Heat transfer and bubble dynamics behaviors in subcooled pool boiling at earth gravity an ISS gravity using high-fidelity CFD simulations

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Presented By

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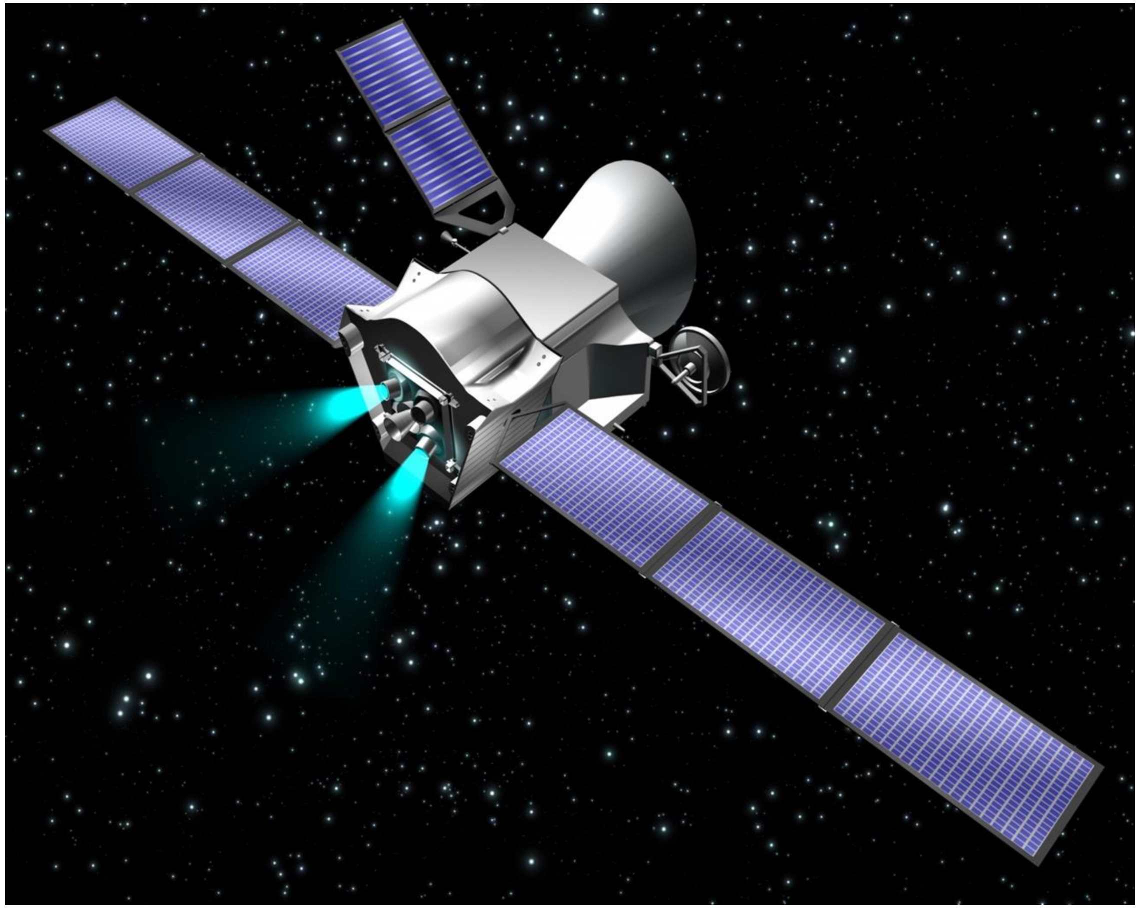
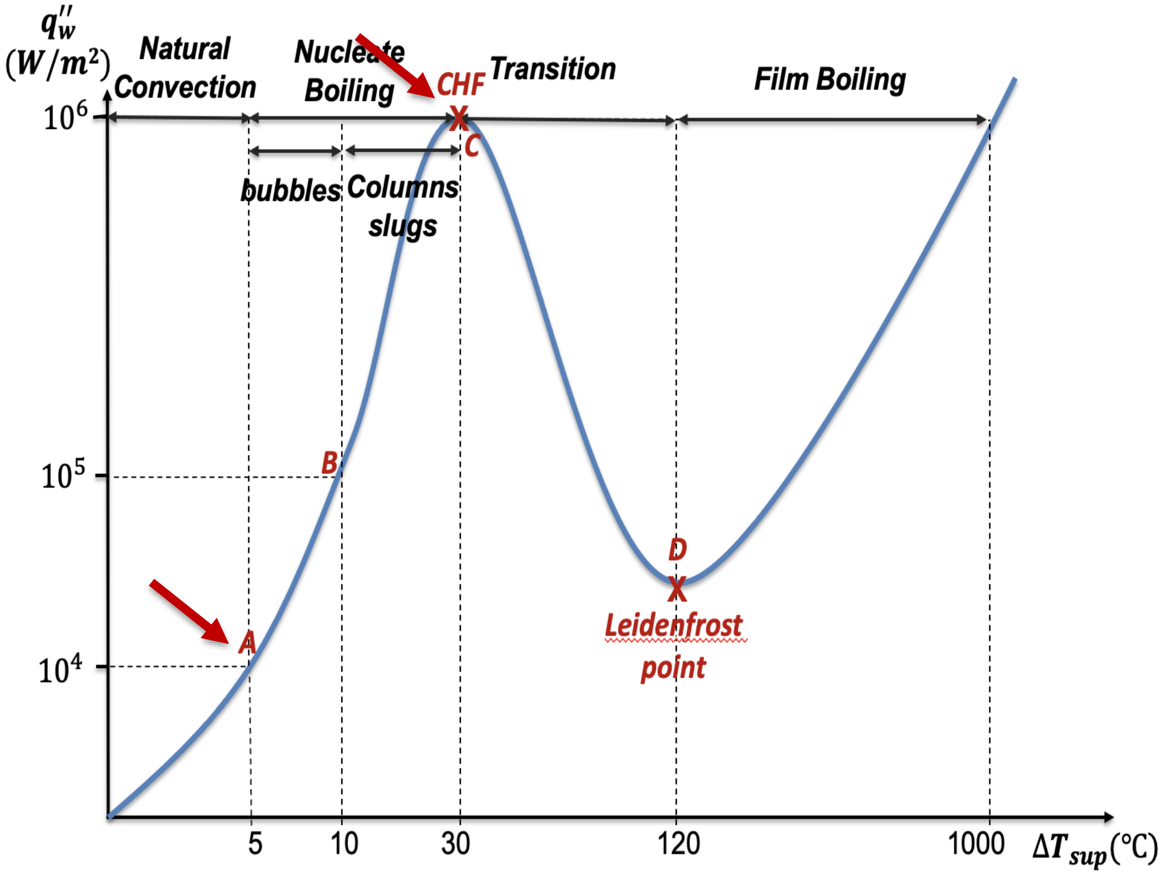
Cleveland, OH

Pool boiling has an important heat transfer mechanism





Motivation

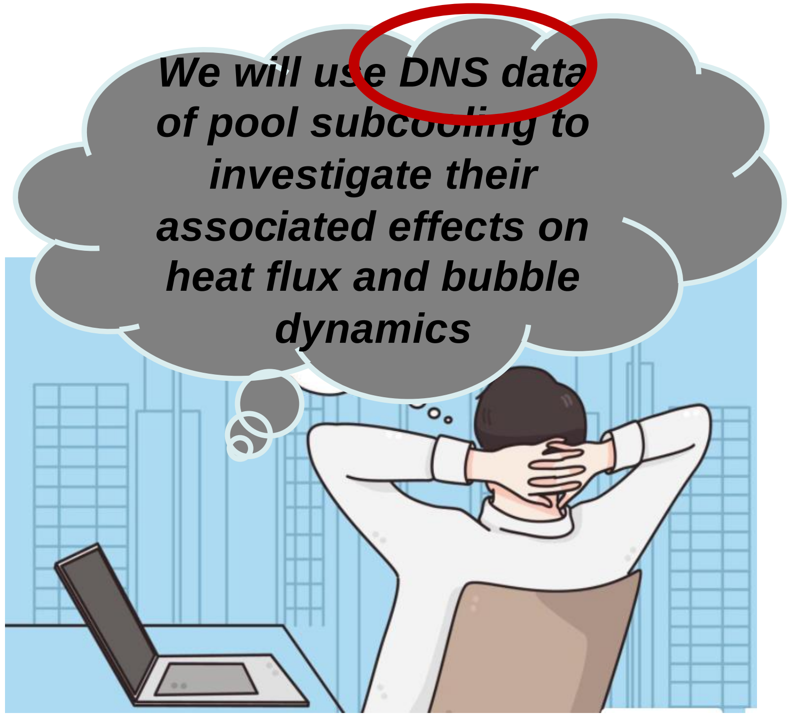
Some researchers argue for the negligible impact of subcooling

- ✗ Rohsenow (1952)
- ✗ Engelberg-Forster & Grief (1959)
- ✗ Tien (1962)
- ✗ Lienhard (1963)
- ✗ Monde and Katto (1978)
- ✗ Incorpera el al. (1996)

Existent heat flux empirical correlations do not account the effect of subcooling: Rohsenow, Yamagata, Zuber, Forster-Zuber Forster-Grief

Others emphasize the influence of subcooling on heat flux, boiling curve, and bubble dynamics

- ✓ Gunther and Kreith (1950)
- ✓ Ibrahim and Judd (1985)
- ✓ Kim et al. (2002)
- ✓ Goel et al. (2017)



Empirical heat flux correlations do not account subcooling

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A Study Of Subcooled Pool Boiling Using Direct Numerical Simulations

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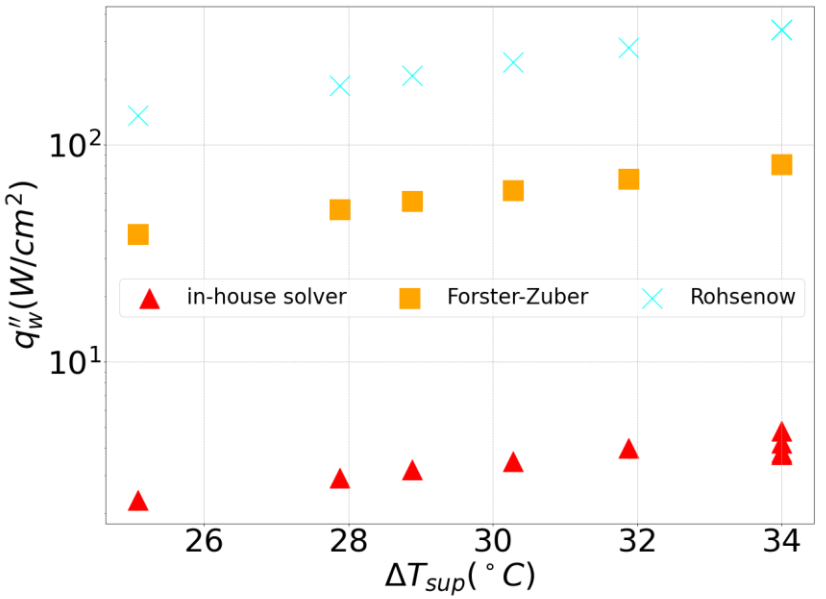
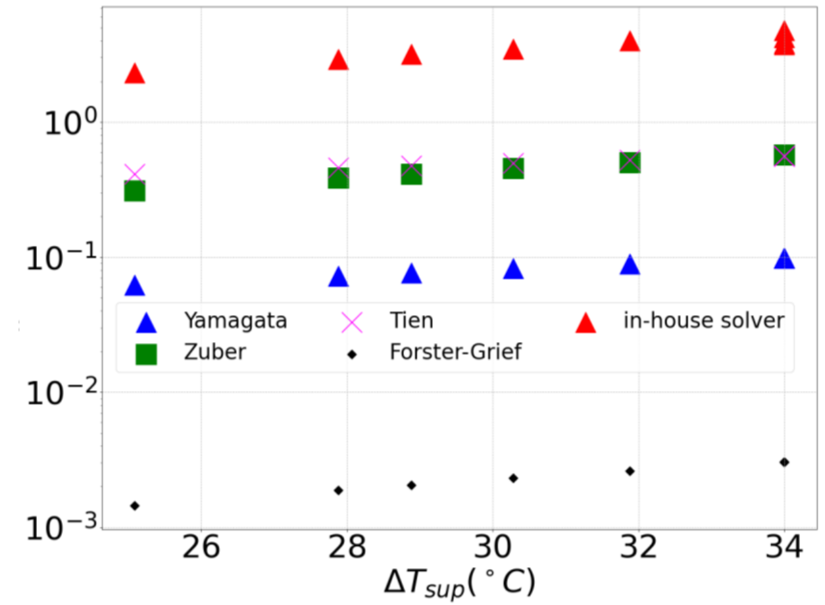
Best Paper Award Winners

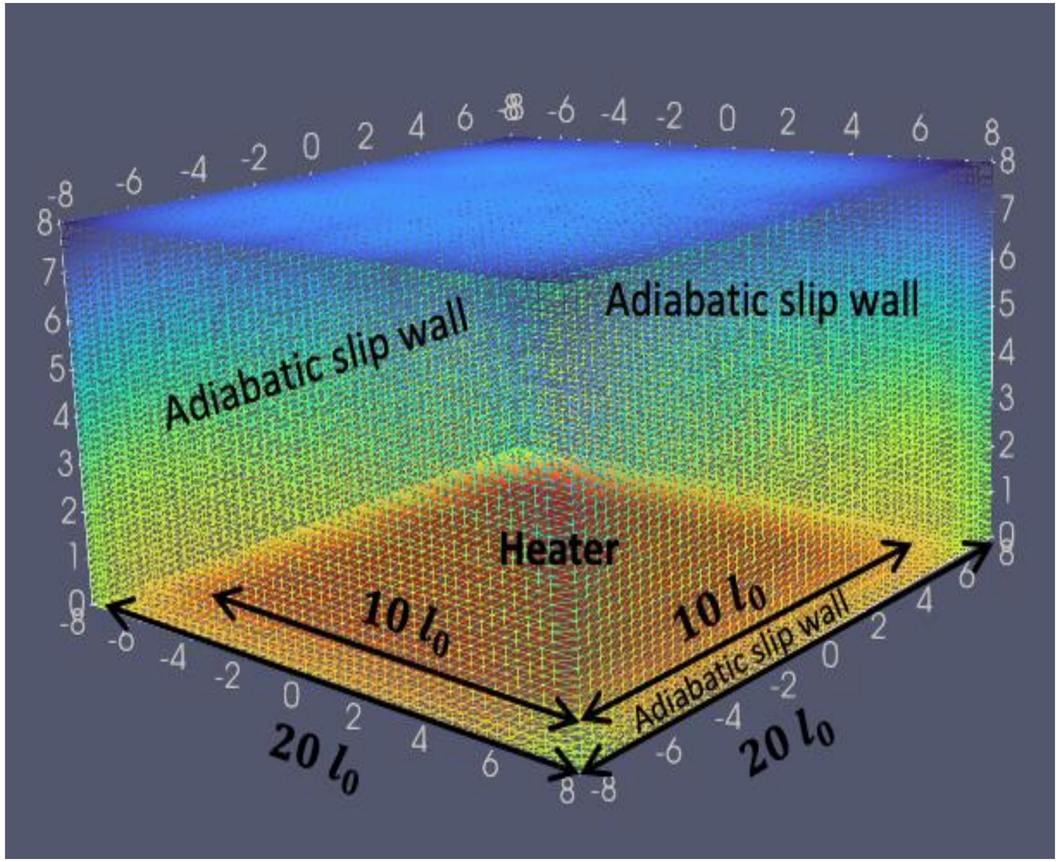
5th International Conference on Fluid Flow and Thermal Science ICFFTS, Lisbon, Portugal

[1]





Computational domain designed to mimic experiments [2]

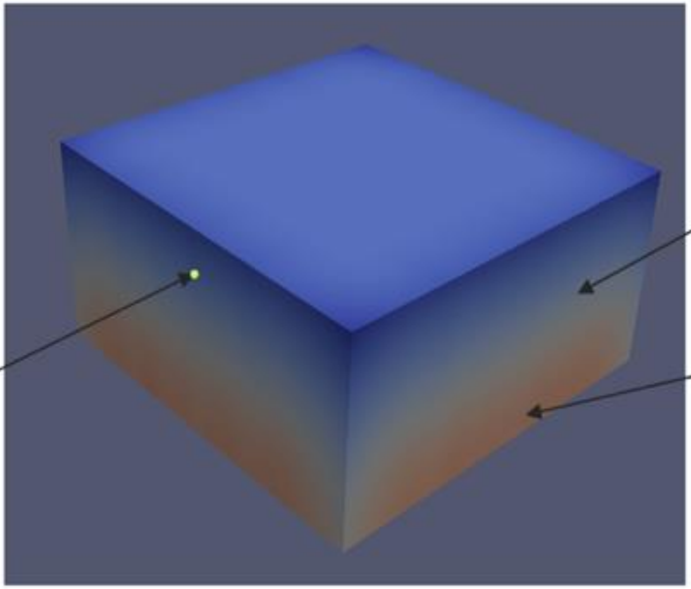


- ***Boiling chamber***
  - $288\ mm \times 144\ mm \times 144\ mm$
- ***Micro-heater***
  - **96 platinum resistance**
  - 10×10 **configuration arrangement**
  - **Each heater has the size of** $0.7\ mm \times 0.7\ mm$
- ***Working fluid***
  - FC72 $T_{sat} = 58℃$
  - Multiphase approach liquid/vapor

Boundary conditions

Top view

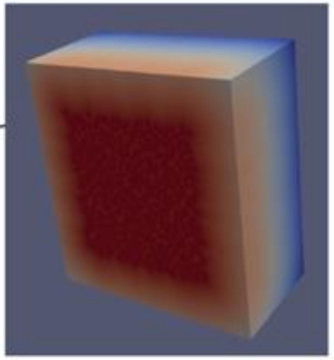
- *velocity: homogeneous Neumann* ($\frac{\partial v}{\partial n} = 0$)
- *pressure: Dirichlet* ($P = 0$)
- *temperature: Dirichlet* ($T = T_{bulk}$)



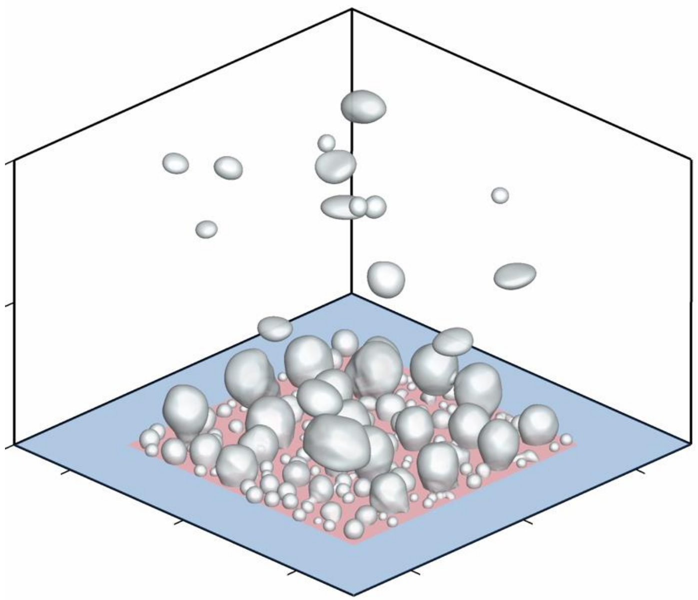
Adiabatic walls

Adiabatic walls

Bottom view

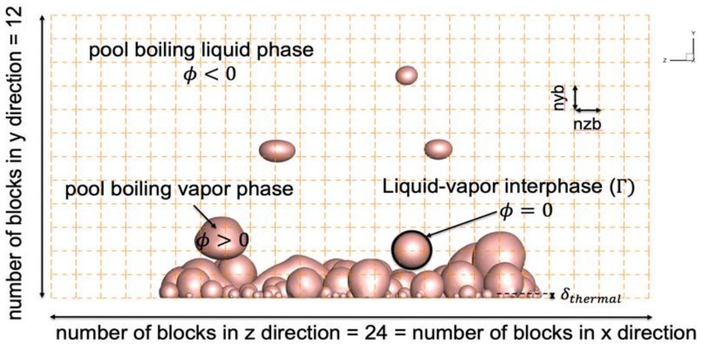


- *velocity: no slip*
- *temperature: Dirichlet* ($T = T_{wall}$)



Numerical methods

Level set method



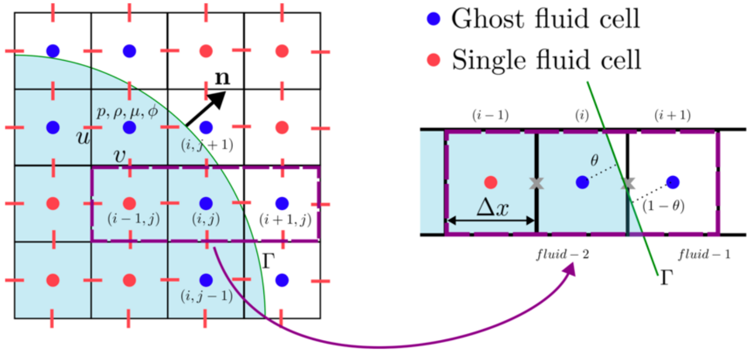
$$\frac{\partial \phi}{\partial t} + \nabla(\overrightarrow{u_\Gamma}.\phi) = 0$$

- ➢ WENO scheme [3]
- ➢ SR re-distancing technique [4]

Dynamic contact angle [5]

$$\theta = \begin{cases} \frac{\theta_a - \theta_r}{2u_{lim}} u_{base} + \frac{\theta_a + \theta_r}{2} & \text{if } |u_{base}| \le u_{lim} \\ \theta_a & \text{otherwise} \end{cases}$$

Ghost fluid method [4]



Poisson equation:

$$\nabla.\left(\frac{1}{\rho'}\nabla p^{n+1}\right) = \frac{1}{\Delta t}\nabla.u^* + \nabla.\xi^{n+1}$$

- The curvature at the interface κ_Γ :

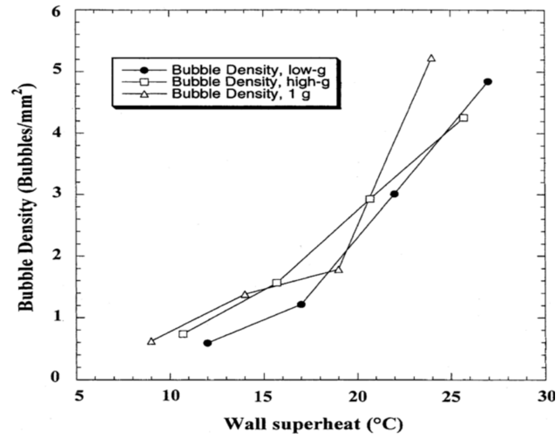
$$\kappa_\Gamma = (1-\theta)\kappa_i + \theta\kappa_{i+1}$$

- θ is the normalized distance from the interface: $\theta = \frac{|\phi_i|}{|\phi_i| + |\phi_{i+1}|}$

Adams Bashforth scheme

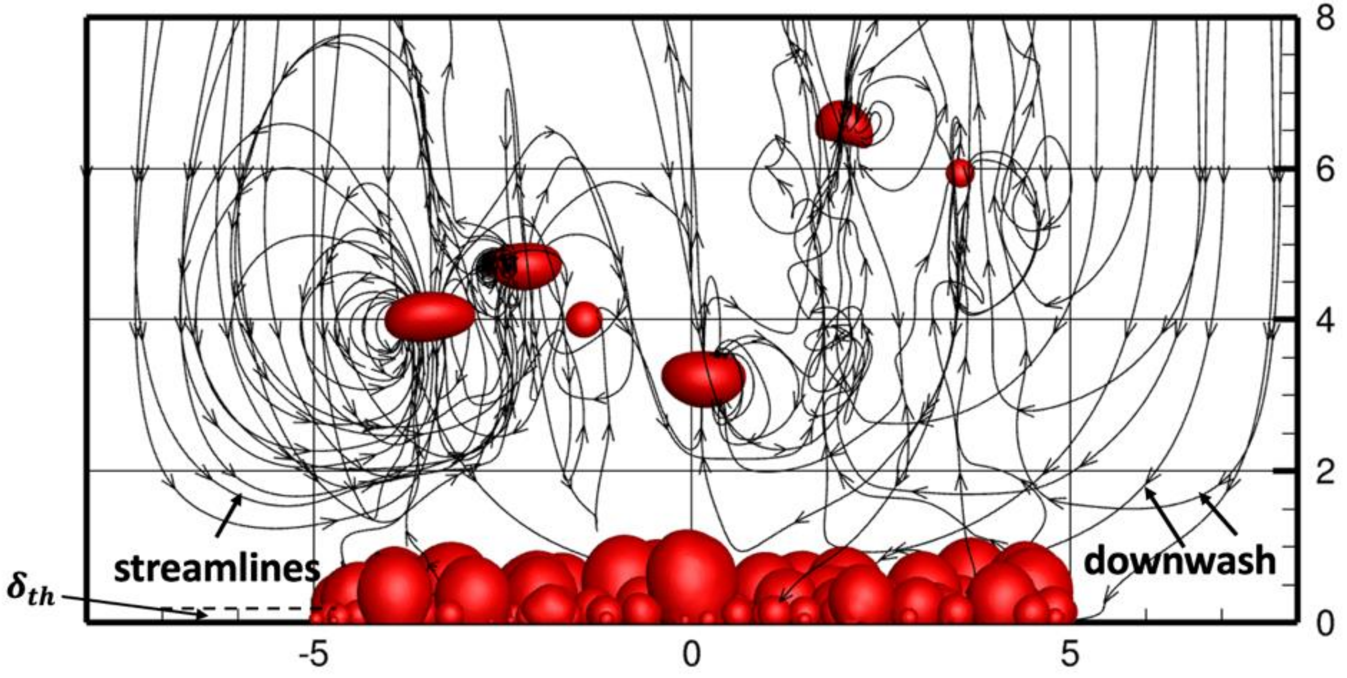
- ➢ Predicted velocity
- ➢ Temperature discretization

Nucleation site density [6]



- ➢ Monte Carlo discretization (Halton sequence)

Governing equations



- Ratio of fluid density to the reference: $\rho' = \frac{\rho_v}{\rho_l}$
- Ratio of phases to the reference: $\alpha' = \frac{\alpha_v}{\alpha_l}$
- Relevant dimensionless numbers

$Re = \rho_l u_0 l_0 / \mu_l$, $Pr = \mu_l C_{pl} / k_l$, $Fr = u_0 / \sqrt{g l_0}$, $We = \rho_l u_0^2 l_0 / \sigma$

Navier-Stokes

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} = -\frac{1}{\rho'} \nabla P + \nabla \cdot \left[\frac{\mu'}{\rho'} \frac{1}{Re} \nabla \vec{u} \right] + \frac{1}{Fr^2}$$

$$\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T = \nabla \cdot \left[\frac{\alpha'}{Re\, Pr} \nabla T \right]$$

Continuity & Mass Conservation

$$\nabla . \vec{u} = -\dot{m} \nabla \frac{1}{\rho'} |_\Gamma \cdot \vec{n}$$

$$\dot{m} = \frac{St}{Re\, Pr} [\nabla T_l|_\Gamma \cdot \vec{n} - k' \nabla T_v|_\Gamma \cdot \vec{n}]$$

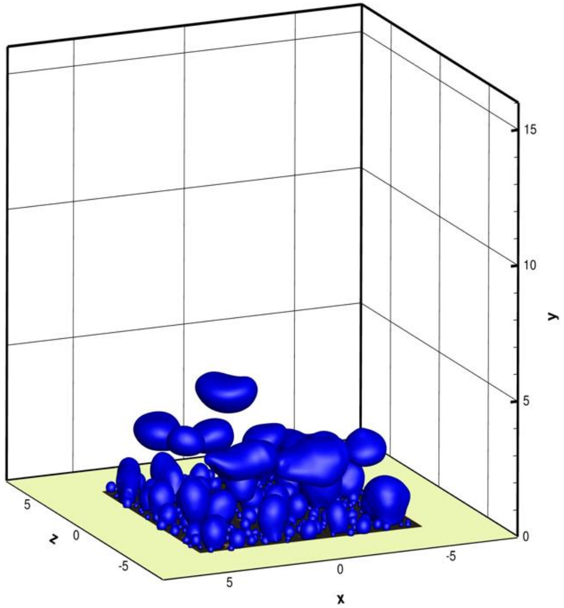
Jump Conditions at the interface (GFM)

$$[P]_\Gamma = P_v - P_l = \frac{k}{We} - \left(\frac{1}{\rho'} - 1 \right) \dot{m}^2$$

$$[\vec{u}]_\Gamma = \vec{u}_v - \vec{u}_l = \dot{m} \left(\frac{1}{\rho'} - 1 \right) \vec{n}$$

$$T_\Gamma = T_{sat}$$

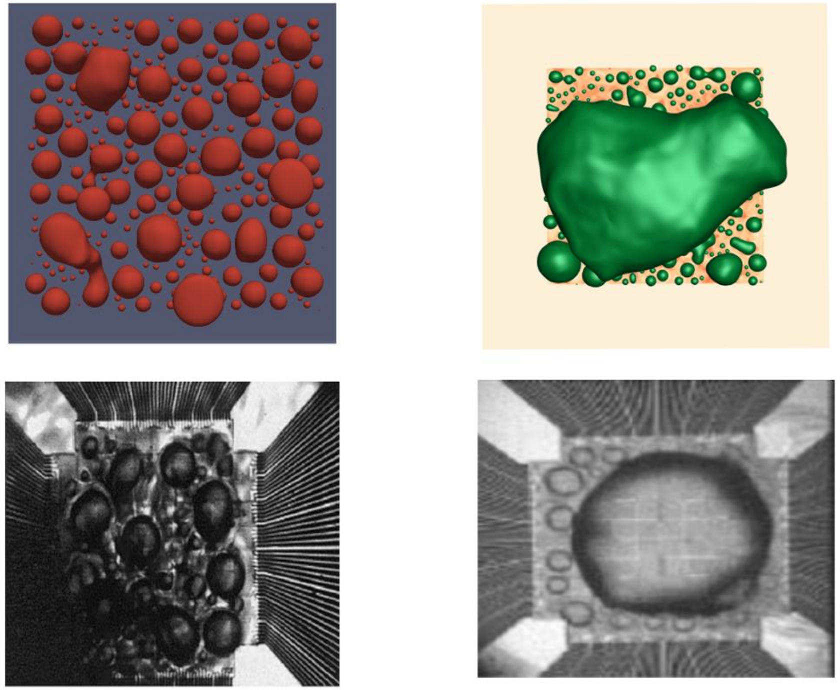
High Fidelity computations match the experiments



DNS simulations
Earth gravity

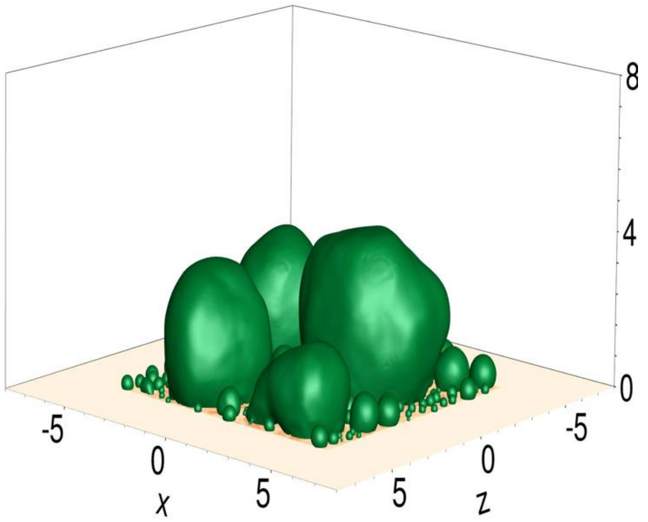
(i) CFD-DNS simulations

(ii) Experiments [6]



(a) Pool boiling on earth gravity

(b) Pool boiling on microgravity



DNS simulations
ISS gravity

Computational Cases

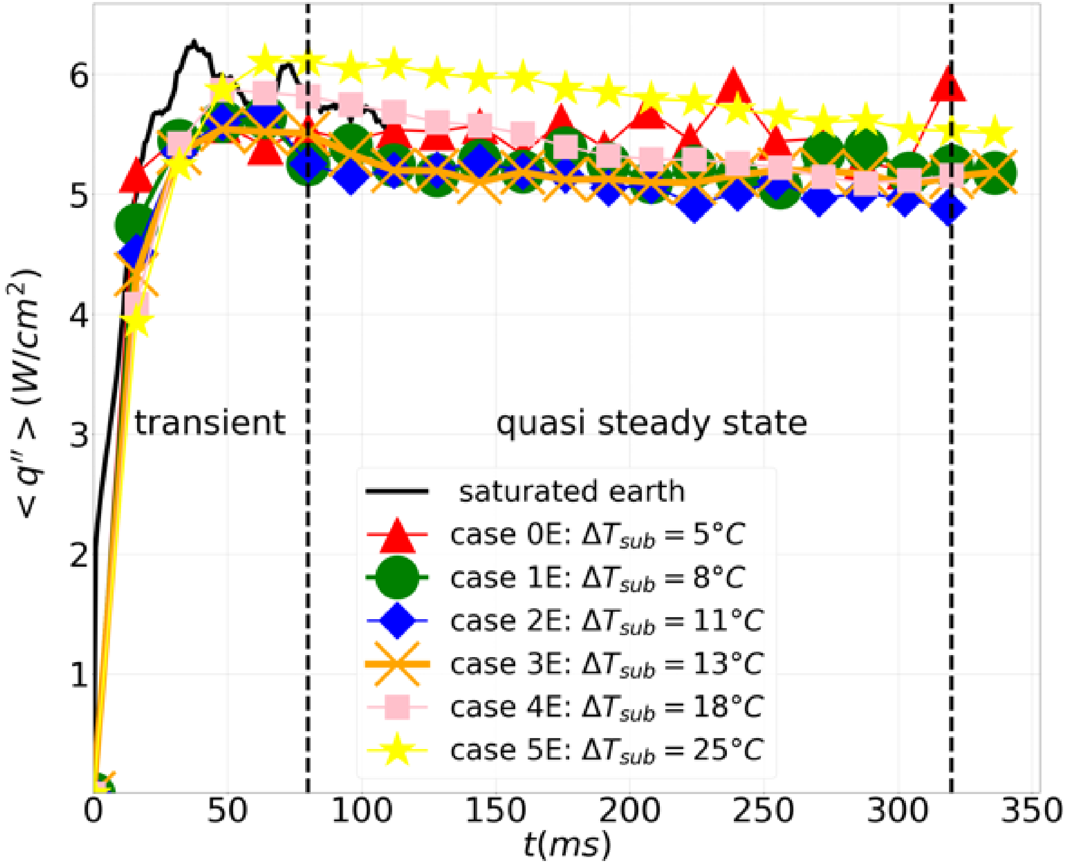
Cases	T_{bulk}(℃)	T_{wall}(℃)	ΔT_{sub}(℃)	st^*
1E, 1ISS	50	92	8	0.5579
2E, 2ISS	47	92	11	0.5978
3E, 3ISS	45	92	13	0.6207
4E	40	92	18	0.6907
5E	33	92	25	0.7837

$\Delta T_{sub} = T_{sat} - T_{bulk}$

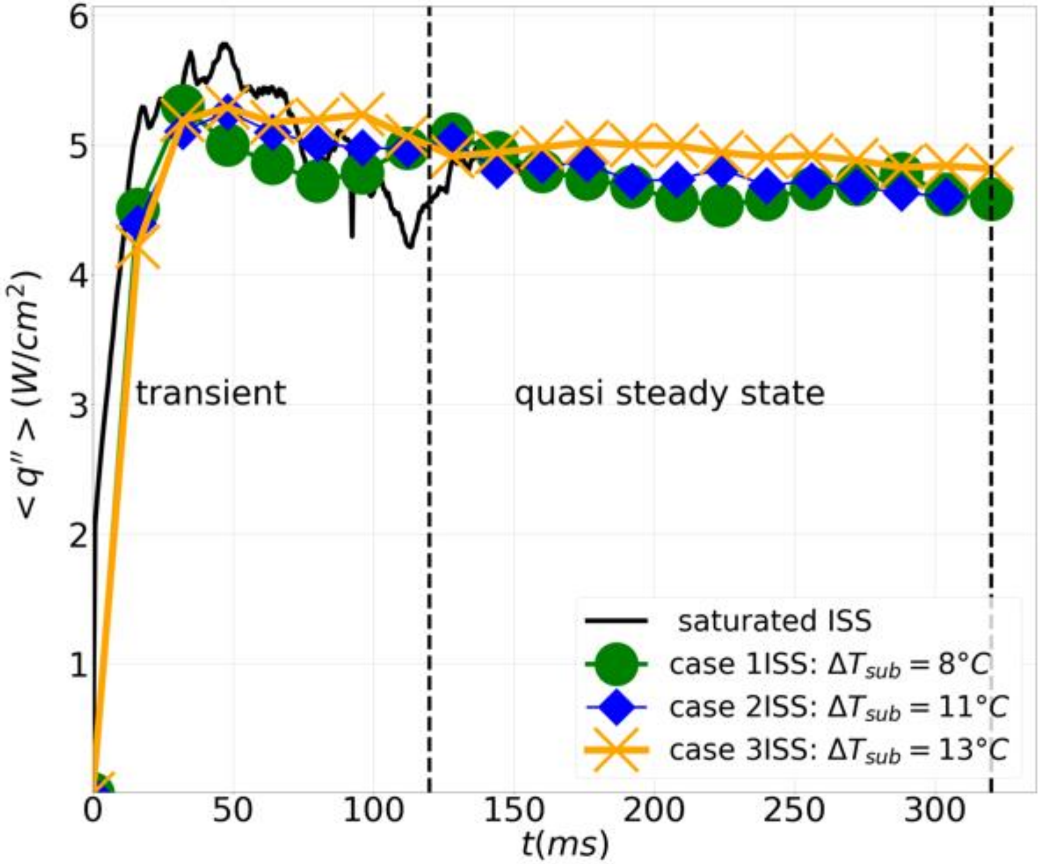
$\Delta T_{sup} = T_{wall} - T_{bulk}$

$St = C_{pl} \Delta T_{sup} / h_{lv}$

Heat flux behavior



(a) Earth gravity

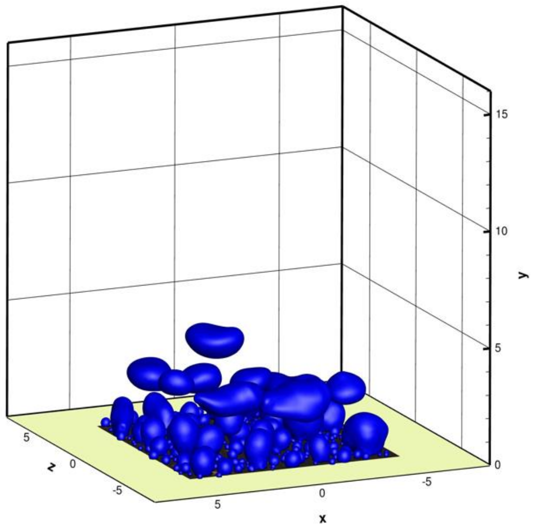


(b) ISS gravity

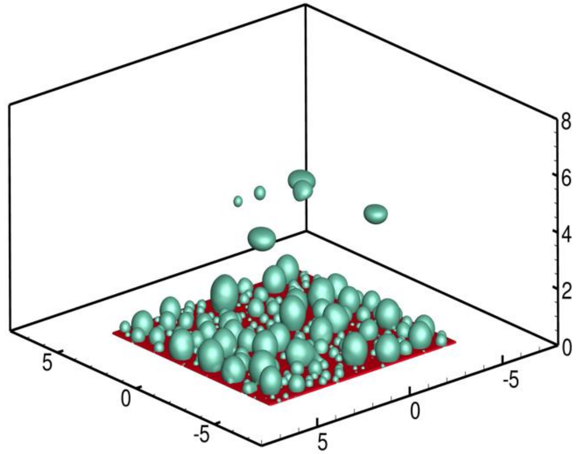
Fig: Temporal variation of the dimensional space averaged wall heat flux $< q'' > \left(W/cm^2\right)$ for different subcooled pool boiling cases

Effect of subcooling and gravity on heat flux

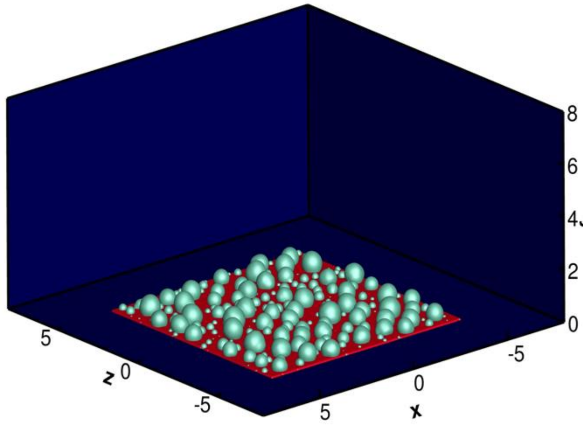
saturated pool boiling, earth



$\Delta T_{sub} = 8$°C



$\Delta T_{sub} = 18$°C



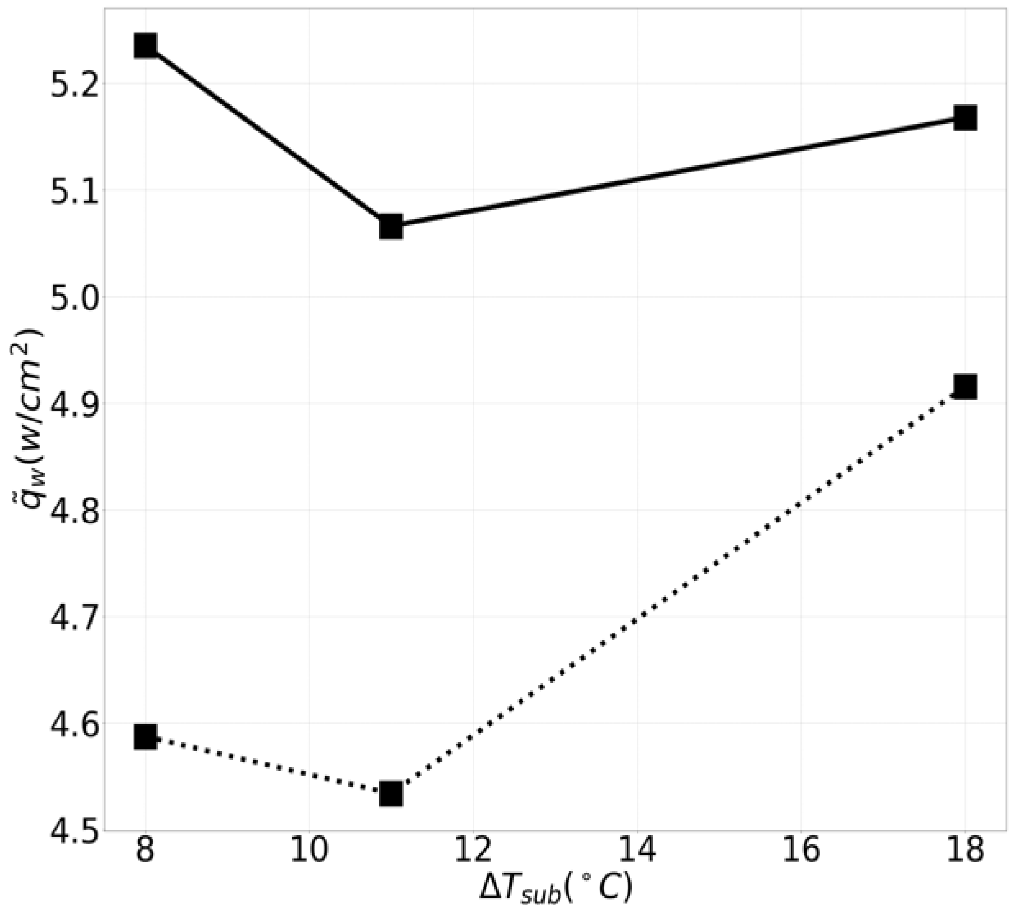
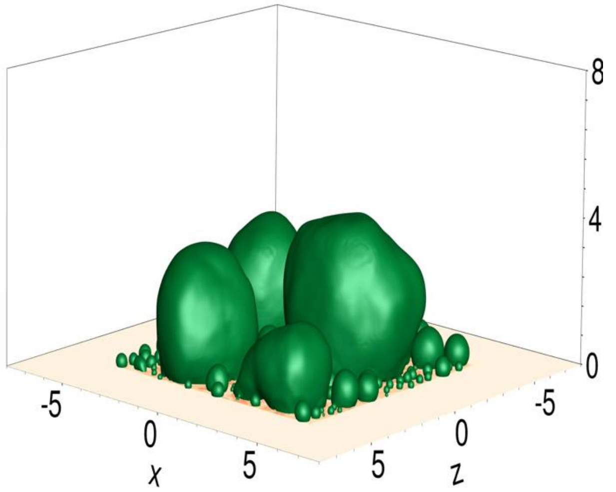


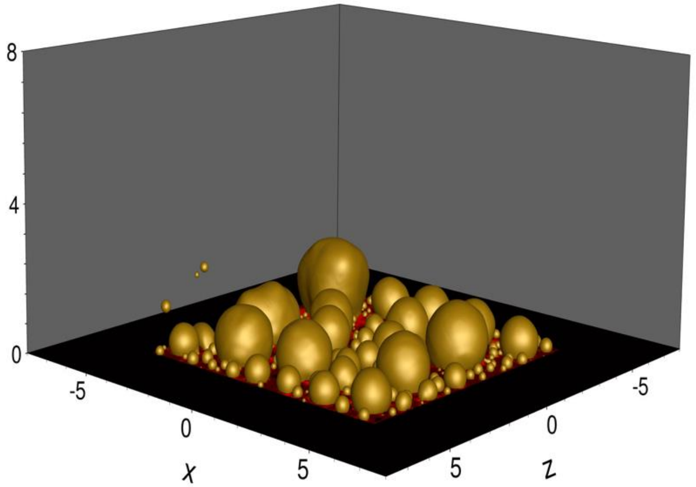
Fig: Ensemble averaged wall heat flux as a function of subcooling temperature at both Earth gravity (___) and ISS gravity (----)

Effect of subcooling and ISS gravity on heat flux

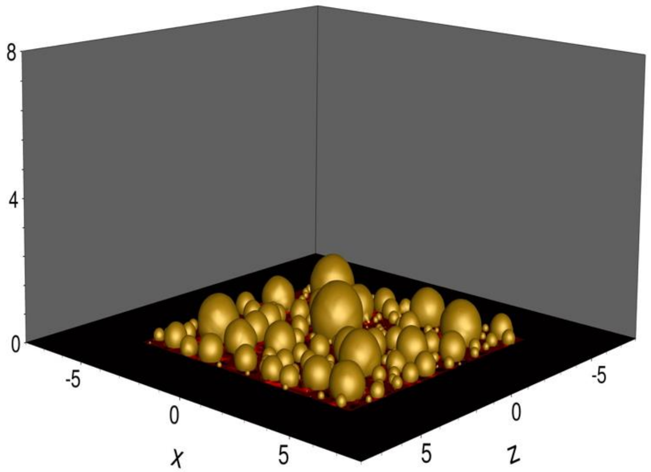
saturated pool boiling, ISS



low subcooling, ISS



high subcooling, ISS



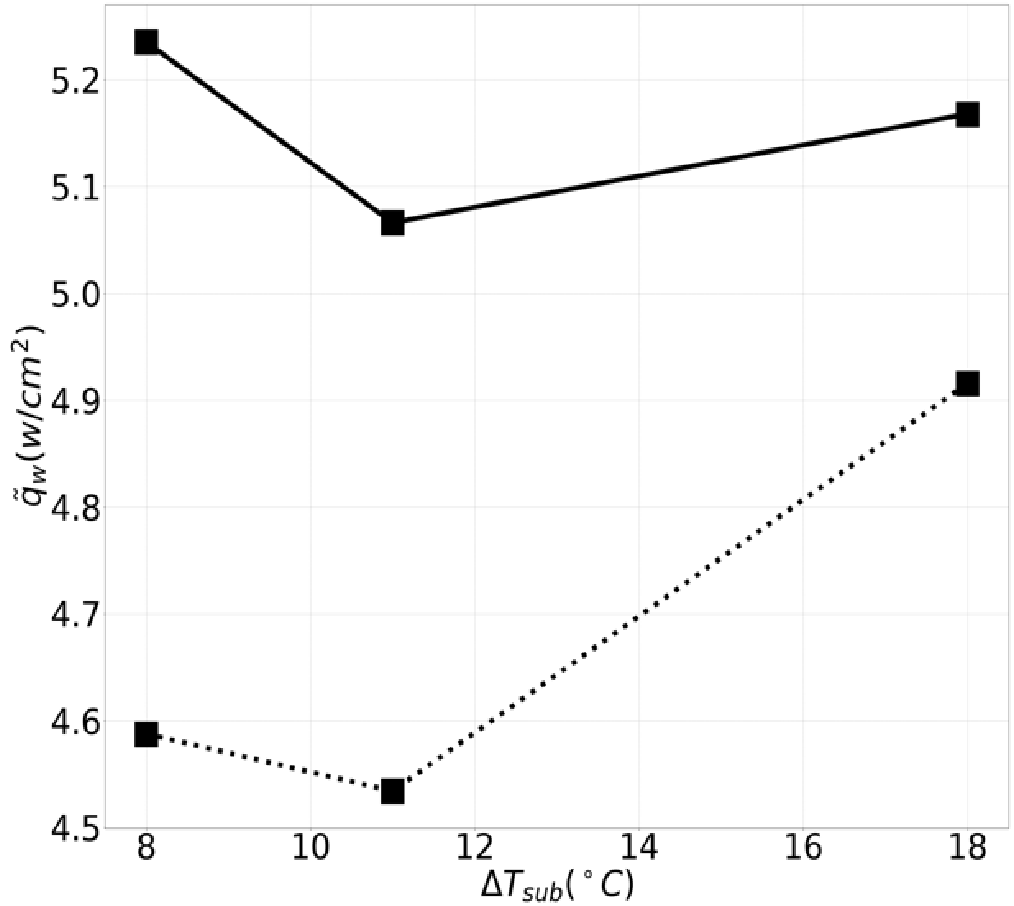
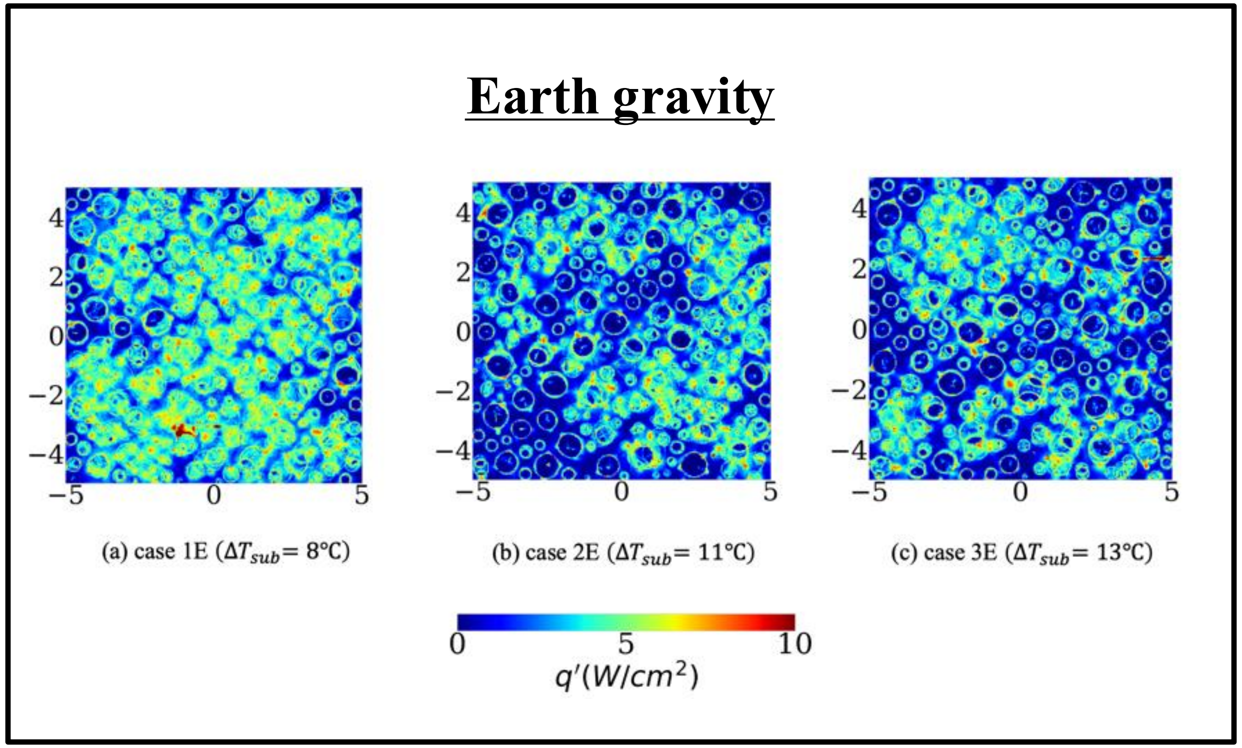
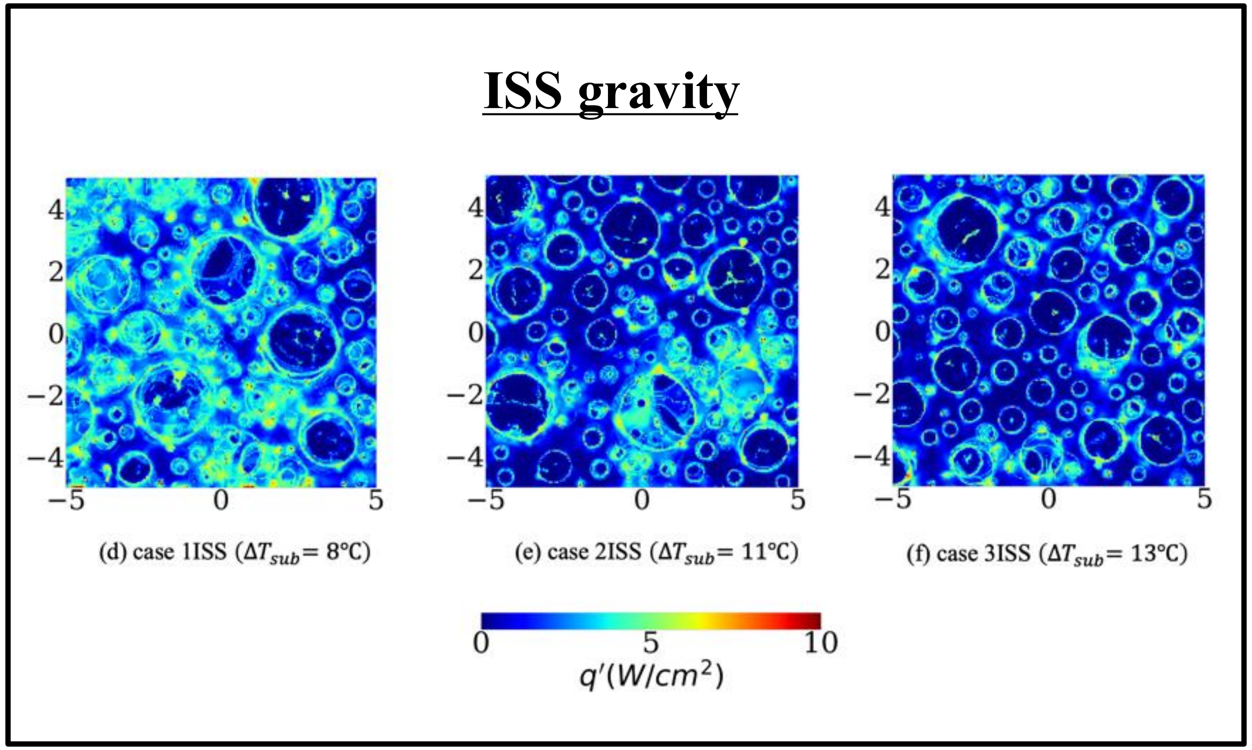


Fig: Ensemble averaged wall heat flux as a function of subcooling temperature at both Earth gravity (___) and ISS gravity (----)

rms heat flux fluctuations

$$q' = \sqrt{\frac{\sum_{n=1}^{N_z} \sum_{n=1}^{N_x} \sum_{n_i}^{N_{samples}} (q - \tilde{q})^2}{\sum_{n=1}^{N_z} \sum_{n=1}^{N_x} \sum_{n_i}^{N_{samples}}}}$$





Algorithm development for bubble's tracking

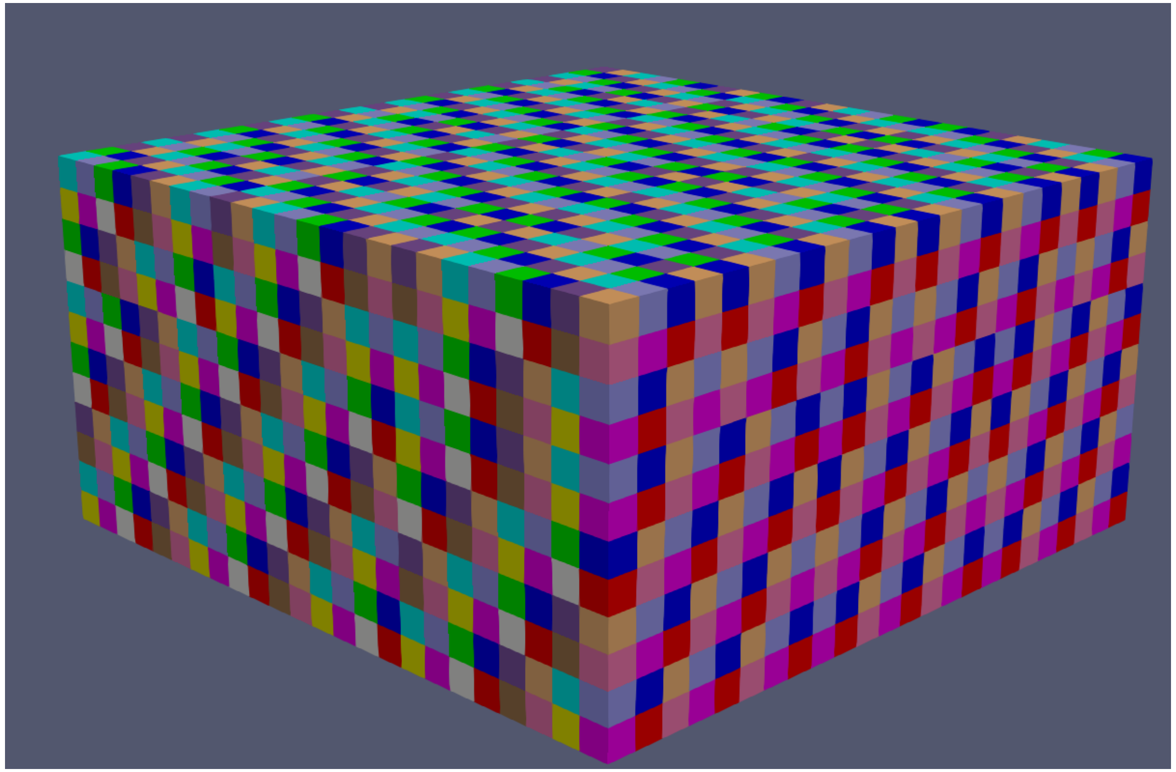


Fig: data structured in blocks

Scikit-image is a collection of image processing algorithms implemented in Python language:

1. Import hdf5 data files
2. Plot the level set function (ϕ)
3. Thresholding data ($Bubble = \phi \leq 0$)
4. Labeling data
5. Measuring bubble properties

The developed algorithm is successful to determine bubble properties

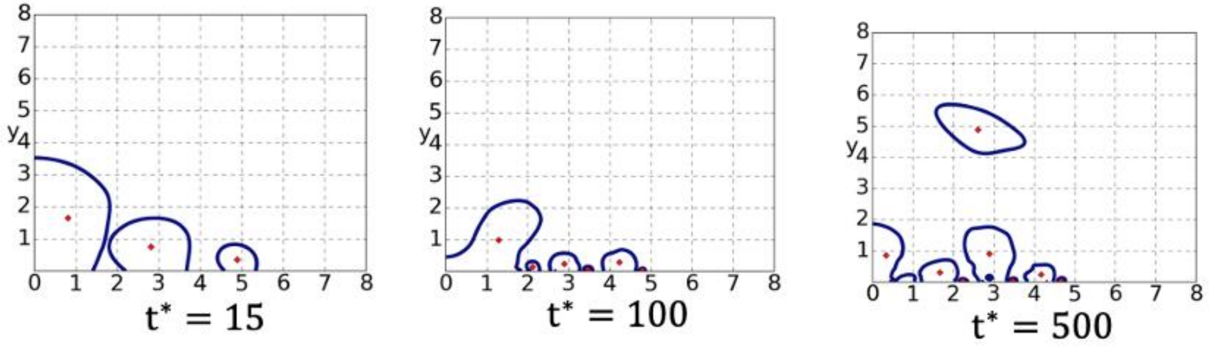


Fig: 2D simulations at Earth gravity

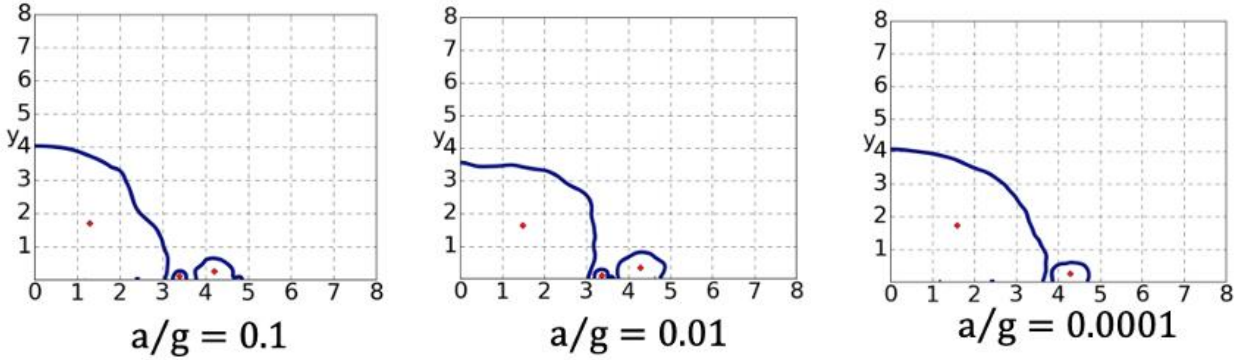
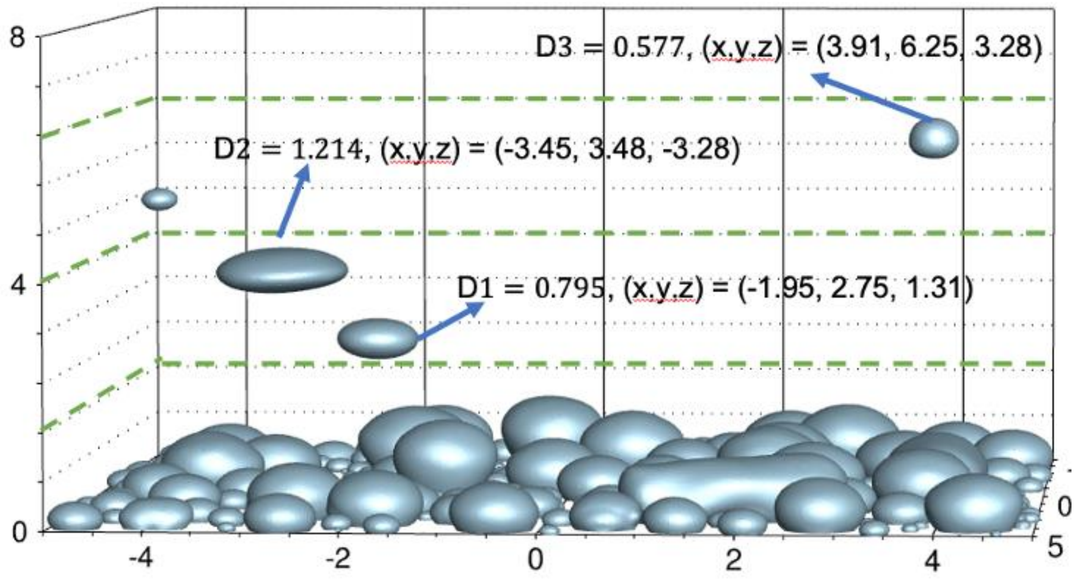
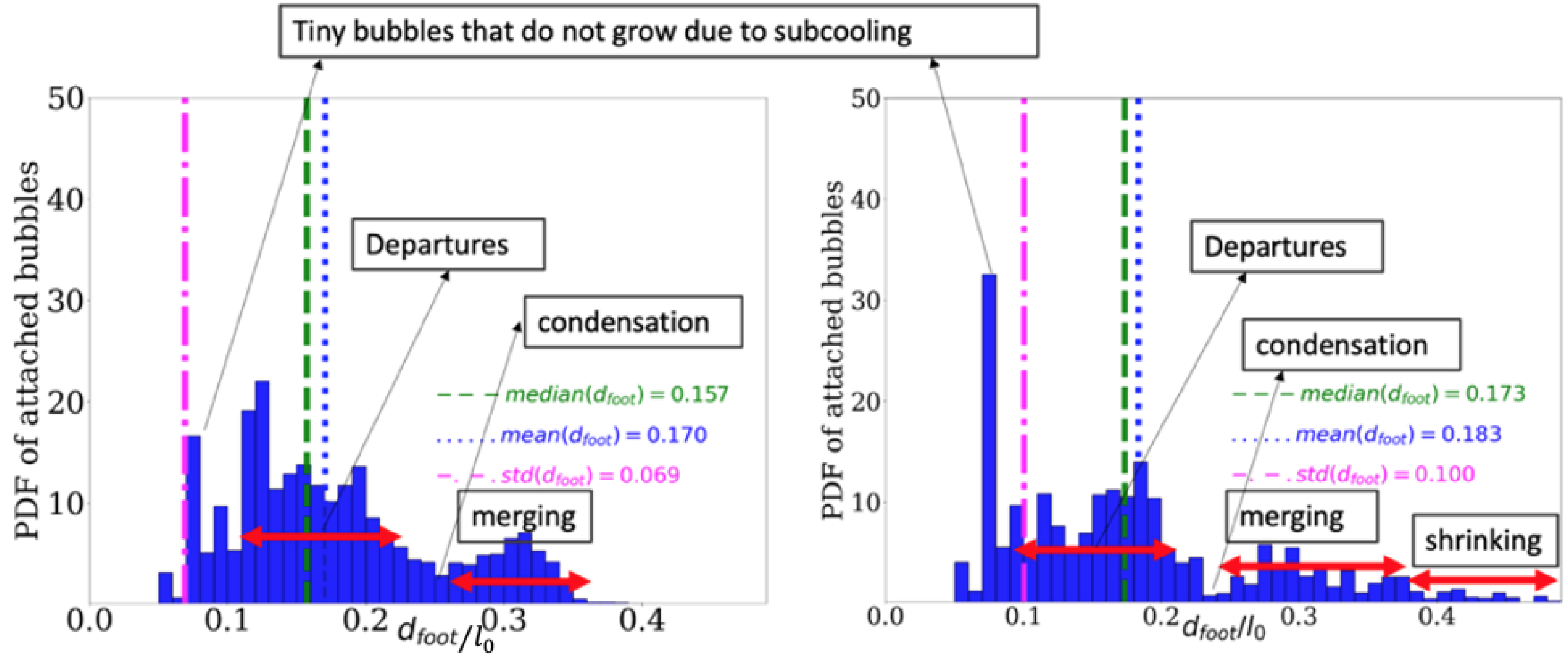


Fig: 2D simulations at microgravity

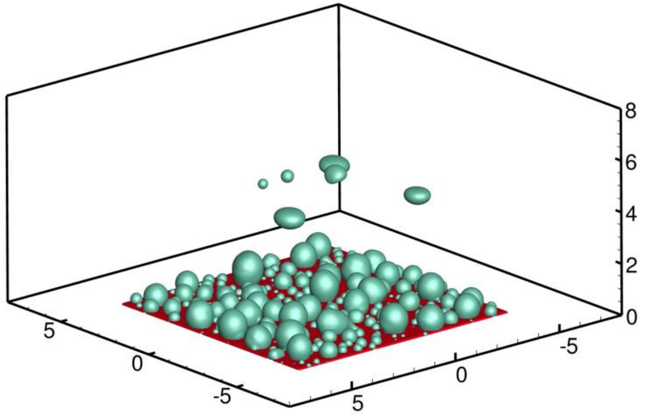


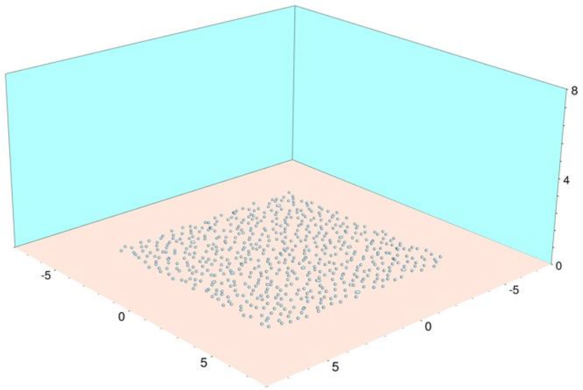
Bubble dynamics at earth gravity



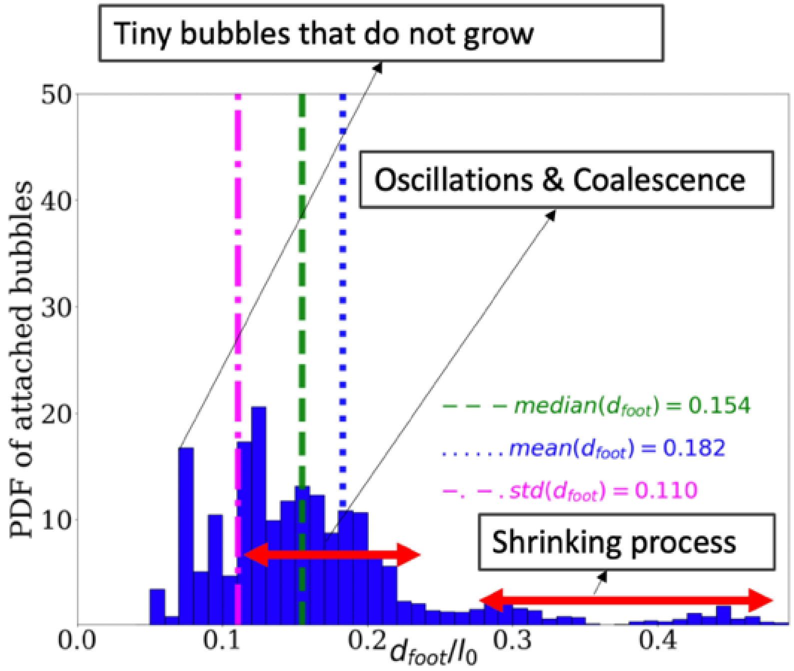
(a) Case 1E

(b) Case 3E

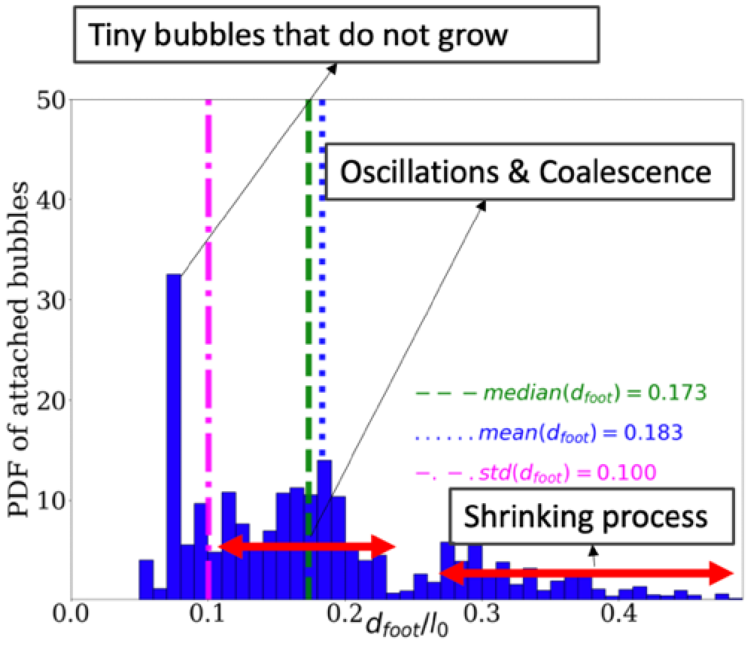




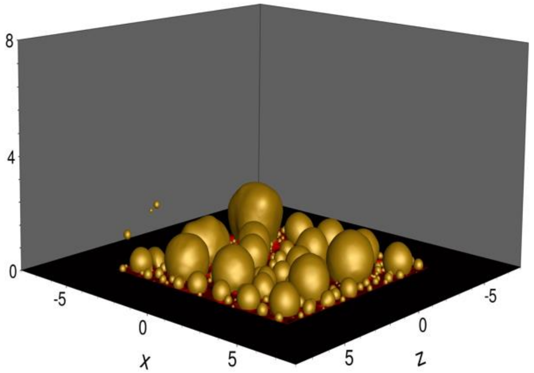
Bubble dynamics at ISS gravity

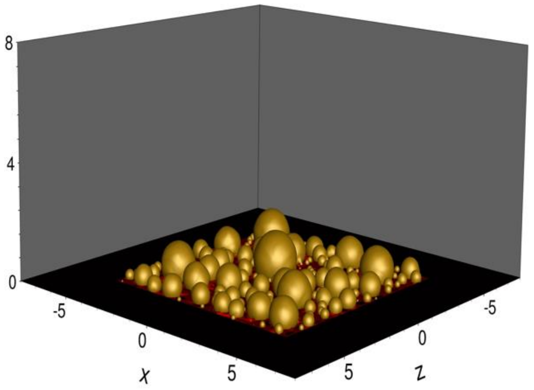


(a) Case 1ISS



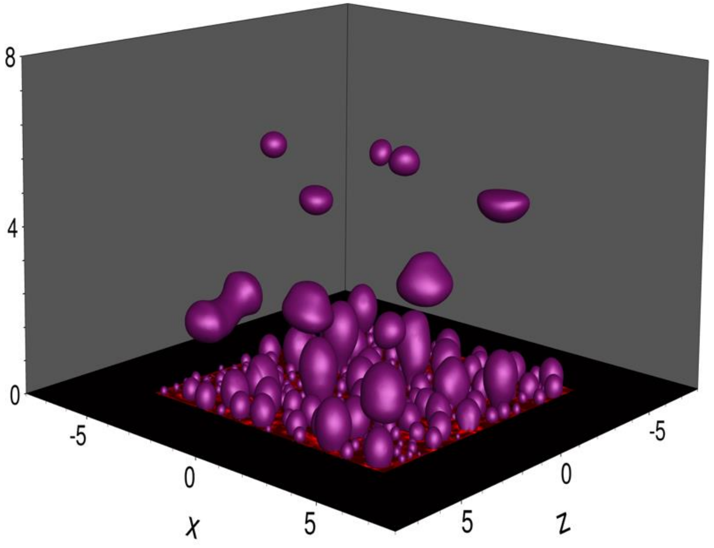
(b) Case 3ISS





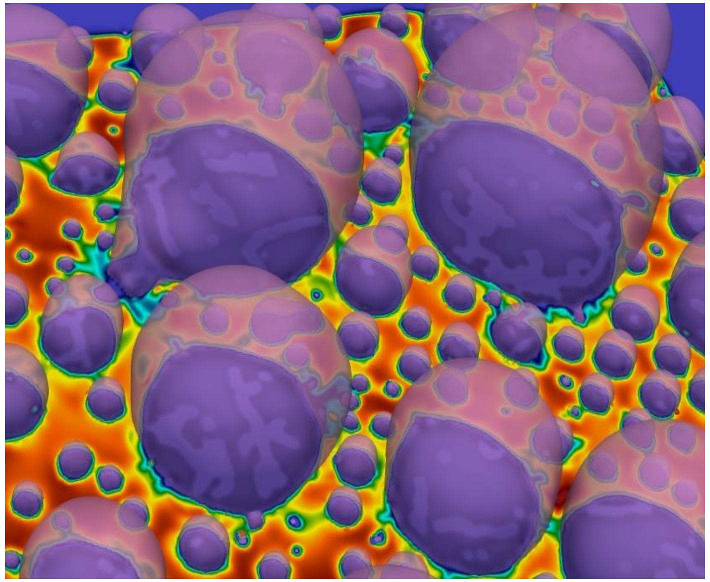
Bubble dynamics overview

Departure process



- observed at low and intermediate subcooling at earth gravity.
- no departure was observed at ISS-g subcooled pool boiling

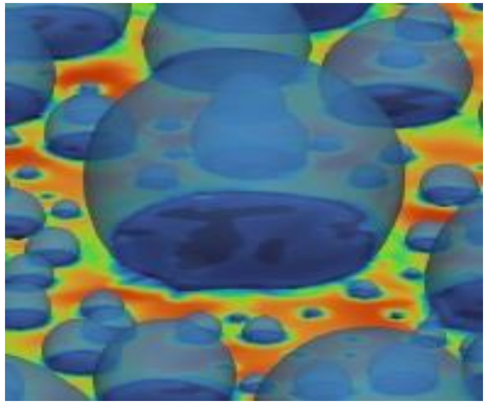
Merging process



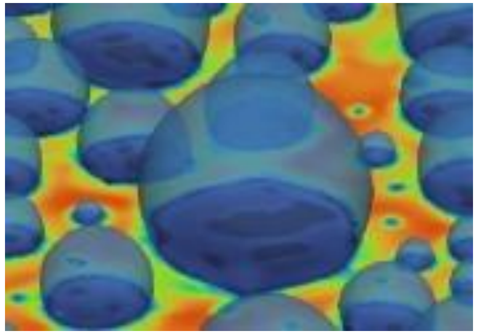
observed at all type of subcooling at earth gravity and ISS gravity

Shrinking process

$t = 120\ ms$

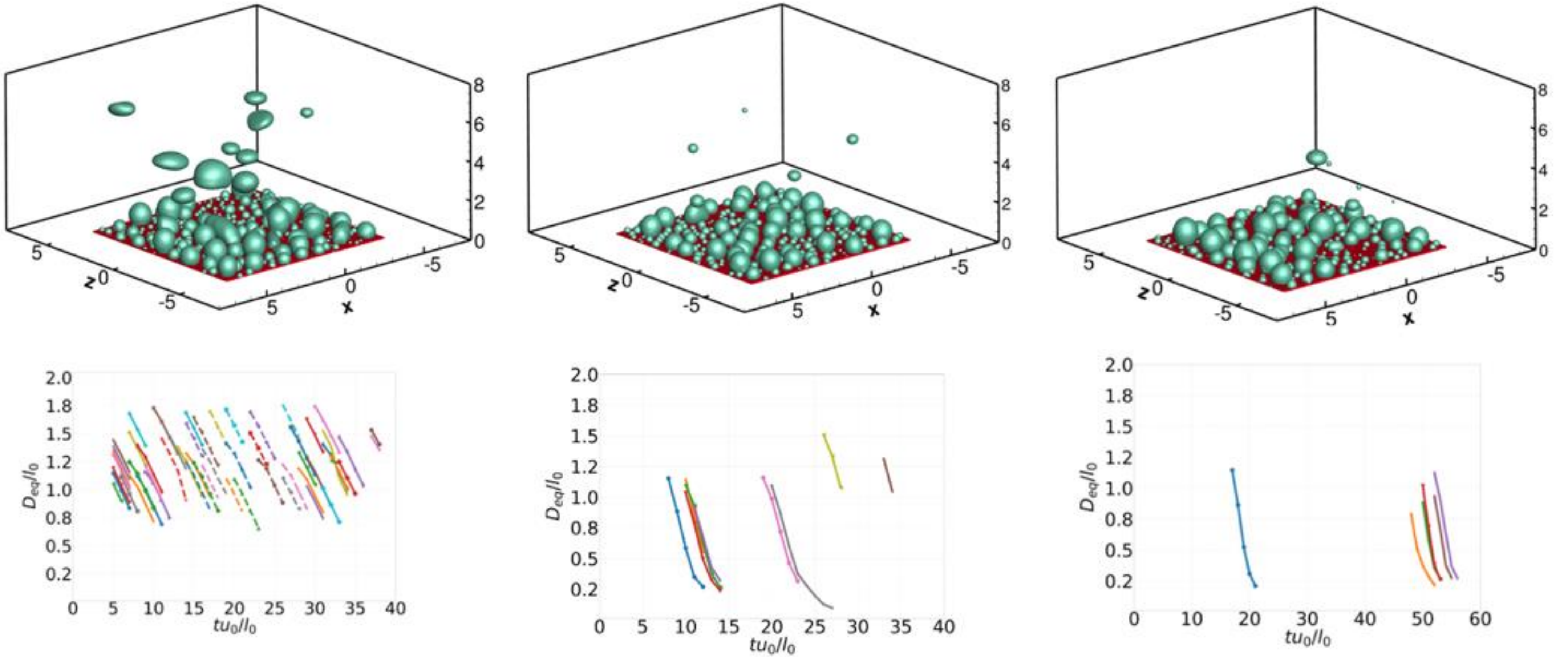


$t = 328\ ms$



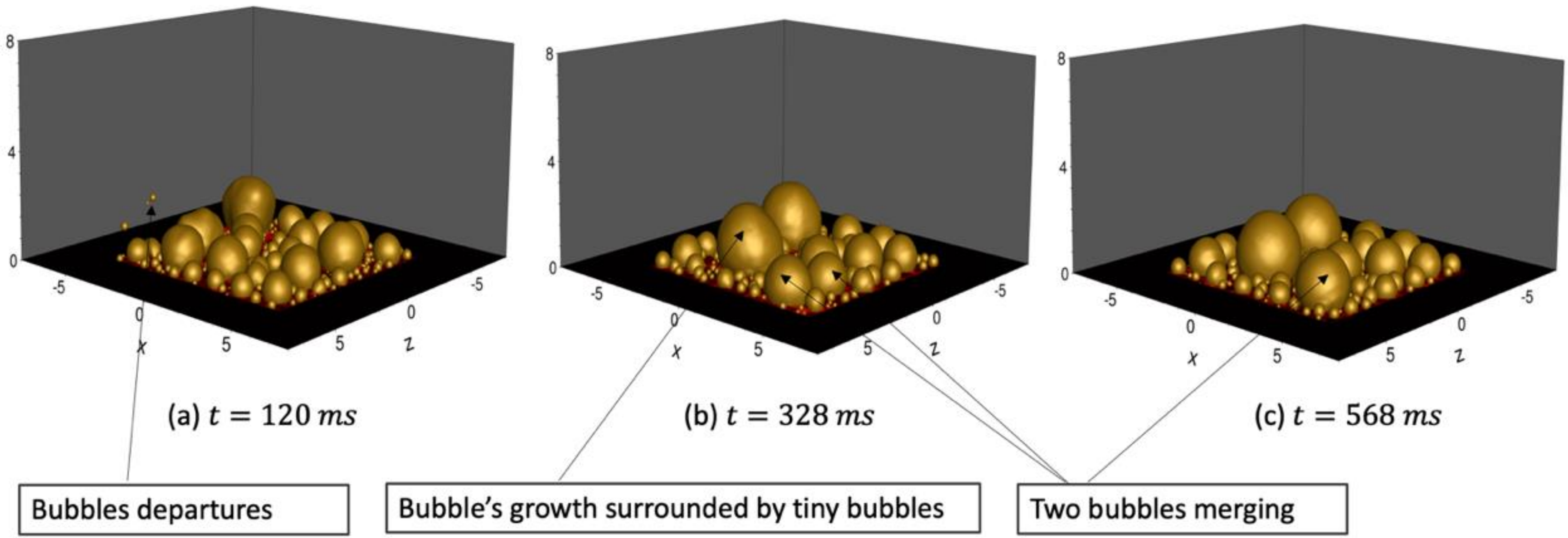
dominant at high subcooling earth gravity and all type of subcooling at ISS-g

Bubble departures at earth gravity decreases with subcooling

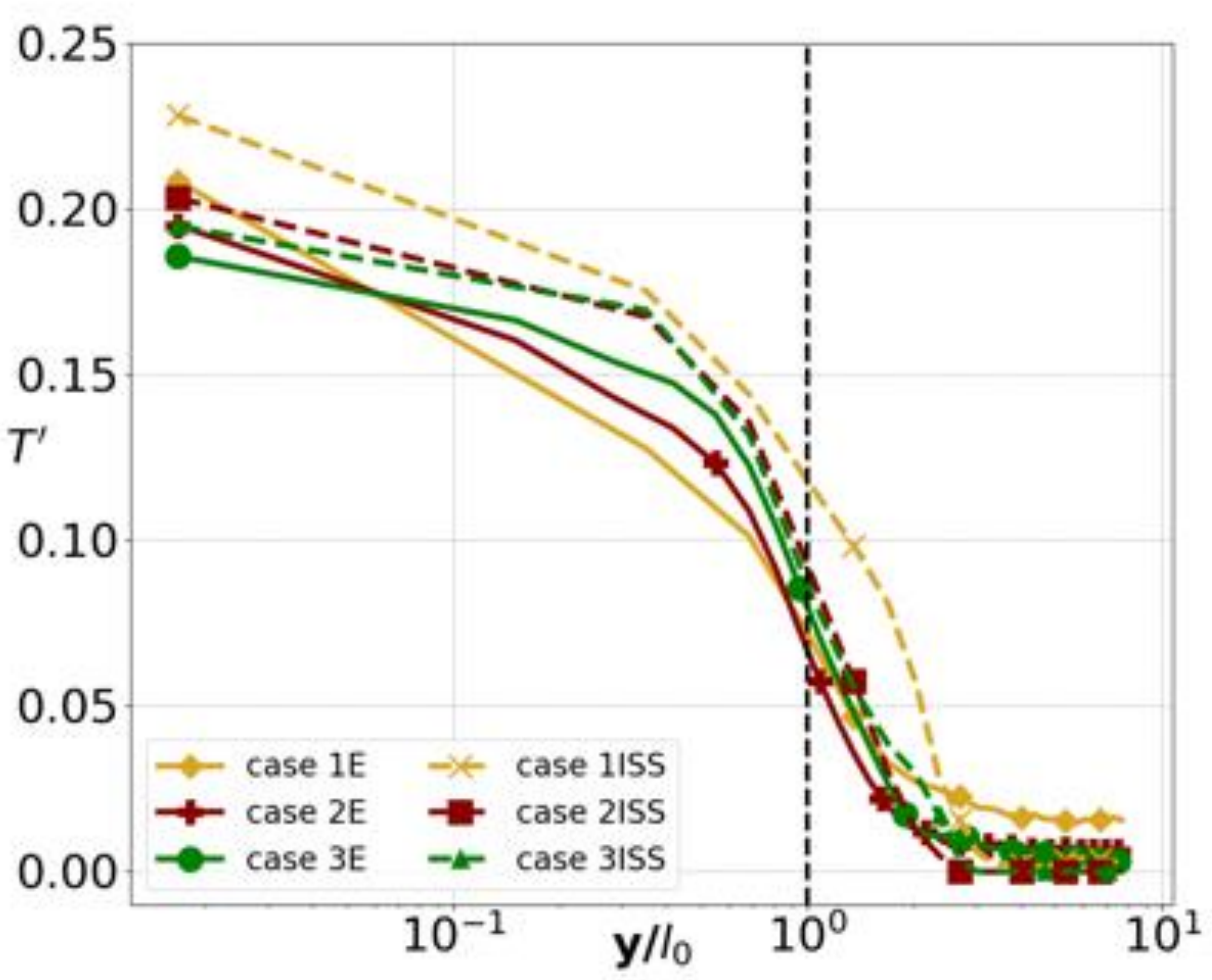


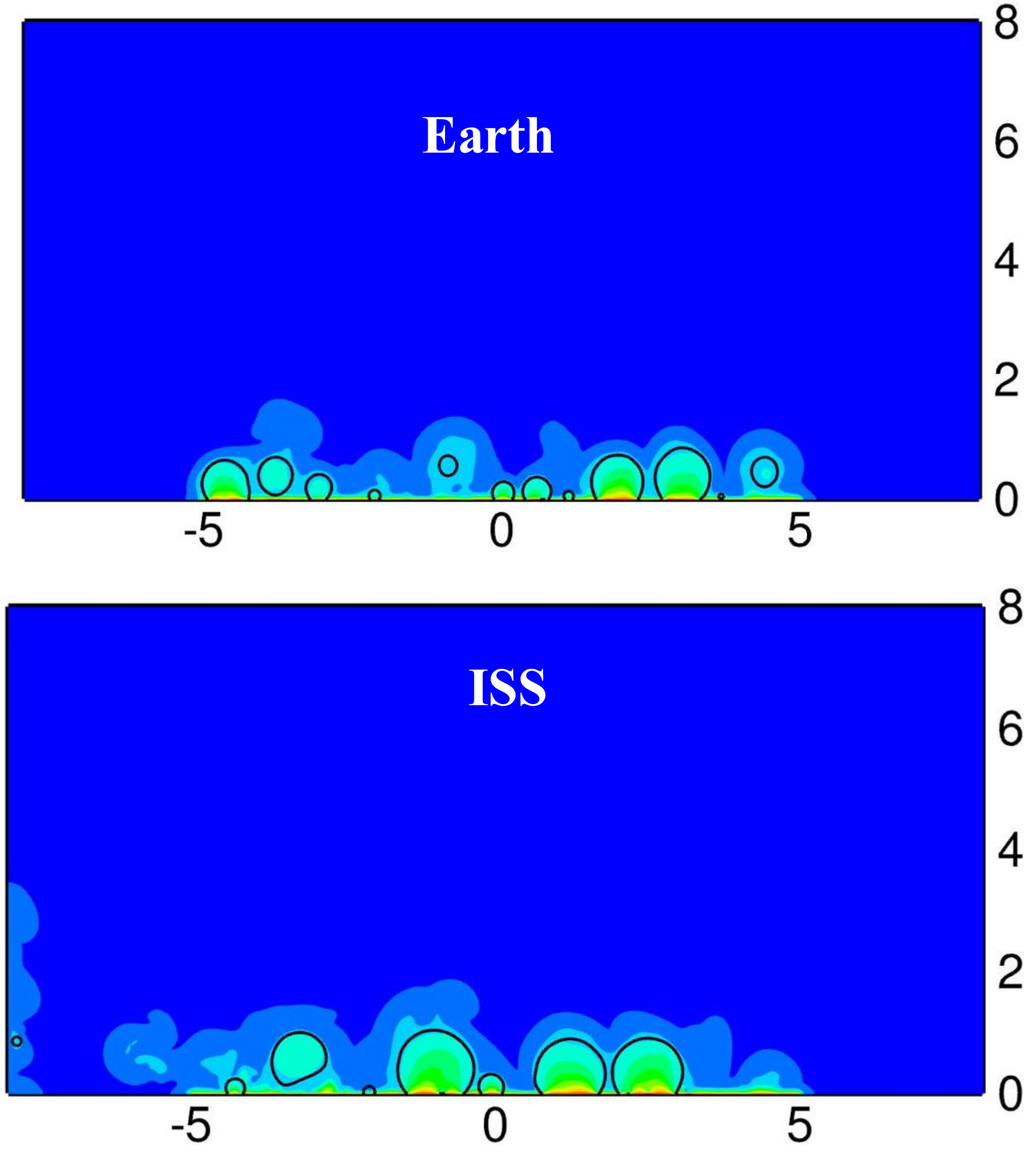
The mean equivalent departure diameter is 0.96 mm for case 1E, 0.77 mm for case 2E, and 0.67 mm for case 3E

No bubble departures was observed at ISS gravity



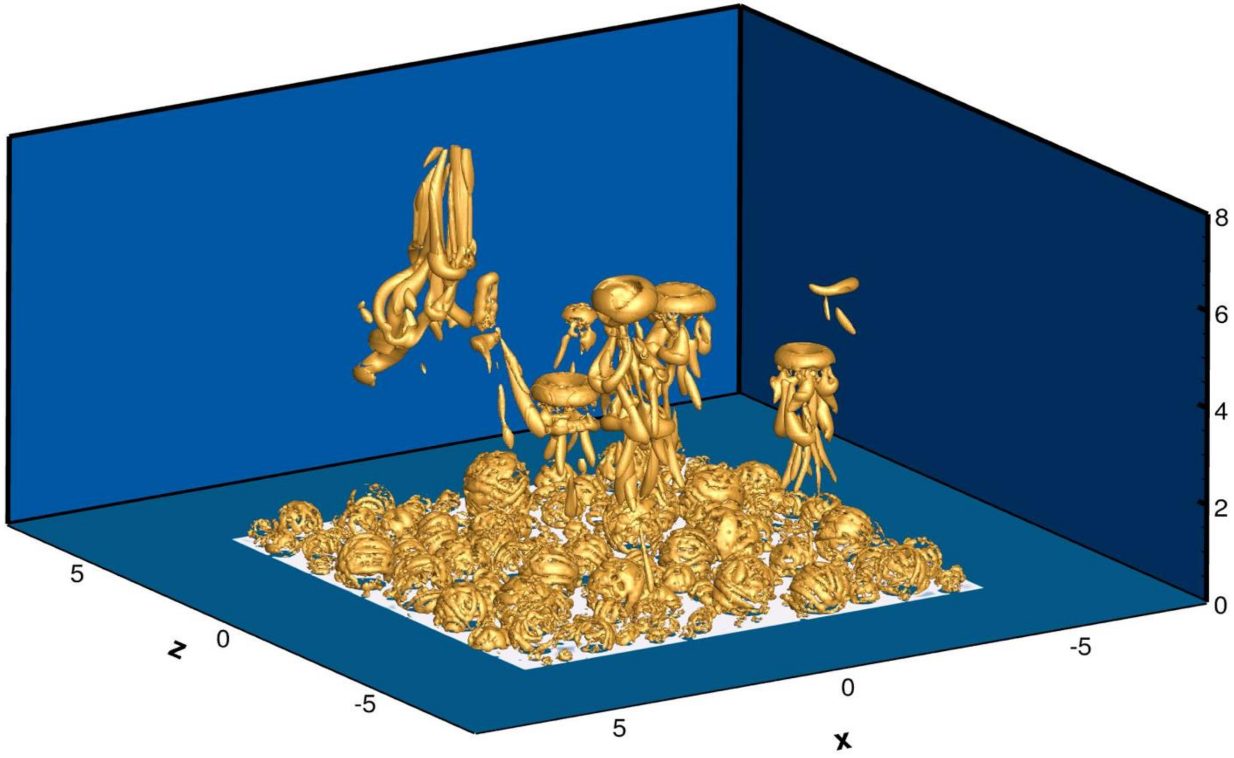
rms temperature fluctuations



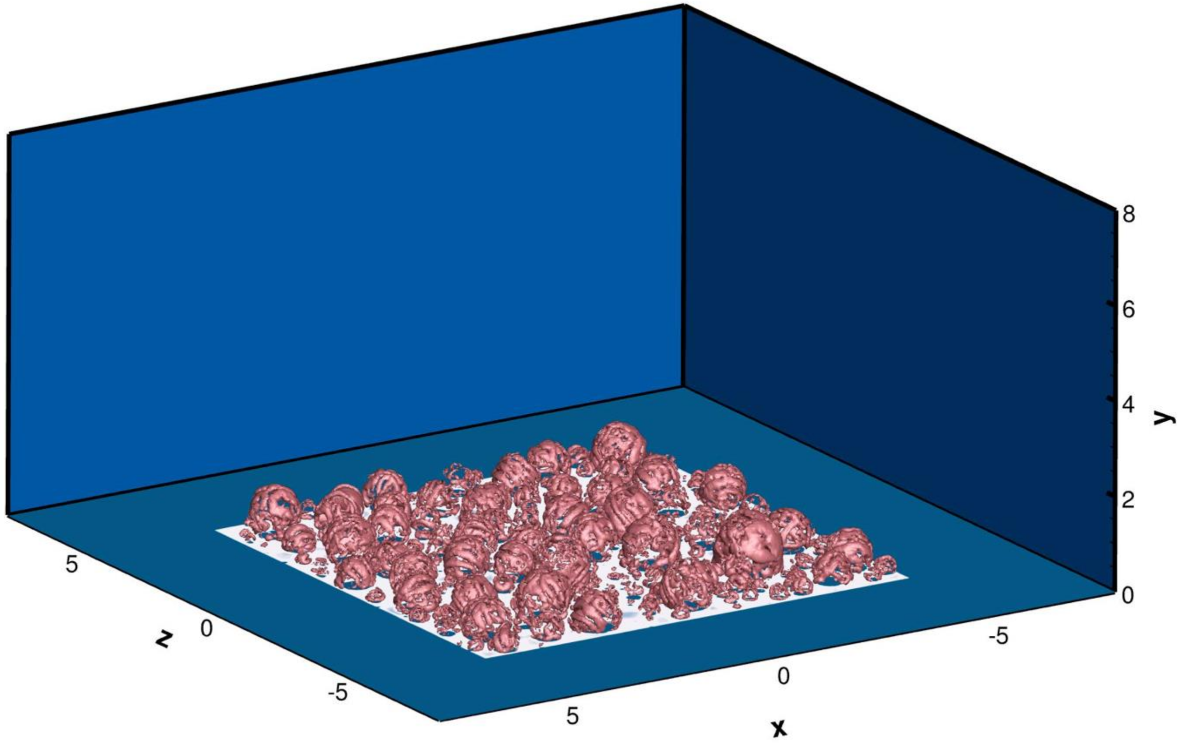


Coherent vortices

Low subcooling

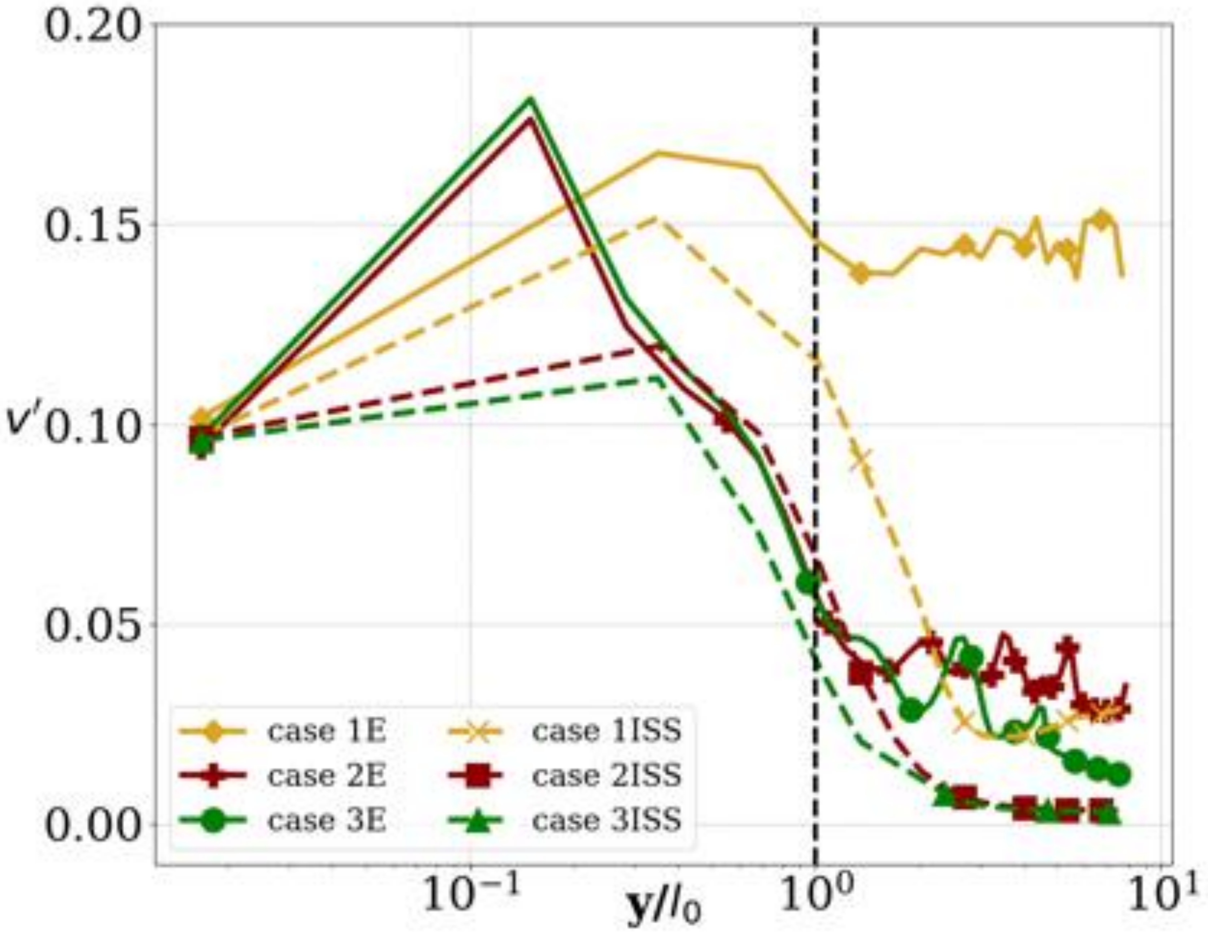


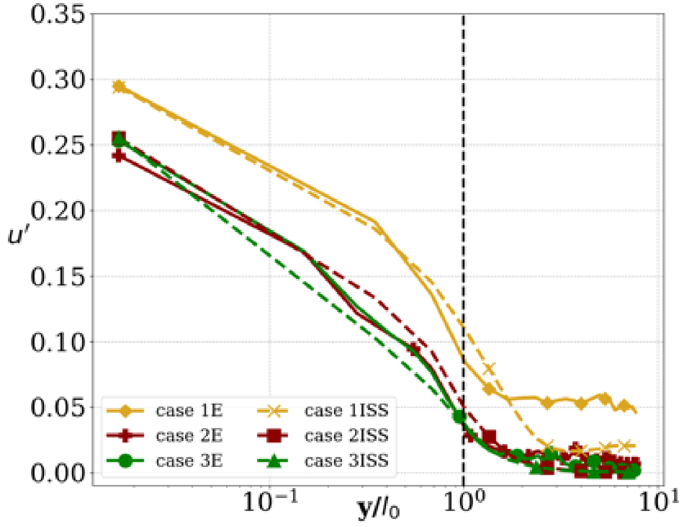
High subcooling

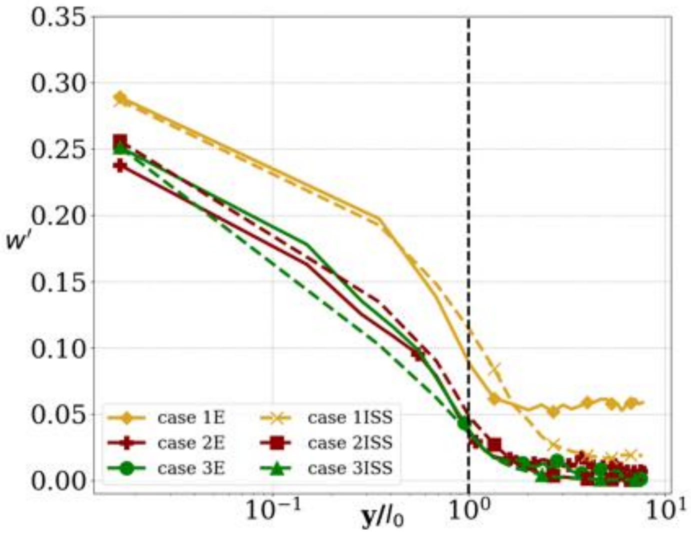


$$Q = \frac{1}{2}\left((\nabla.\vec{u})^2 - \nabla\vec{u}:\nabla\vec{u}^T\right) = \frac{1}{2}\left((\nabla.\vec{u})^2 + ||\Omega||_2^2 - ||S||_2^2\right)$$

rms velocity fluctuations







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