Numerical modeling of bubble sliding and merge for heat flux partitioning model on horizontal tube

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2. Numerical modeling
3. Calculation results
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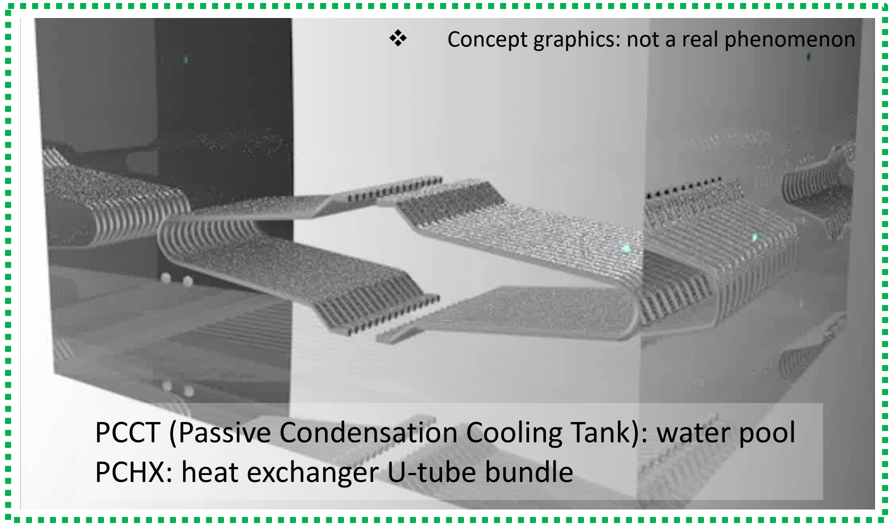
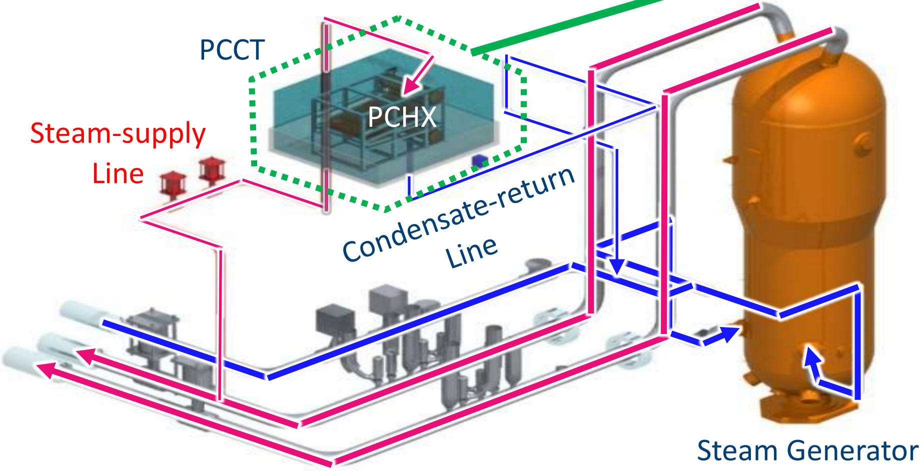
1. Introduction (1/4)

- **Passive Auxiliary Feed-water System (PAFS) on APR+**
  - Applied on Korean advanced nuclear reactor APR+
  - Passive safety feature to enhance safety
  - Large water pool + horizontal U-tube heat exchanger
- **As new concepts are rapidly proposed**
  - A need for a general heat transfer prediction model that can be applied in various configurations

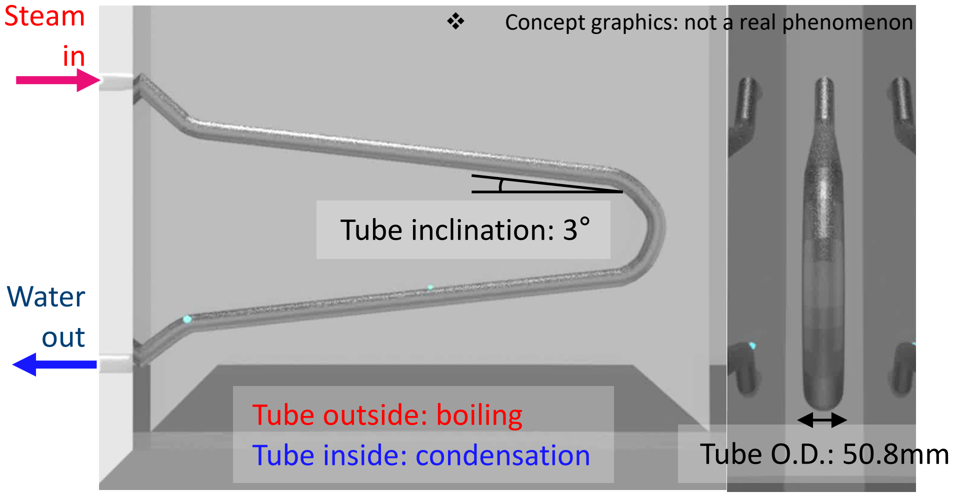

❖ Concept graphics: not a real phenomenon

PCCT (Passive Condensation Cooling Tank): water pool
PCHX: heat exchanger U-tube bundle

- Concept of PAFS: PCHX-PCCT



- PAFS, Korea Hydro & Nuclear Power Co.



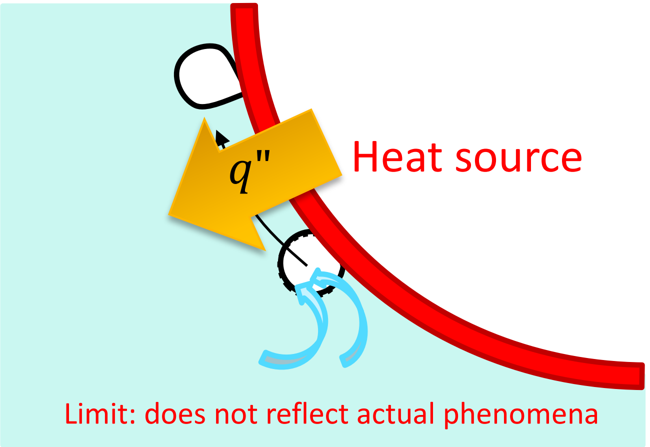
❖ Concept graphics: not a real phenomenon

Tube outside: boiling
Tube inside: condensation

- Heat transfer concept of PCHX U-tube

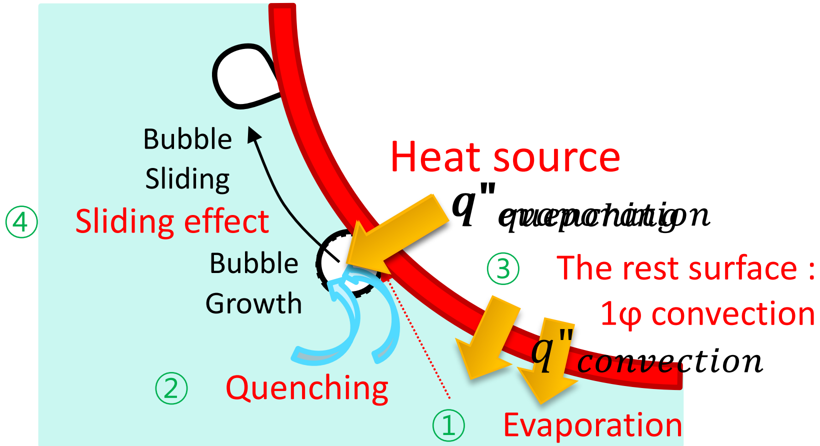
1. Introduction (2/4)

▪ Mechanistic boiling models: heat partitioning model



q : Curve fitting from results

- Empirical boiling models



q : ①+②+③+④

- Mechanistic boiling models

- Widely accepted boiling heat transfer model in Computational Fluid Dynamics(CFD)
- Decomposition of heat transfer mechanism
  - ① Evaporation
  - ② Quenching (transient conduction)
  - ③ Single-phase convection
  - **④ Sliding bubble effect**

$$q''_{tot} = (q''_{me} + q''_{tc})x_{st} + \boxed{(q''_{mes} + q''_{tcs}}) x_s + q''_{sp}$$

① ② ④ ③

$$q''_{mes} = \frac{1}{6}\pi\left(\boxed{d_l{}^3} - \boxed{d_d{}^3}\right)\boxed{\rho_v h_{fg}}\boxed{n_b f}$$

$$q''_{tcs} = 2\sqrt{\frac{\boxed{k_f \rho_f c_{pf}}}{\pi \boxed{t_w}}}\boxed{\Delta T}\boxed{n_b t_w f}\int_{\boxed{t_d}}^{\boxed{t_l}} K\boxed{d(t)U_b(t)}dt$$

🟥 : Bubble parameters 🟦 : Fluid properties

- Sateesh model(2005)

1. Introduction (3/4)

Comparison of the heat partitioning models:		Sateesh et al.(2005) horizontal tube, vertical plate, natural convection	Basu et al.(2005) vertical plate, forced convection	This Study Horizontal tube, natural convection
Bubble life cycle	**Sub-models**	**Model characteristics**		
Nucleation	Site distribution	Uniform (grid)	Uniform (grid)	**Random distribution** with Monte Carlo simulation
Departure	Departure diameter	Force balance on horizontal plate (Cornwell and Schuller)	Empirical correlation based on Maity's experiment	**Based on force balance model of a horizontal tube**
Sliding	Bubble velocity	Pseudo-static force balance model (Cornwell and Schuller)	Empirical correlation based on Maity's experiment	**Based on force balance model of a horizontal tube**
	Sliding distance	Assumed with half the distance between two nucleation sites	Empirical correlation based on Maity's experiment	Nucleation site to the lift-off location
Merger	-	Dividing bubble merger cases with area ratio parameter	Dividing bubble merger cases with lift-off diameter	**Mechanistically calculated based on bubble tracking**
Lift-off	-	Approximate with sliding distance	Empirical correlation based on Maity's experiment	**Lower side:** **Numerically calculated and averaged through Monte Carlo simulation** **Upper side:** Basu et al.'s model

New model is proposed which can:

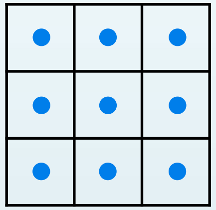
- Reflect the realistic bubble sliding based on a mechanistic force balance model
- Consider bubble mergers using a bubble tracking method
- Bubble behavior based heat transfer calculation

1. Introduction (4/4)

- **Excessive simplification of existing studies**
  - Uniform sites: the distribution of the nucleation sites is not uniform (grid) on the boiling surfaces.
  - Arithmetic merger calculation: Interaction between bubbles is too complex to be solved analytically.
- **Concepts of numerical modeling**
  - Reflects realistic behavior through force balance equation.
  - Realistic behavior and merger by tracking individual bubbles.
  - Reflects the boiling characteristics of the horizontal tube.

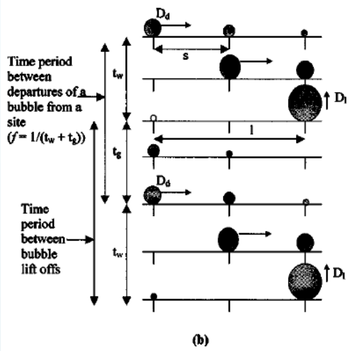
Complex phenomenon

Nucleation sites distribution:



Grid sampling

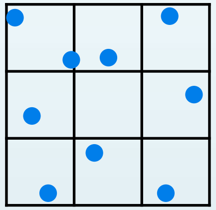
Bubble merger:



Dividing bubble merger cases with lift-off diameter (Basu et al.)

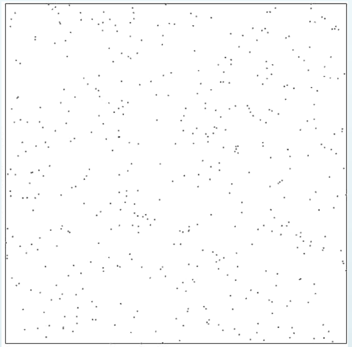
Previous models (arithmetic approach)

Nucleation sites distribution:



Random sampling (w/ Monte-Carlo)

Bubble merger:

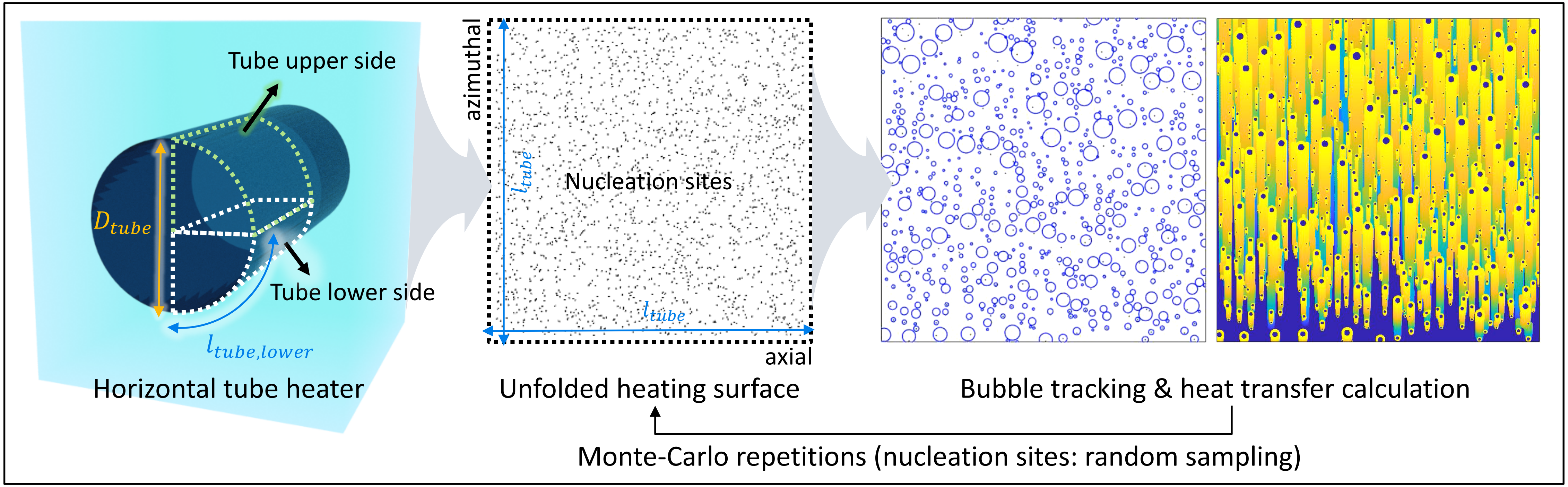


Bubble tracking (w/ Monte-Carlo)

This study (numerical model)

2. Numerical modeling (1/8)

Overview of numerical model



Horizontal tube heater

Unfolded heating surface

Bubble tracking & heat transfer calculation

Monte-Carlo repetitions (nucleation sites: random sampling)

TH conditions

P, T_{sup}, T_{sub}, U_{bulk}, D_{tube}

Calculation options

- Nucleation site distribution (uniform/random)
- Tube upper / lower side
- Number of repeated calculations (Monte-Carlo method)

Outputs

$\frac{A_{fc}}{A_{tot}}, \frac{A_{evap}}{A_{tot}}, \frac{A_{tc}}{A_{tot}}, V_{lift}, I_{tc}, q_{sc}'', q_{tc}'', q_{evap}'', q_{wall}''$

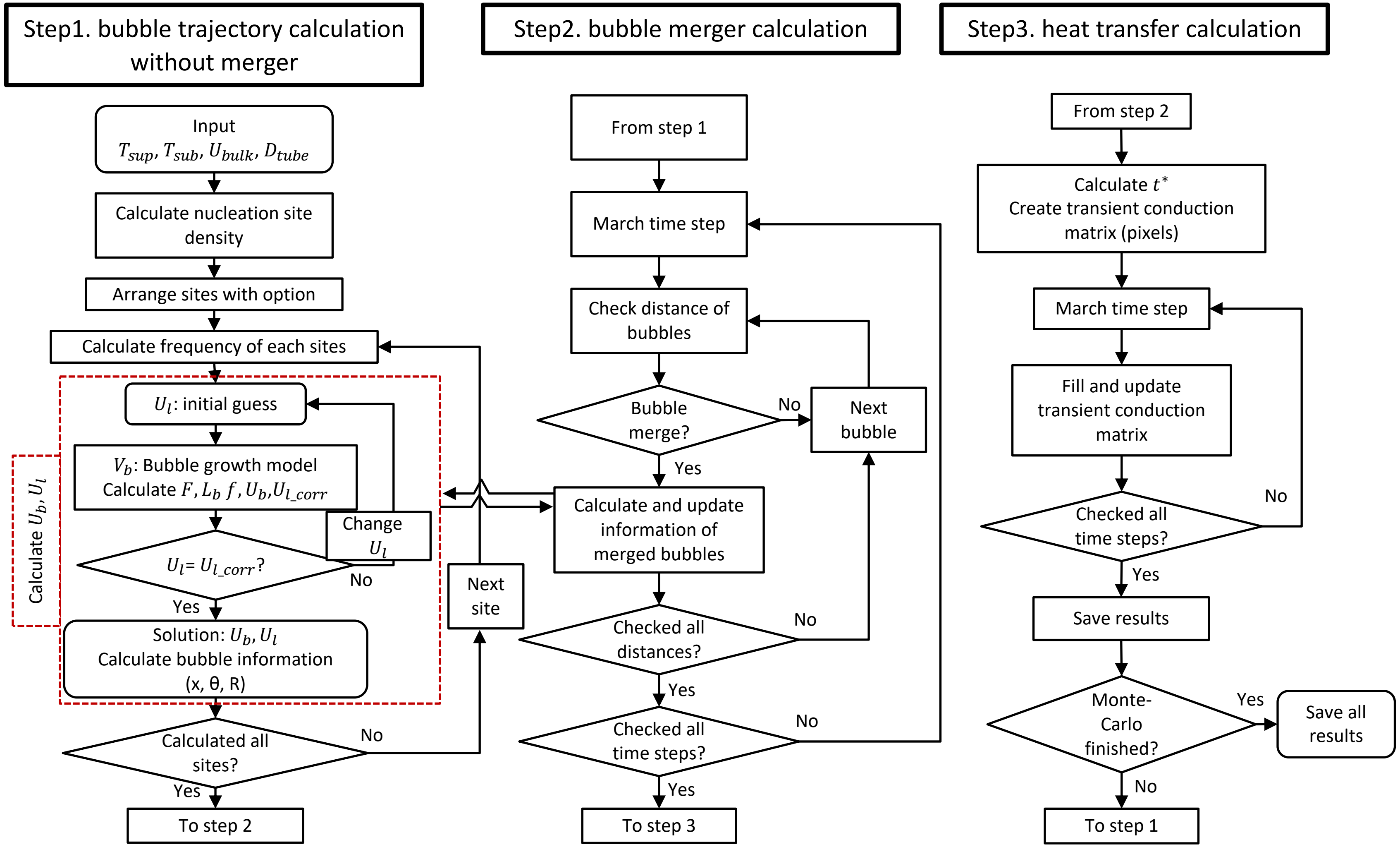
2. Numerical modeling (2/8)

- **Sub-model application on numerical model**

Models	Author or model type	Description
Nucleation site density	Hibiki & Ishii	$P < 19.8\ MPa$
Nucleation site distribution	Random/uniform sampling	
Bubble growth	Yoo et al.	$T_{sub} < 13.5\ K$
Bubble velocity model	Modified force balance model	For a horizontal tube
Contact angle	Experimental observation	$\alpha = 20^o$, $\beta = 15^o$
Drag coefficient	Newton's law	$C_d = 0.44$
Bubble wake effect	Experimental observation	$L_{bubble} < 2D_b$
Bubble frequency	Cole	
Departure diameter	Mechanistic model	
Area of influence	Amidu et al.	$K = 0.5$
Contact diameter	Experimental observation	$d_w = 0.35D_b$
Bubble shape	Spherical shape assumption	
Bubble interaction	Bubble tracking	
Lift-off diameter	Basu et al.	$T_{sub} < 60\ K$
Heat transfer coefficient	Jeon et al.	$T_{sub} < 40\ K$

2. Numerical modeling (3/8)

Calculation procedure



Step1. bubble trajectory calculation without merger

Input
$T_{sup}, T_{sub}, U_{bulk}, D_{tube}$

Calculate nucleation site density

Arrange sites with option

Calculate frequency of each sites

Calculate U_b, U_l

U_l: initial guess

V_b: Bubble growth model
Calculate $F, L_b\ f, U_b, U_{l\_corr}$

$U_l = U_{l\_corr}$?

No

Change U_l

Yes

Solution: U_b, U_l
Calculate bubble information
(x, θ, R)

Calculated all sites?

No

Next site

Yes

To step 2

Step2. bubble merger calculation

From step 1

March time step

Check distance of bubbles

Bubble merge?

No

Next bubble

Yes

Calculate and update information of merged bubbles

Checked all distances?

No

Yes

Checked all time steps?

No

Yes

To step 3

Step3. heat transfer calculation

From step 2

Calculate t^*
Create transient conduction matrix (pixels)

March time step

Fill and update transient conduction matrix

Checked all time steps?

No

Yes

Save results

Monte-Carlo finished?

Yes

Save all results

No

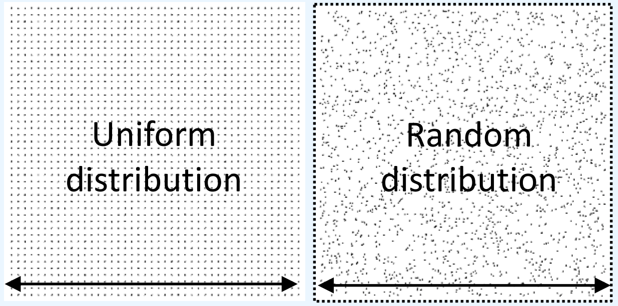
To step 1

Calculation process flowchart

2. Numerical modeling (4/8)

Step1. Bubble trajectory calculation without merger

1. Calculate nucleation site density.
   - $T_{sup} \rightarrow NSD_{Hibiki\&Ishii} \rightarrow N_{site}$
2. Arrange nucleation sites. (uniform / random)
3. Calculate bubble trajectory without merger

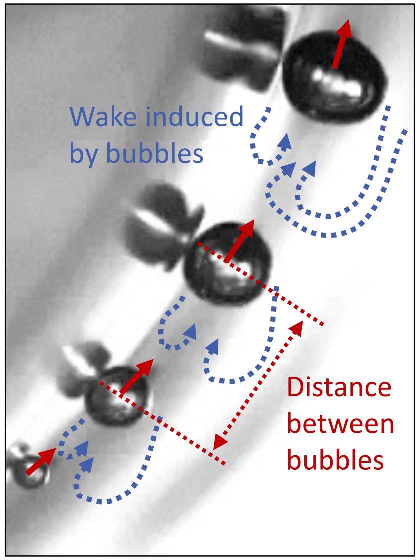


3.927cm for D=50mm

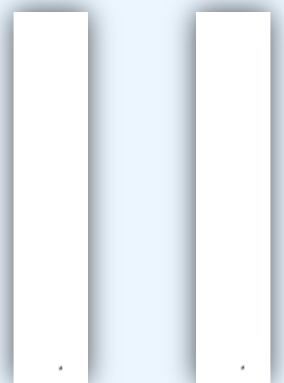
(Hibiki-Ishii: Tsup=15K, 2000#/4cmX4cm)

2. Nucleation site distribution

$F_{b\theta} = (\rho_l - \rho_v) g V_b \sin\theta_b$	Buoyancy force
$F_{qs\theta} = -\frac{1}{2} C_D \rho_l (U_b - U_l)\lvert U_b - U_l \rvert A$	Quasi-steady drag
$F_{s\theta} = -\int_0^{\pi} d_w \sigma \cos\gamma \cos\emptyset \, d\emptyset$ $\sim d_w \sigma \frac{\pi(\alpha-\beta)}{\pi^2 - (\alpha-\beta)^2}[\sin\alpha + \sin\beta]$	Surface tension for sliding bubble
$F_{am\theta} = -\frac{1}{2} \alpha_\theta \rho_l V_b - 2A\rho_l (U_b - U_l)\dot{r}_b$	Added mass
$\rho_v V_b \alpha_\theta = F_{tot,\theta} = F_{b\theta} + F_{qs\theta} + F_{s\theta} + F_{am\theta}$	Total



3. Calculate forces on a bubble and wake effect



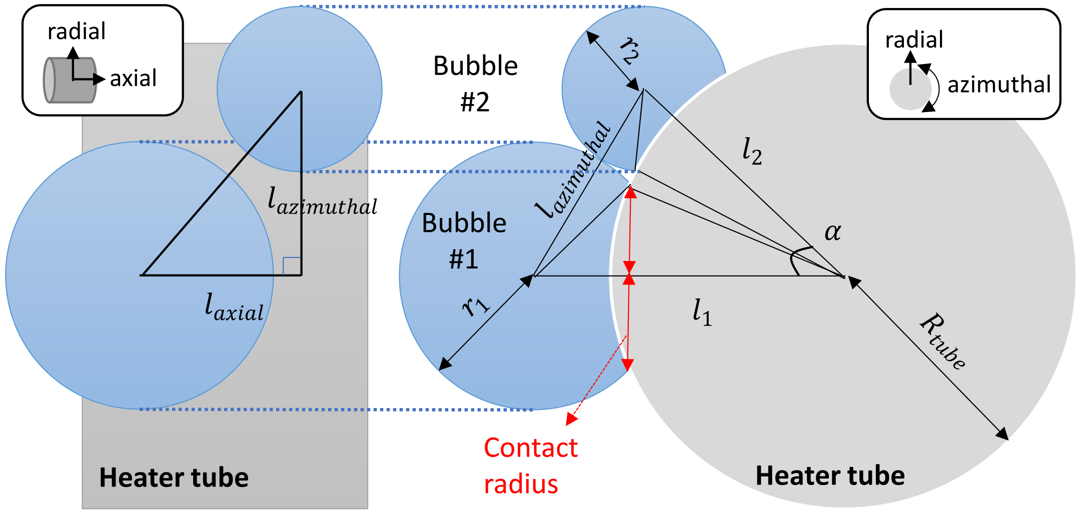
($f\uparrow \rightarrow U_b\uparrow$ wake effect)

Results of Step 1

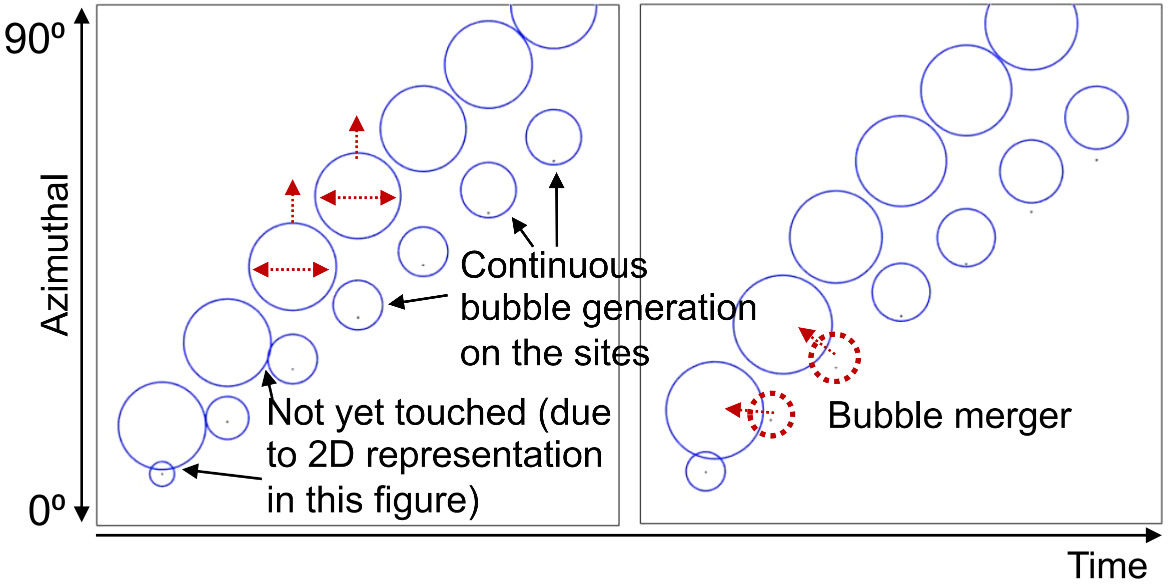
2. Numerical modeling (5/8)

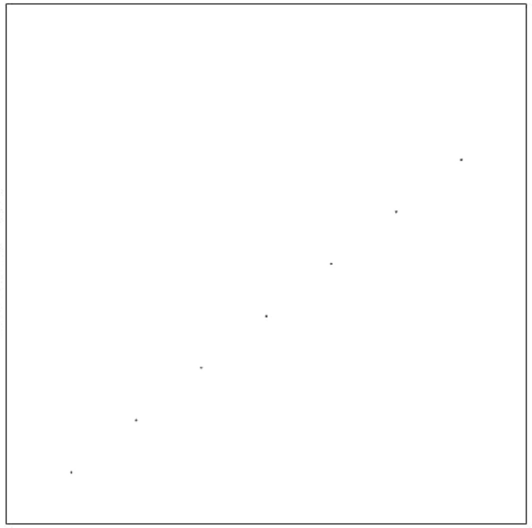
Step2. Bubble merger calculation

1. Check bubble merger in this time step
   - Collisions and mergers when
     - $r_1 + r_2 \geq \sqrt{l_{axial}{}^2 + l_{azimuthal}{}^2}$
     - $l_{azimuthal} = \sqrt{\left(l_1{}^2 + l_2{}^2 - 2l_1 l_2 \cos\alpha\right)}$
   - Mass, momentum conserved before / after merge
2. Time marching



Distance between bubbles

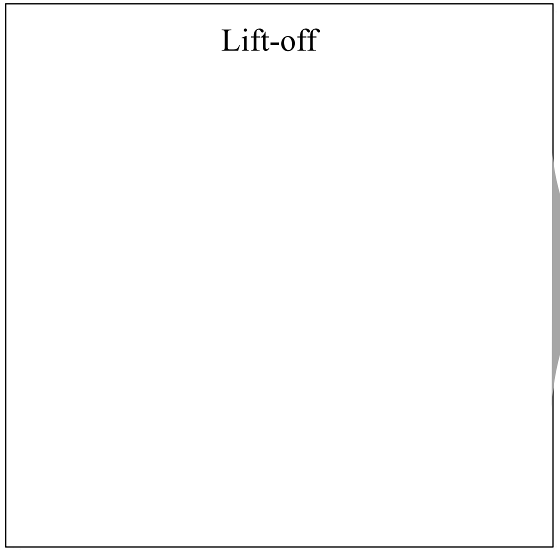




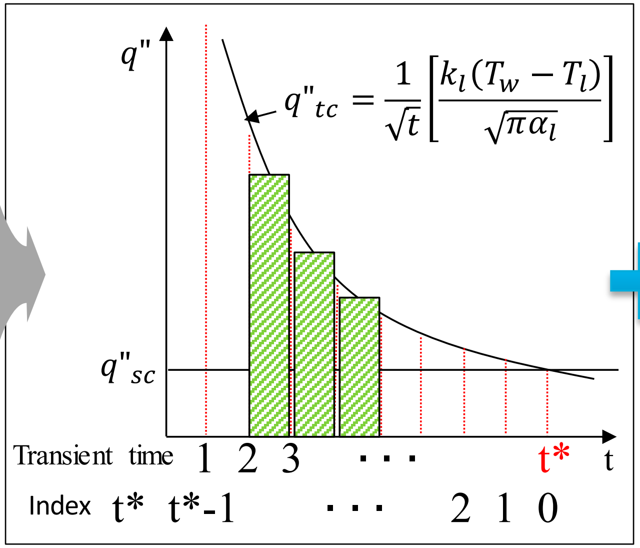
Results of Step 2

2. Numerical modeling (6/8)

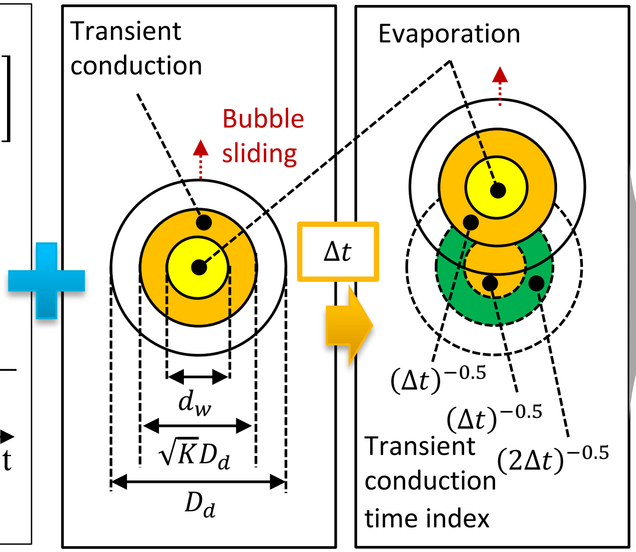
- **Step3. Heat transfer calculation**
  1. Create transient conduction time matrix.
  2. From the bubble behavior, heat transfer is evaluated per each pixels
     - Heat transfer mechanism of the each pixels
     - Intensity of transient conduction of the each pixels (transient conduction time index)
  3. Time marching



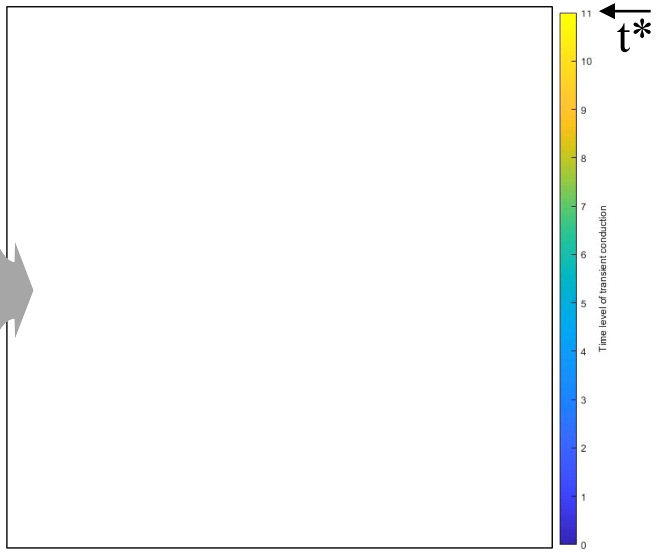
Bubble trajectory



Transient conduction time



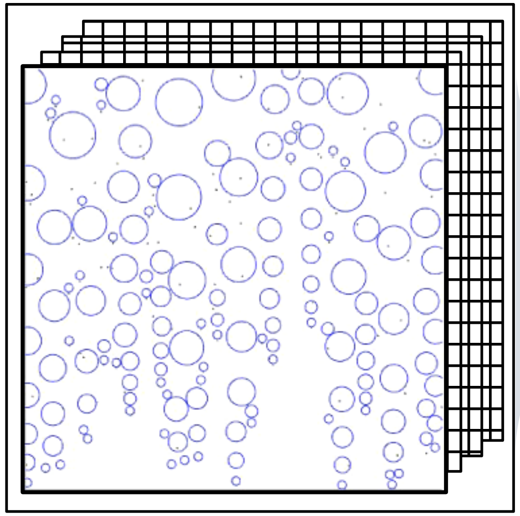
Heat transfer evaluation



Transient conduction time index

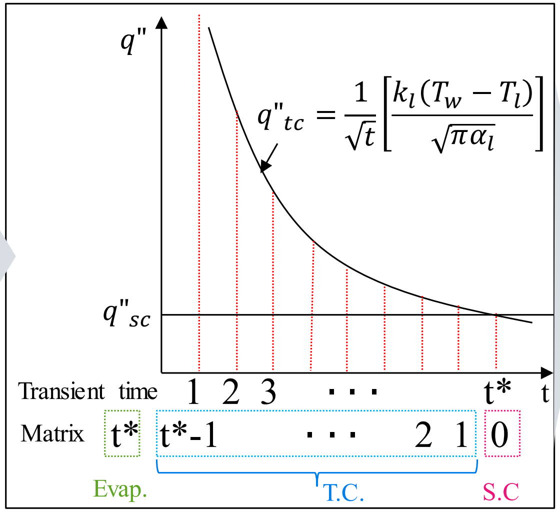
2. Numerical modeling (7/8)

Heat flux calculation



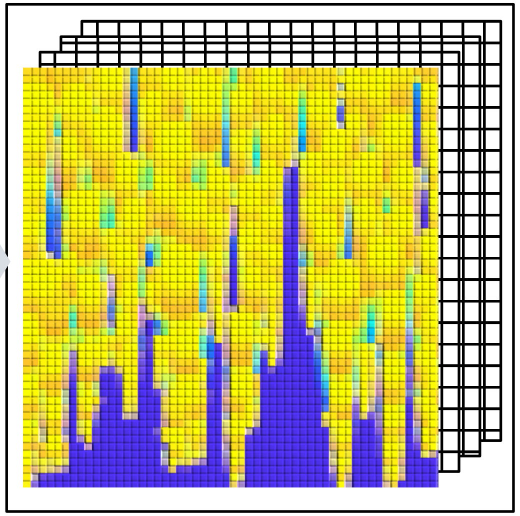
Bubble information

$$\sum_{t=0}^{tot} \boldsymbol{V_{lift}}$$



Transient conduction time index

$$\boldsymbol{I_{tc}} = \frac{1}{t_{calc}A_{T.C.}} \sum_{j=1}^{N_{timestep.}} \sum_{i=1}^{N_{pixel}} \frac{1}{\sqrt{t_{i,j}}} \Delta t \Delta A$$



Transient conduction matrix

$$\frac{\boldsymbol{A_{sc}}}{\boldsymbol{A_{tot}}}, \frac{\boldsymbol{A_{tc}}}{\boldsymbol{A_{tot}}}, \frac{\boldsymbol{A_{evap}}}{\boldsymbol{A_{tot}}}$$

Single-phase convection	**Transient conduction**	**Evaporation**
$\boldsymbol{q_{sc}}'' = h_{sc}\frac{A_{sc}}{A_{tot}}(T_w - T_l)$	$\boldsymbol{q_{tc}}'' = \frac{A_{tc}}{A_{tot}}\int \frac{k_l(T_w - T_l)}{\sqrt{\pi\alpha_l t}}dt = \frac{k_l(T_w - T_l)}{\sqrt{\pi\alpha_l}} I_{T.C.}\frac{A_{tc}}{A_{tot}}$	$\boldsymbol{q_{ev}}'' = \frac{A_{evap}}{A_{tot}}\delta_{ml}\rho_f h_{fg}\frac{1}{t_{tot}}$

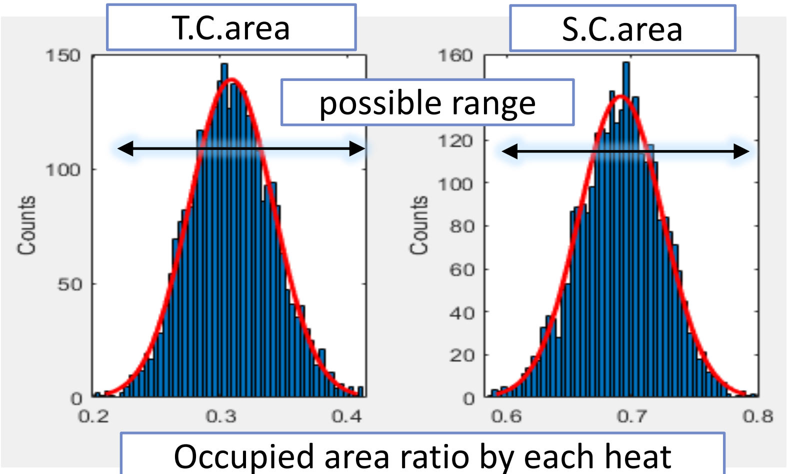
Wall heat flux

$$\boldsymbol{q_w}'' = \frac{\boldsymbol{A_{sc}}}{\boldsymbol{A_{tot}}} h_{sc}(T_w - T_l) + \frac{\boldsymbol{A_{tc}}}{\boldsymbol{A_{tot}}}\boldsymbol{I_{tc}}\frac{k_l(T_w - T_l)}{\sqrt{\pi\alpha_l}} + \frac{\boldsymbol{A_{evap}}}{\boldsymbol{A_{tot}}}\delta_{ml}\rho_f h_{fg}\frac{1}{t_{tot}}$$

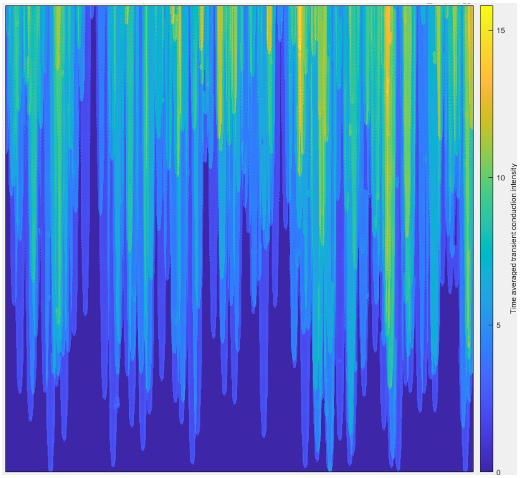
2. Numerical modeling (8/8)

Monte-Carlo simulation on random distribution

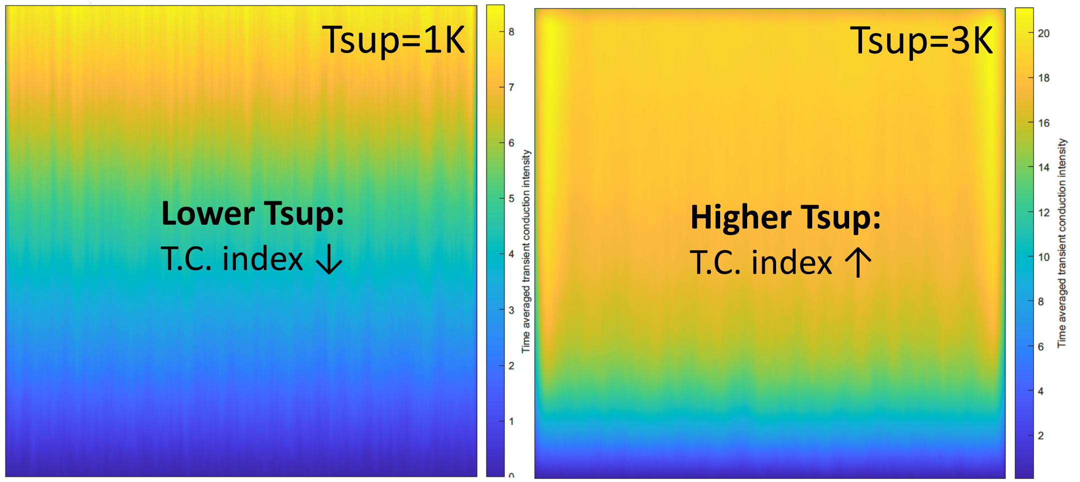
- Uniform distribution is difficult to be seen in the actual boiling.
- Random distribution is closer to the actual phenomenon.
- Calculates results repeatedly under various random cases.
  - Each time, using a different set of site distribution
- Results: possible range of values
  - Area of each heat transfer mechanism and T.C. intensity



Occupied area ratio by each heat transfer mechanisms



Single calculation results (T.C. index)

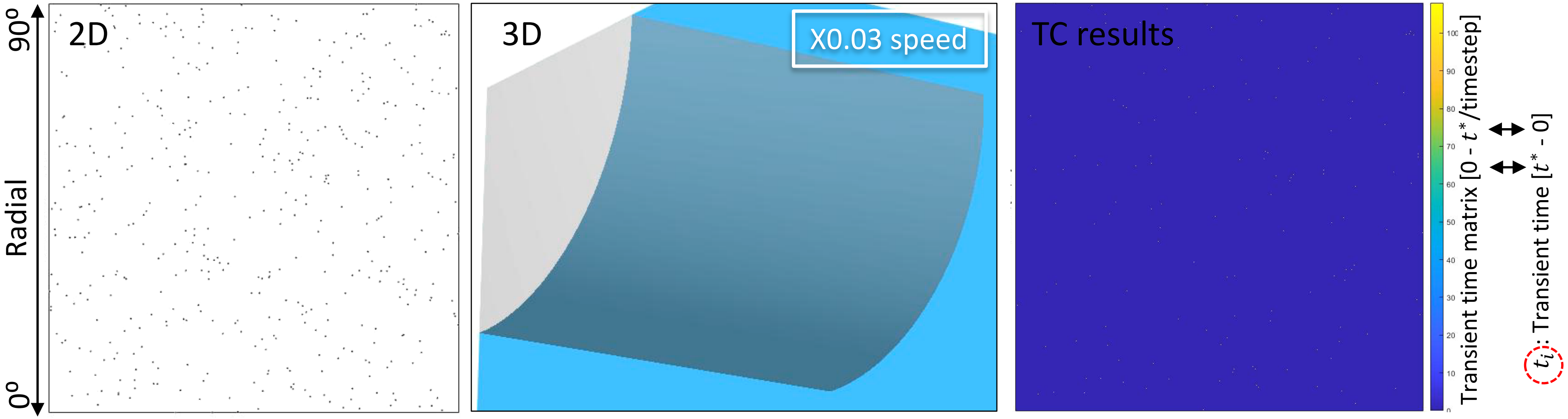


Monte-Carlo simulation results (X3000times)

3. Calculation results (1/5)

Simulation results

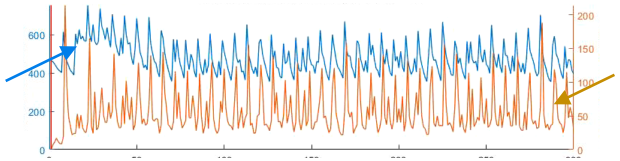
- Results showed realistic bubble phenomenon according to the radial direction.



Lower angle: Axial

Velocity↓, departure D↑, frequency ↓

T_{sup}=10K, T_{sub}=0.1K, contact D=35%, K=0.5 (N=466 sites, f=135#/sec@90°)



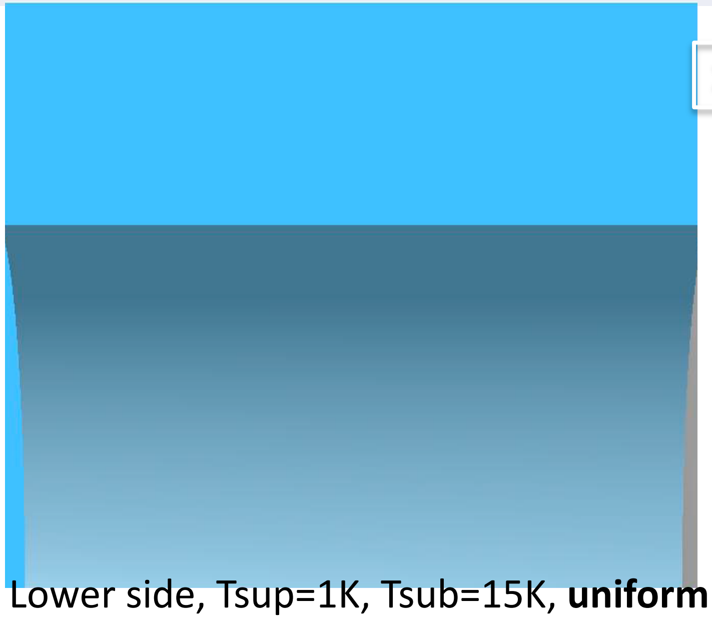
Number of total bubbles

Number of merged bubbles in this timestep

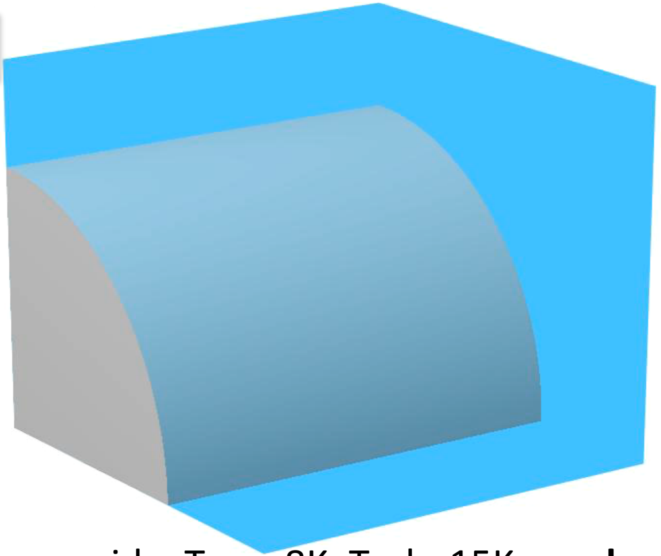
$$\boldsymbol{q_{tc}}'' = \int \frac{k_l(T_w - T_l)}{\sqrt{\pi\alpha_l t}}dt$$	Time related term $$\frac{k_l(T_w - T_l)}{\sqrt{\pi\alpha_l}}\boxed{2f\sqrt{t_w}}\boxed{A_s K N_a}$$ Area related term	T.C. time index $$\frac{k_l(T_w - T_l)}{\sqrt{\pi\alpha_l}}\frac{1}{t_{calc}A_{T.C.}}\sum_{j=1}^{N_{time}}\sum_{i=1}^{N_{area}}\frac{1}{\sqrt{t_{i,j}}}\Delta t\Delta A = \frac{k_l(T_w - T_l)}{\sqrt{\pi\alpha_l}}\boxed{I_{T.C}}\boxed{\frac{A_{T.C}}{A_{tot}}}$$ T.C. area ratio
Transient conduction	Other studies	This study

3. Calculation results (2/5)

X0.03 speed



- Lower side, Tsup=1K, Tsub=15K, **uniform**

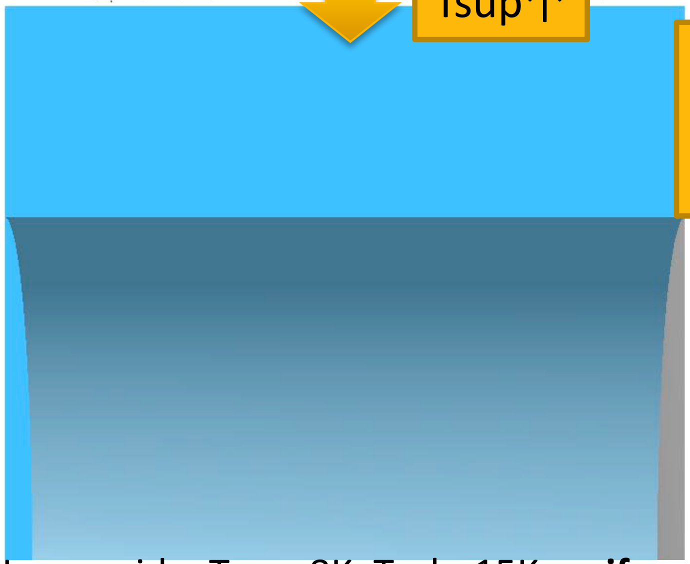


- Upper side, Tsup=8K, Tsub=15K, **random**

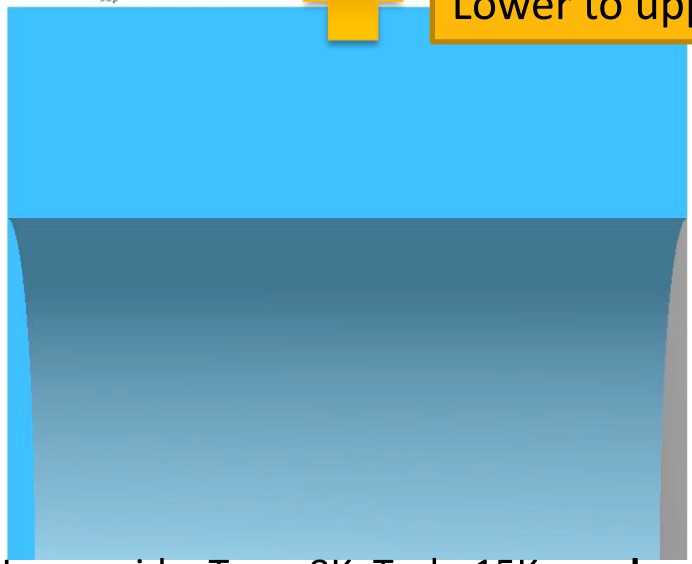
Tsup↑

Lower to upper

Uniform to random

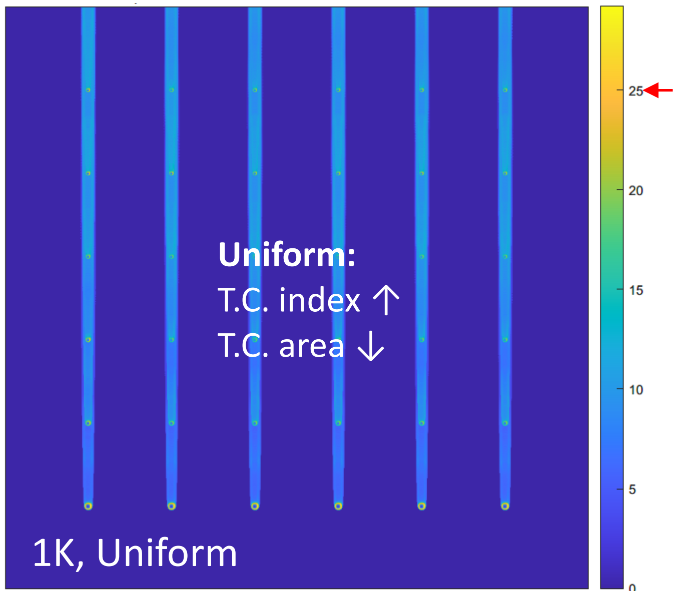


- Lower side, Tsup=8K, Tsub=15K, **uniform**



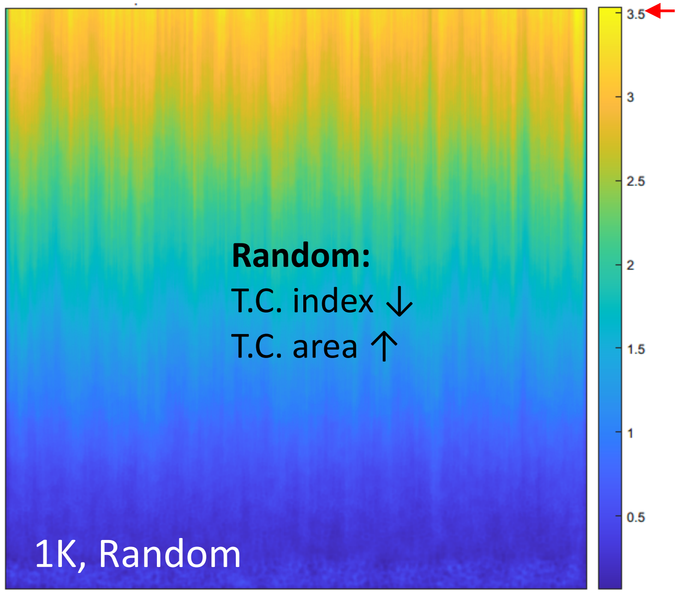
- Lower side, Tsup=8K, Tsub=15K, **random**

3. Calculation results (3/5)



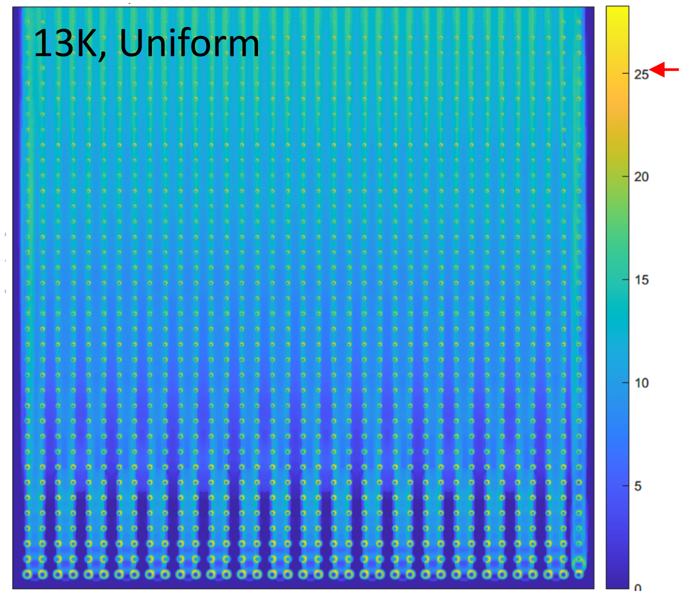
1K, Uniform

Uniform:
T.C. index ↑
T.C. area ↓

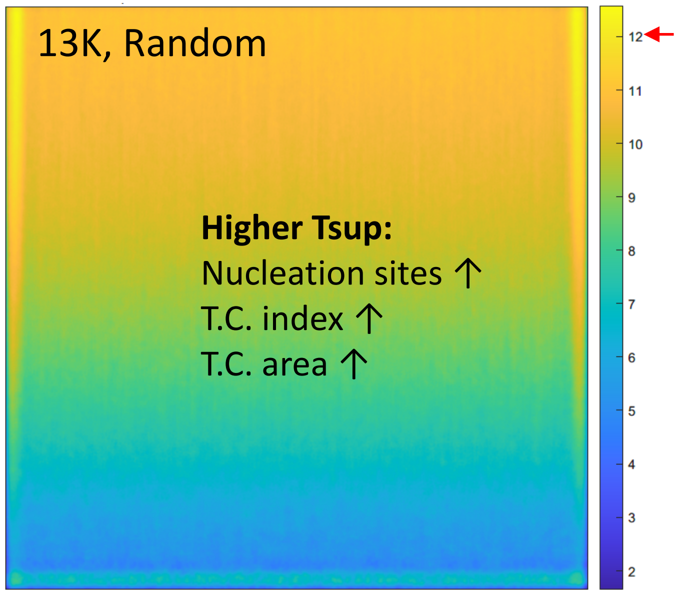


1K, Random

Random:
T.C. index ↓
T.C. area ↑



13K, Uniform



13K, Random

Higher Tsup:
Nucleation sites ↑
T.C. index ↑
T.C. area ↑

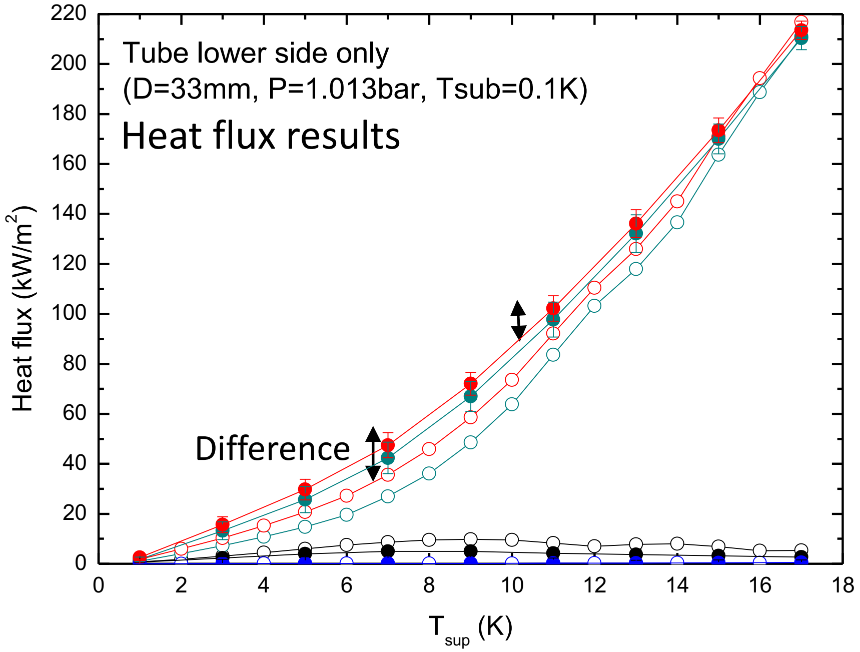
3. Calculation results (4/5)

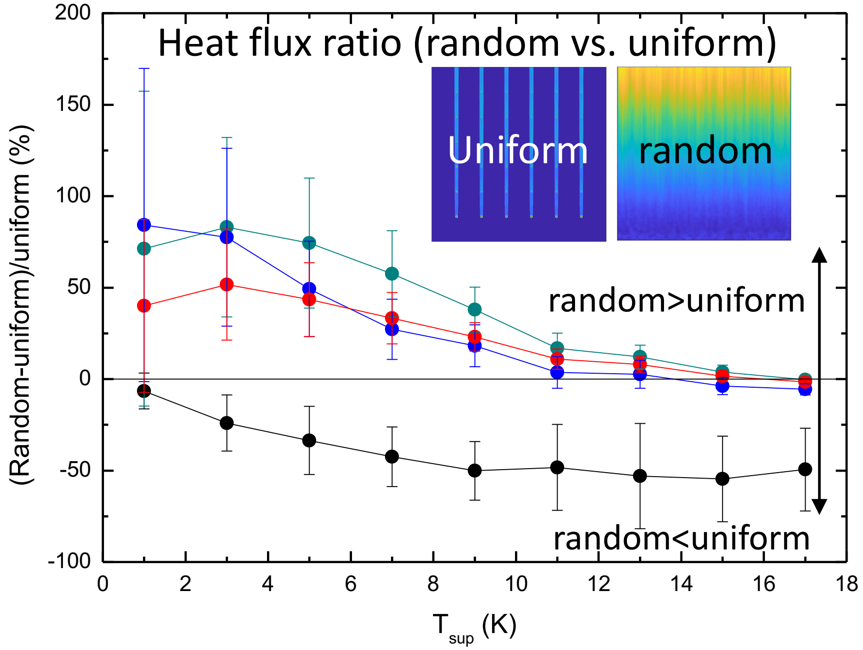
Heat flux results: random (w/ Monte-Carlo) VS. uniform distribution

- Overall heat flux shows differences under 50 ± 30 % .
- There is a large difference in
  - Contribution of each heat transfer mechanism
    - T.C. up to 150%., S.C. up to -80%
  - As T_{sup} increased, heat flux difference between random and uniform ↓.

Shape
● **Solid : random**
○ **Hollow: uniform**

Color
🟥 Wall heat flux
● Single-phase Convection
🟩 Transient Conduction
🟦 Evaporation



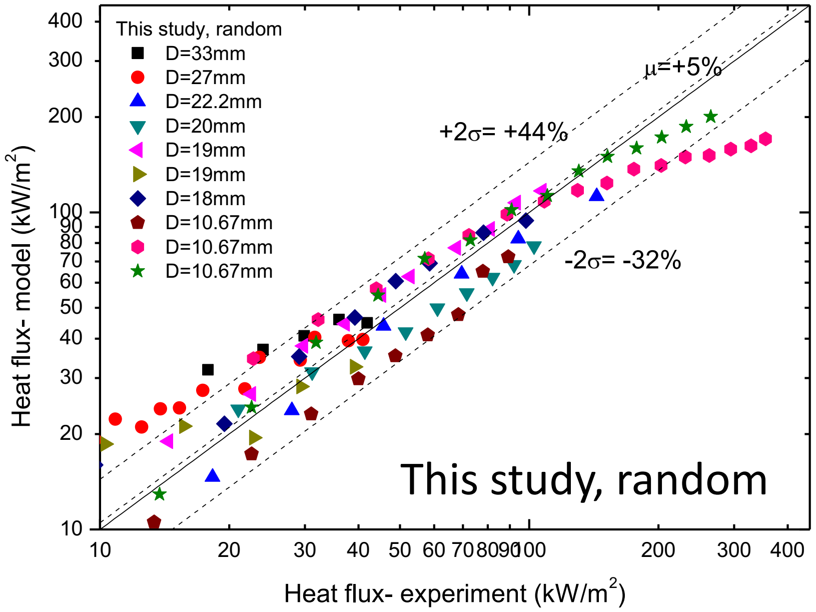


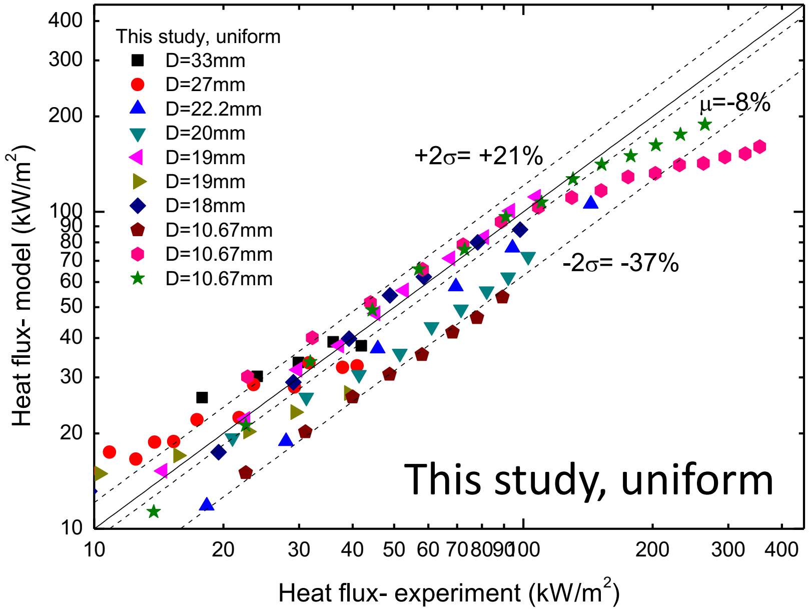
3. Calculation results (5/5)

Validation results

- The model's heat transfer prediction performance was validated for
  - various heater diameters (10.76 – 50mm)
  - pressures (1.0 – 1.8 bar)
  - subcooling (0 – 14 K).
- New model shows good agreement with experiments.
  - Regardless of site distribution (random or uniform)

Model	Assessment results	
This study, **random**	+2σ	+44%
	Average	**+5%**
	-2σ	-32%
This study, uniform	+2σ	+21%
	Average	**-8%**
	-2σ	-37%

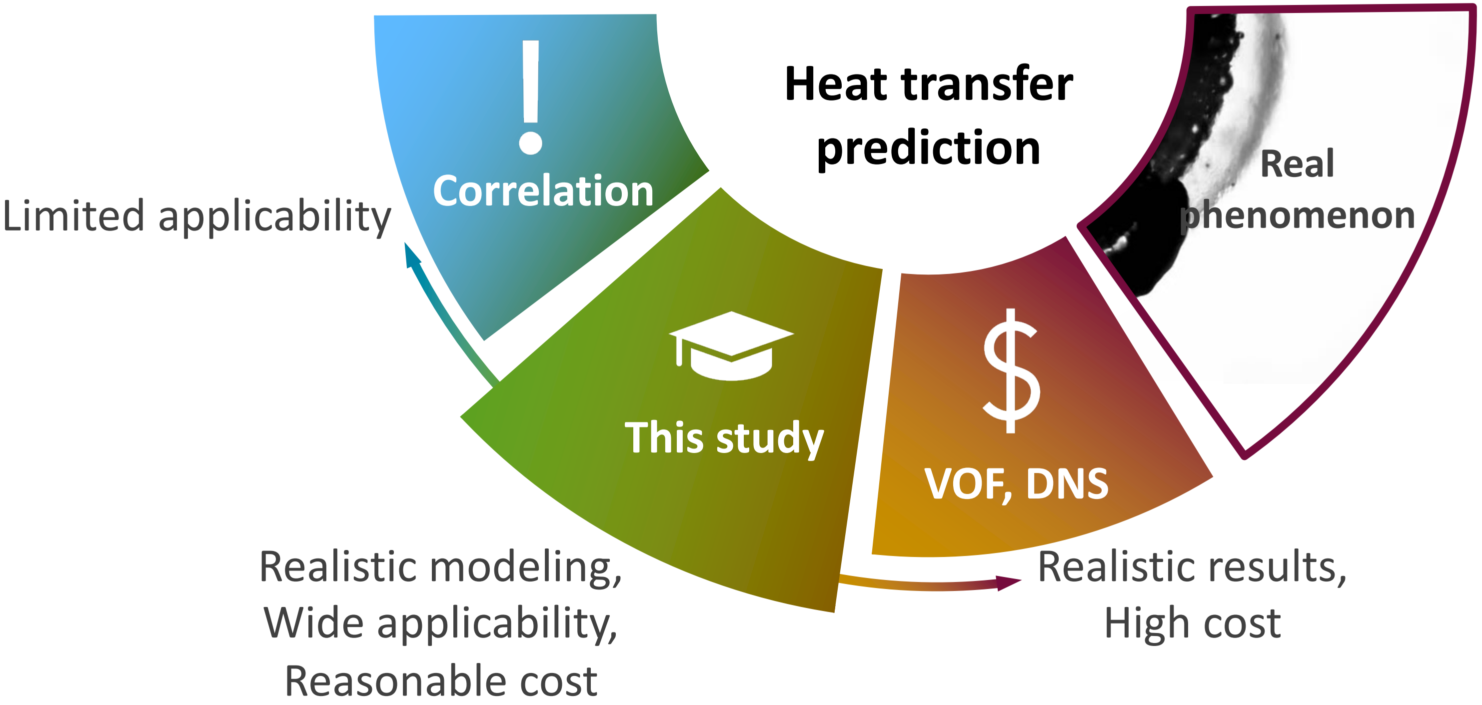




4. Summary and conclusion

Summary and conclusion

- Numerical modeling for complex bubble phenomenon
  - The model reflected the realistic phenomenon of the top and bottom portions of the horizontal tube.
  - Monte-Carlo method to mimic the actual boiling phenomenon
- Validation of developed heat partitioning model with various horizontal experiment results
  - Predictive performance showed an error of less than ±30% at 2 sigma, with an average error of 5%

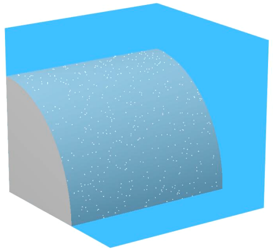


On-going work: simulation of inclined heater

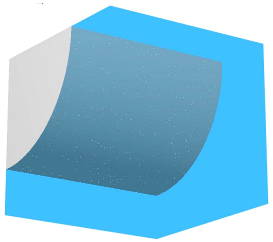
- **Objective**
  - Simulation of bubble dynamics under ocean condition.
- **Research plan to extend the code simulation capability**
  - Dynamic motion model
  - High pressure, high heat flux condition

Horizontal heater	Inclined heater
Heater side is separated by lower or upper tube.	**Entire side** of heater is analyzed. (Bubble sliding, lift-off)
Force for azimuthal direction on the lower side	Force for azimuthal **and axial** direction
Horizontal condition	Inclined condition (0 ~ 90°)
	Periodic boundary to axial direction

- Code improvement for inclined heater and ocean condition



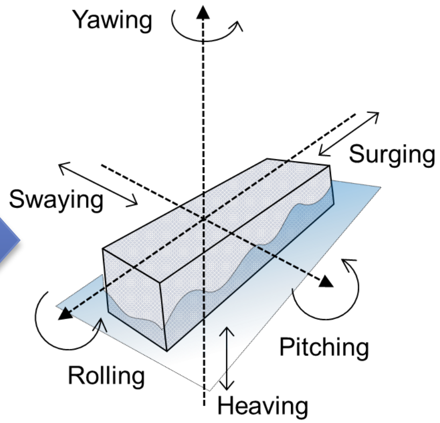
90 deg, upper side



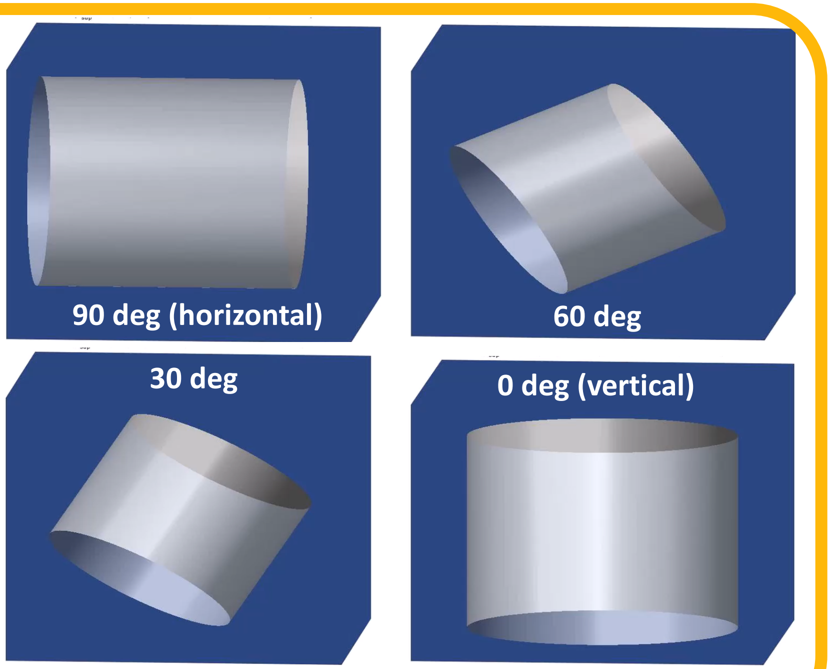
90 deg, lower side

- This presentation

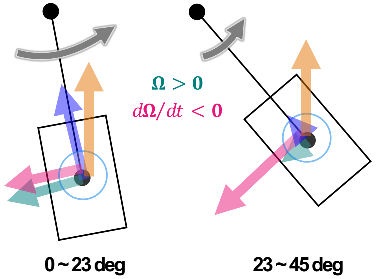
On-going



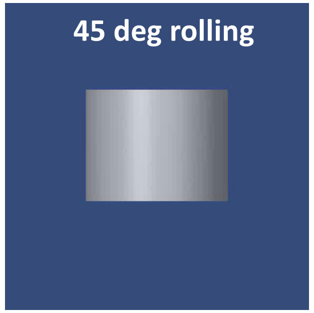
- Ship motions



- Preliminary simulation results (Sub. 15 K, 1 bar)



Forces acting on bubbles



- Ocean condition

Thank you!

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