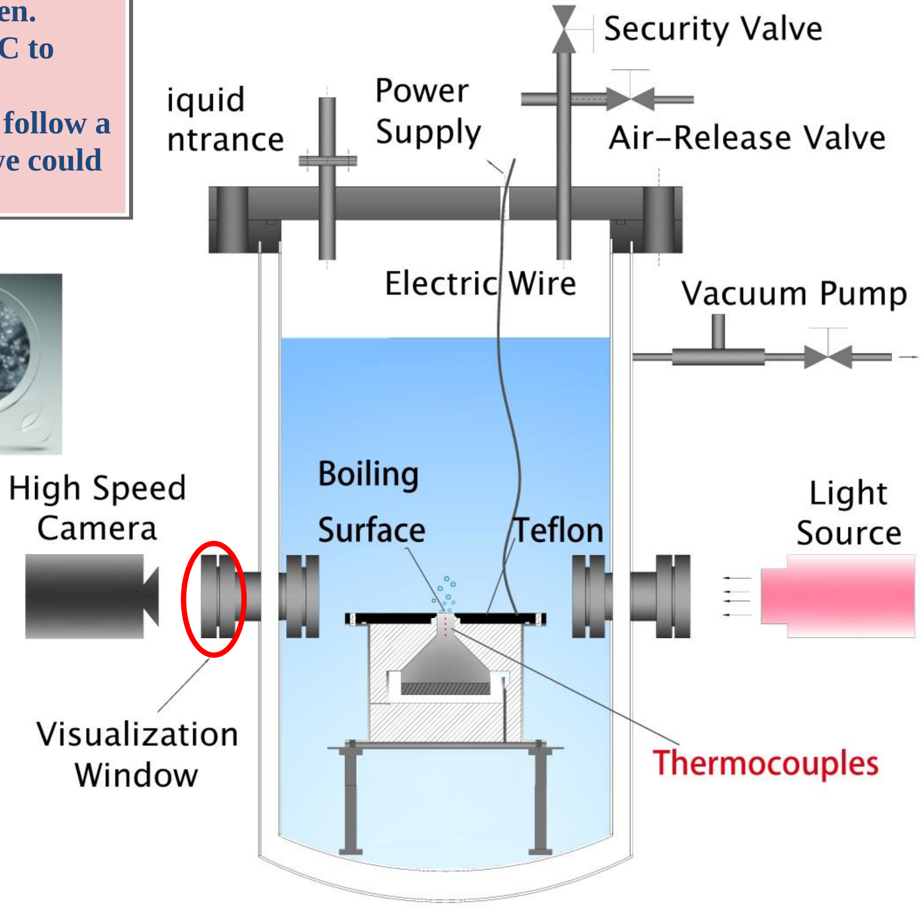


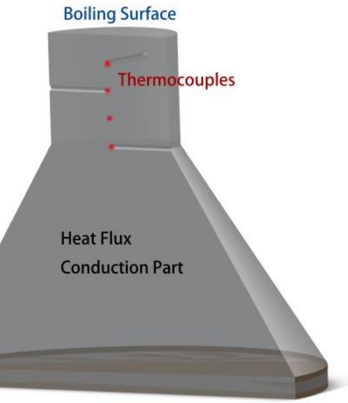


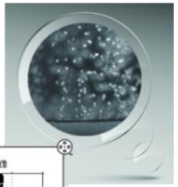
Experimental Setup

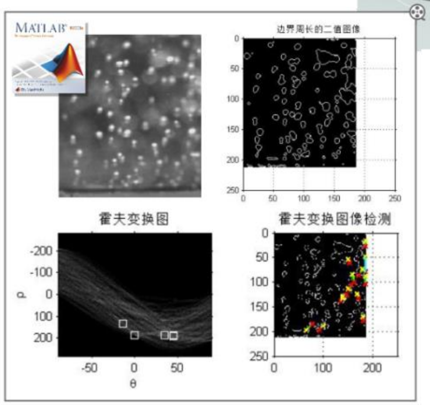
- 4 thermocouples are set in the cone, another thermocouple measures the temperature of liquid nitrogen.
- Using Keithley 2700 and HSC to acquire the measured data.
- The 4 points are expected to follow a linear pattern, from which we could derive the wall temperature.

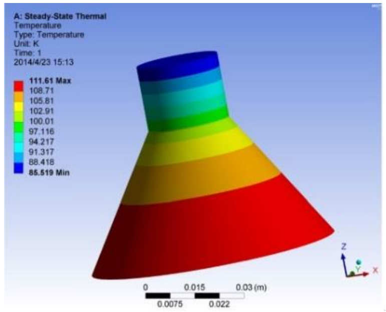






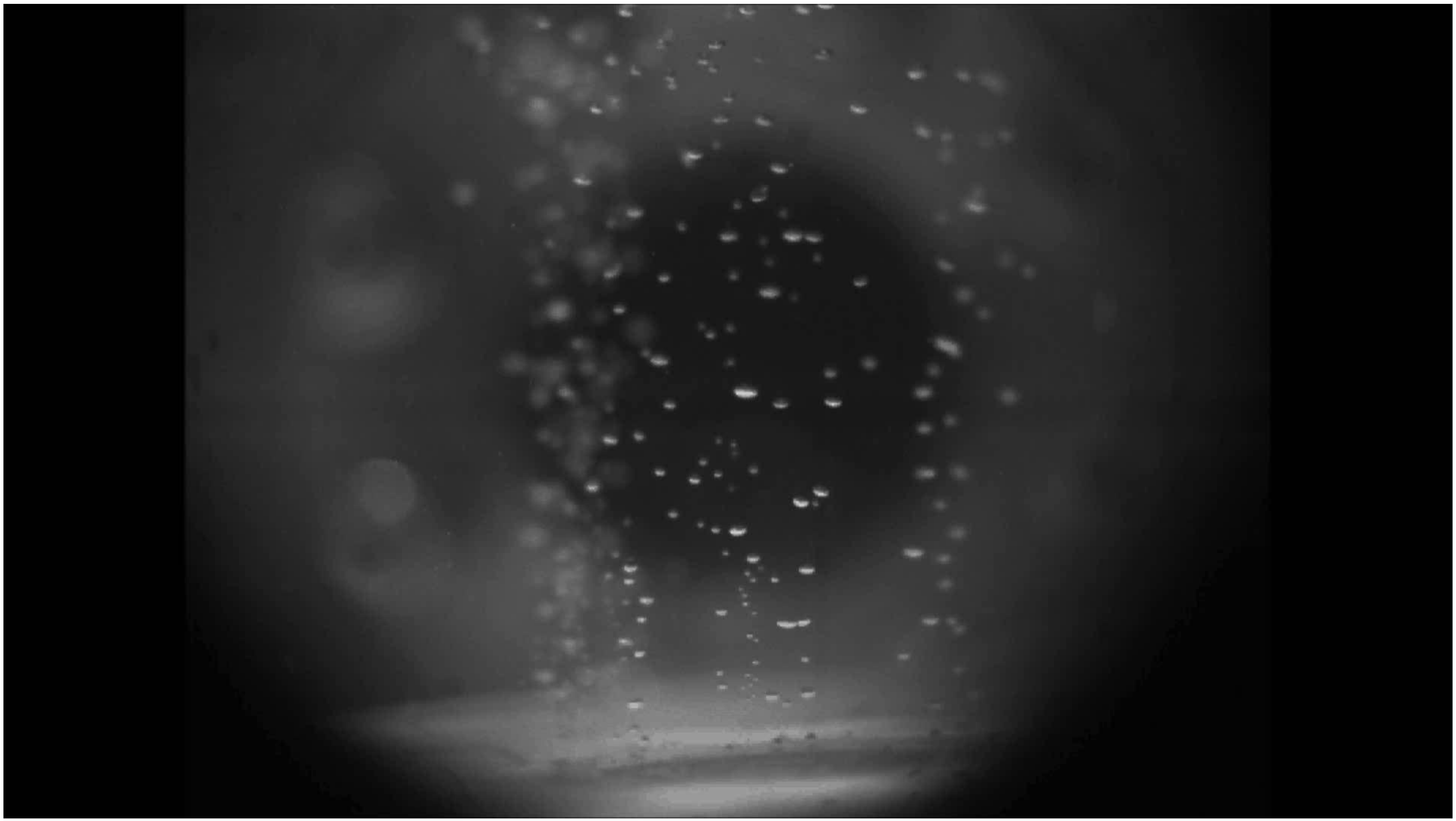




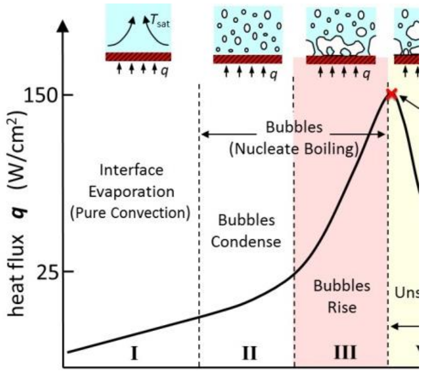


Video Clip From Experiment

What's about this magic?

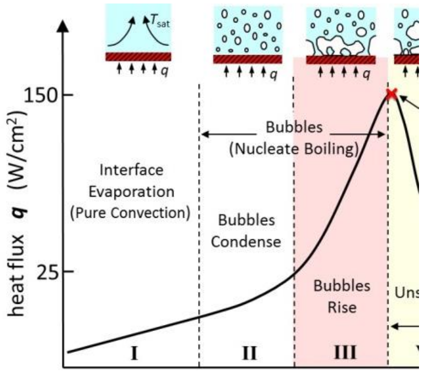


Experimental Phenomena

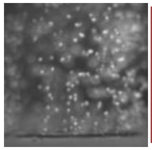


[1] Jin T, Zhang S Y, Tang K, et al. Observation and analysis of the detachment frequency of coalesced bubbles in pool boiling liquid nitrogen[J]. Cryogenics, 2011, 51(9): 516-520.

Experimental Phenomena



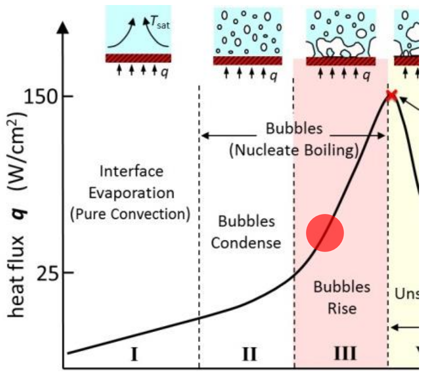
$$\dot{q} < \dot{q}_{LHF}$$



1st Stage: Bubbles tend to be discrete. Experimental data can be **patched into CFD models** for a more accurate verification.

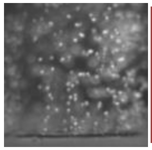
[1] Jin T, Zhang S Y, Tang K, et al. Observation and analysis of the detachment frequency of coalesced bubbles in pool boiling liquid nitrogen[J]. Cryogenics, 2011, 51(9): 516-520.

Experimental Phenomena



Low Heat Flux

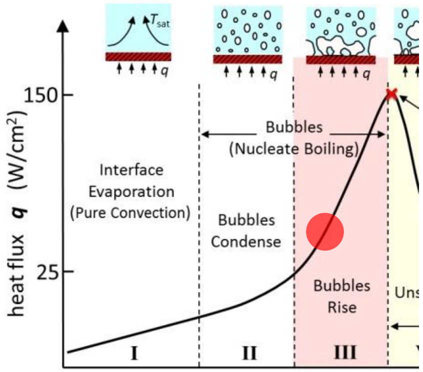
$$\dot{q} < \dot{q}_{LHF}$$



1st Stage: Bubbles tend to be discrete. Experimental data can be **patched into CFD models** for a more accurate verification.

[1] Jin T, Zhang S Y, Tang K, et al. Observation and analysis of the detachment frequency of coalesced bubbles in pool boiling liquid nitrogen[J]. Cryogenics, 2011, 51(9): 516-520.

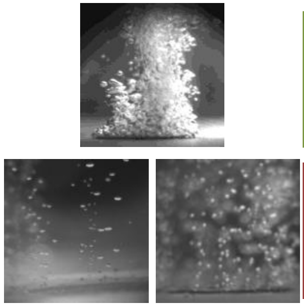
Experimental Phenomena



$\dot{q}_{LHF} < \dot{q} < \dot{q}_{FDNB}$

Low Heat Flux

$\dot{q} < \dot{q}_{LHF}$

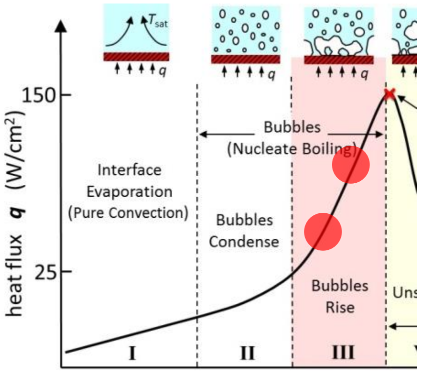


2nd Stage: Difficult to define the exact diameter. Bubbles followed a random pattern neither discretely nor as bubble stems.

1st Stage: Bubbles tend to be discrete. Experimental data can be **patched into CFD models** for a more accurate verification.

[1] Jin T, Zhang S Y, Tang K, et al. Observation and analysis of the detachment frequency of coalesced bubbles in pool boiling liquid nitrogen[J]. Cryogenics, 2011, 51(9): 516-520.

Experimental Phenomena

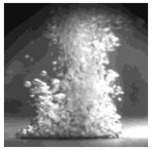


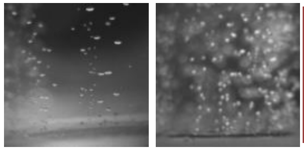
Fully Developed Nucleate Boiling

$$\dot{q}_{LHF} < \dot{q} < \dot{q}_{FDNB}$$

Low Heat Flux

$$\dot{q} < \dot{q}_{LHF}$$



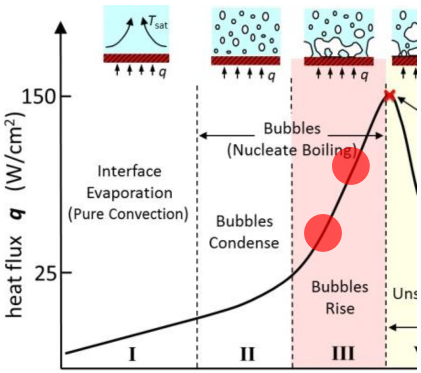


2nd Stage: Difficult to define the exact diameter. Bubbles followed a random pattern neither discretely nor as bubble stems.

1st Stage: Bubbles tend to be discrete. Experimental data can be **patched into CFD models** for a more accurate verification.

[1] Jin T, Zhang S Y, Tang K, et al. Observation and analysis of the detachment frequency of coalesced bubbles in pool boiling liquid nitrogen[J]. Cryogenics, 2011, 51(9): 516-520.

Experimental Phenomena



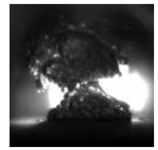
$\dot{q}_{FDNB} < \dot{q} < \dot{q}_{CHF}$

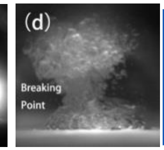
Fully Developed Nucleate Boiling

$\dot{q}_{LHF} < \dot{q} < \dot{q}_{FDNB}$

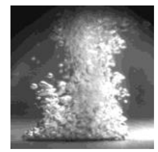
Low Heat Flux

$\dot{q} < \dot{q}_{LHF}$

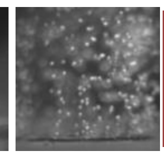




3rd Stage: The merged bubble is **a unity-Bubble Stem**. $f = 13.47s^{-1}$[1] ,the merged bubble stem is treated as one bulk.



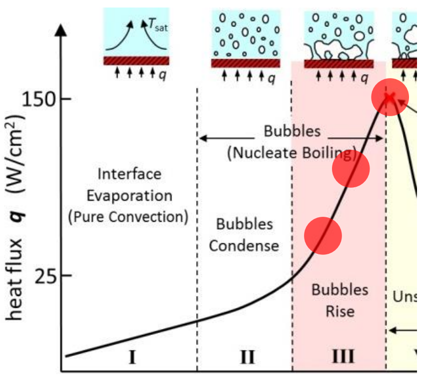
2nd Stage: Difficult to define the exact diameter. Bubbles followed a random pattern neither discretely nor as bubble stems.



1st Stage: Bubbles tend to be discrete. Experimental data can be **patched into CFD models** for a more accurate verification.

[1] Jin T, Zhang S Y, Tang K, et al. Observation and analysis of the detachment frequency of coalesced bubbles in pool boiling liquid nitrogen[J]. Cryogenics, 2011, 51(9): 516-520.

Experimental Phenomena



Critical Heat Flux

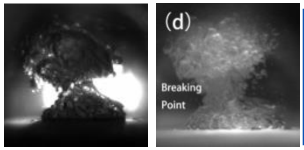
$$\dot{q}_{FDNB} < \dot{q} < \dot{q}_{CHF}$$

Fully Developed Nucleate Boiling

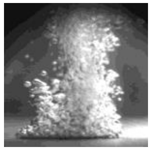
$$\dot{q}_{LHF} < \dot{q} < \dot{q}_{FDNB}$$

Low Heat Flux

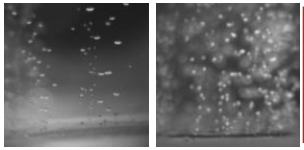
$$\dot{q} < \dot{q}_{LHF}$$



3rd Stage: The merged bubble is **a unity-Bubble Stem**. $f = 13.47s^{-1}$[1] ,the merged bubble stem is treated as one bulk.



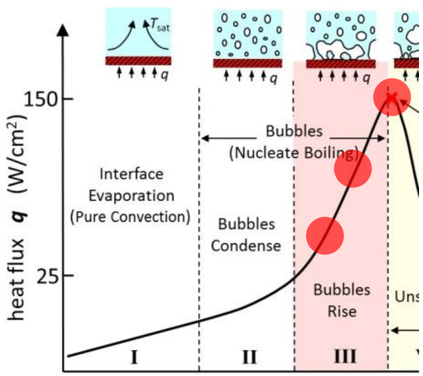
2nd Stage: Difficult to define the exact diameter. Bubbles followed a random pattern neither discretely nor as bubble stems.



1st Stage: Bubbles tend to be discrete. Experimental data can be **patched into CFD models** for a more accurate verification.

[1] Jin T, Zhang S Y, Tang K, et al. Observation and analysis of the detachment frequency of coalesced bubbles in pool boiling liquid nitrogen[J]. Cryogenics, 2011, 51(9): 516-520.

Experimental Phenomena



Critical Heat Flux

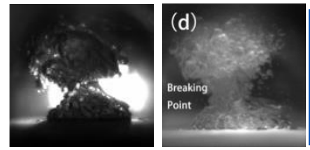
$\dot{q}_{FDNB} < \dot{q} < \dot{q}_{CHF}$

Fully Developed Nucleate Boiling

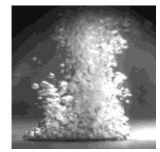
$\dot{q}_{LHF} < \dot{q} < \dot{q}_{FDNB}$

Low Heat Flux

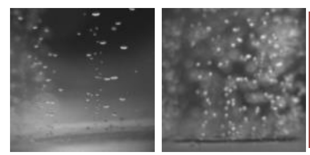
$\dot{q} < \dot{q}_{LHF}$



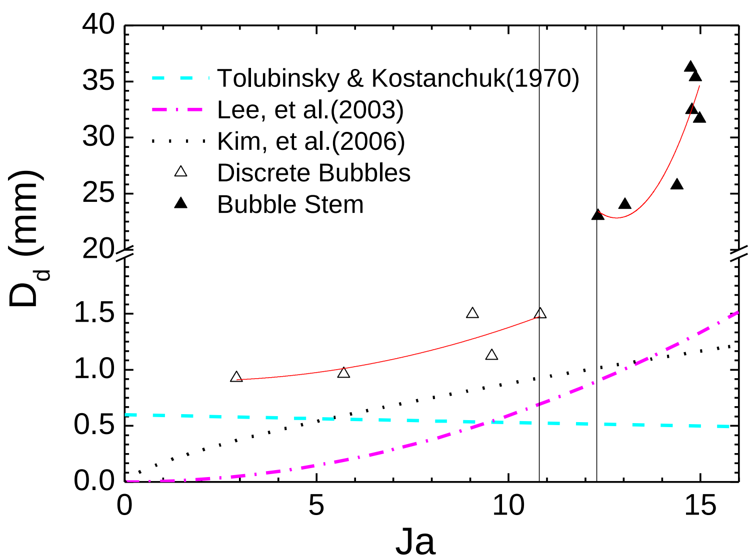
3rd Stage: The merged bubble is **a unity-Bubble Stem**. $f = 13.47s^{-1}$[1] ,the merged bubble stem is treated as one bulk.



2nd Stage: Difficult to define the exact diameter. Bubbles followed a random pattern neither discretely nor as bubble stems.



1st Stage: Bubbles tend to be discrete. Experimental data can be **patched into CFD models** for a more accurate verification.



For low heat flux:

f =Experimental Data

$D_d = 0.007Ja^2 - 0.024Ja + 0.92$;

For fully developed nucleate boiling:

$f = 13.47s^{-1}$

$D_d = 2.526Ja^2 - 64.74Ja + 437.63$.

[1] Jin T, Zhang S Y, Tang K, et al. Observation and analysis of the detachment frequency of coalesced bubbles in pool boiling liquid nitrogen[J]. Cryogenics, 2011, 51(9): 516-520.

Boiling Models

- **Area of influence:**

$$A_b = KN_A\frac{\pi}{4}D_d^2 \quad , \quad K = 4.8e^{\left(-\frac{Ja}{80}\right)}$$

- **Nucleate side density:**

$$N_A = C \cdot \left(\frac{h_{fv}\rho_v(T_w - T_l)}{\sigma T_{sat}}\right)^3$$

$$C = 625 \times 10^{-16}.$$

- **Bubble departure diameter**

$$D_d = 0.007Ja^2 - 0.024Ja + 0.92$$

$$D_d = 2.526Ja^2 - 64.74Ja + 437.63$$

Compared with the observations, the existing correlations are far from satisfactory. Data is correlated based on our experimental results.

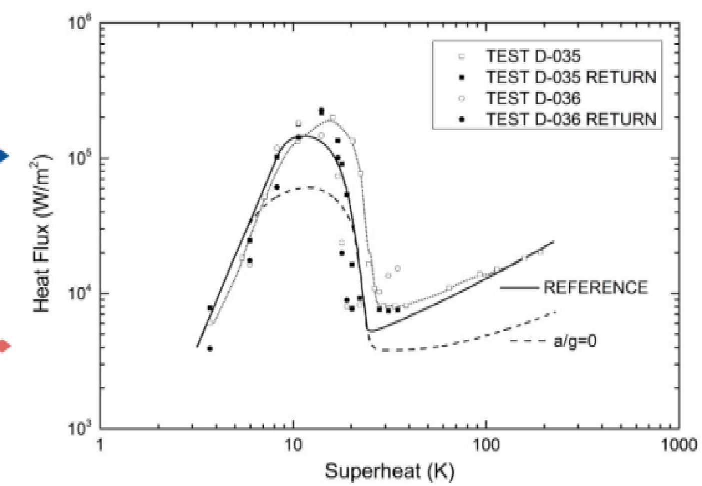
- **Bubble departure frequency**

Similar to the situations of the departure diameter, the bubble departure frequency is also obtained from our experimental results.

Research Procedures

UMich & NASA Experimental Data

【Heat Flux】 vs. 【Super-heat】

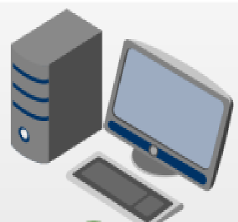


Our Experimental Data

Data

【Heat Flux】 vs. 【Super-heat】

Analyse



【Heat Flux】 vs. 【Super-heat】

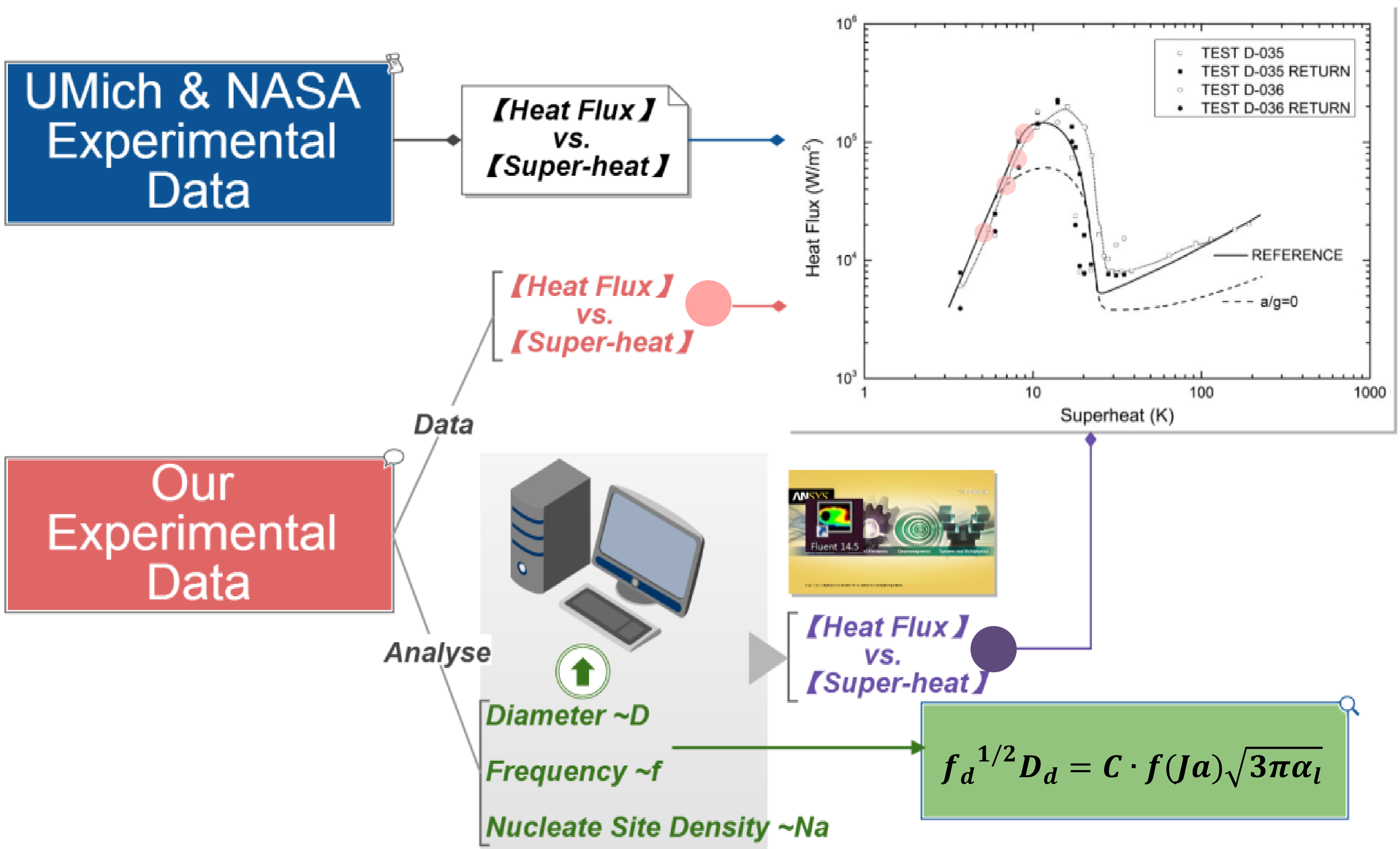
Diameter ~D

Frequency ~f

Nucleate Site Density ~Na

$$f_d^{1/2} D_d = C \cdot f(Ja)\sqrt{3\pi\alpha_l}$$

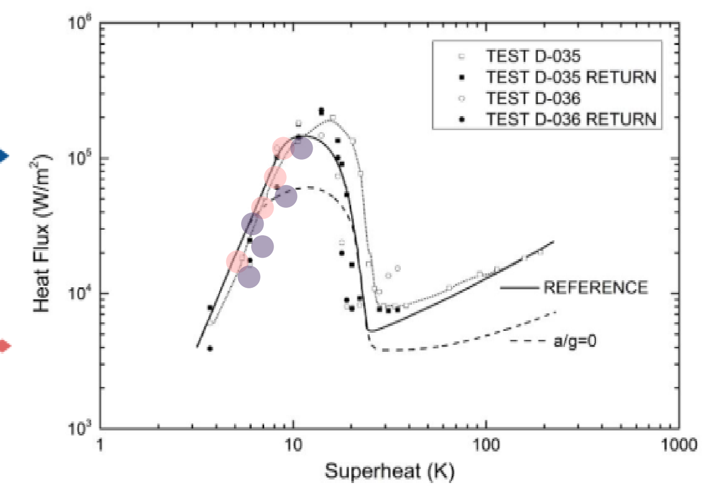
Research Procedures



Research Procedures

UMich & NASA Experimental Data

【Heat Flux】 vs. 【Super-heat】



【Heat Flux】 vs. 【Super-heat】

Data

Our Experimental Data

Analyse

【Heat Flux】 vs. 【Super-heat】

Diameter ~D

Frequency ~f

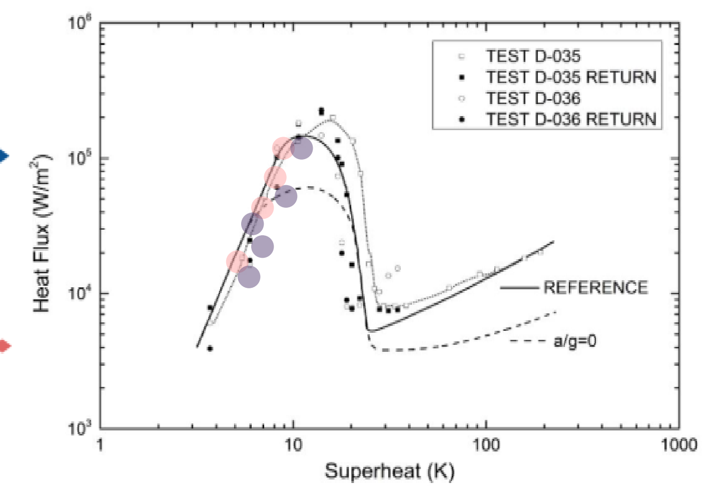
Nucleate Site Density ~Na

$$f_d^{1/2} D_d = C \cdot f(Ja) \sqrt{3\pi\alpha_l}$$

Research Procedures

UMich & NASA Experimental Data

【Heat Flux】 vs. 【Super-heat】

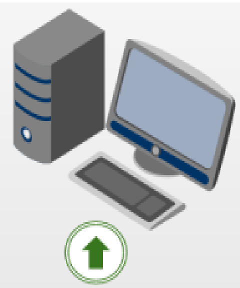


【Heat Flux】 vs. 【Super-heat】

Data

Our Experimental Data

Analyse



【Heat Flux】 vs. 【Super-heat】

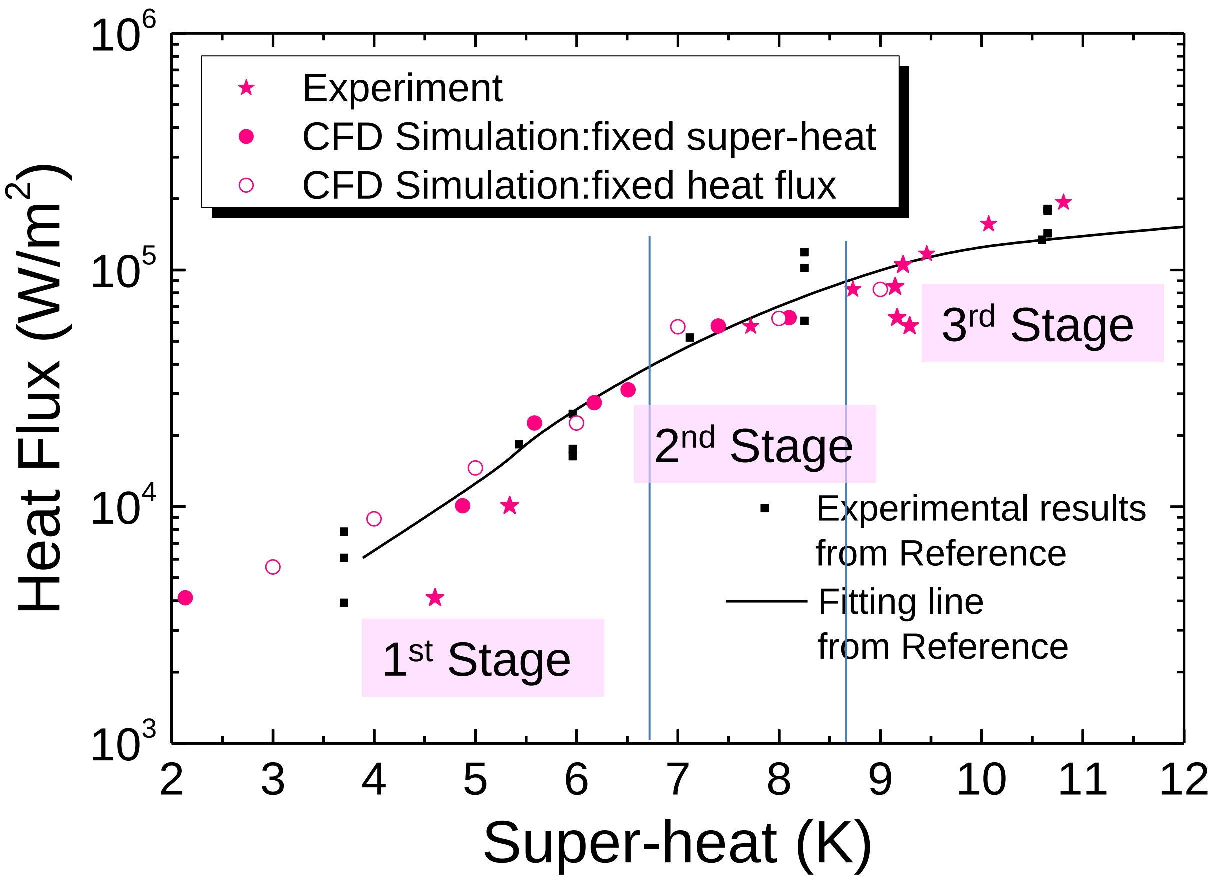
Diameter ~D

Frequency ~f

Nucleate Site Density ~Na

$$f_d^{1/2} D_d = C \cdot f(Ja)\sqrt{3\pi\alpha_l}$$

Results & Conclusions



❑The measured relation between heat flux and super-heat accorded well with the previous reported experimental data by other researchers.
❑Three different boiling stages with different bubble departure structure were distinguished.
❑The modeled relations between heat flux and super-heat for LN2 pool boiling were in good accordance with the measured data.

Thank You