Modeling and Measurement of Interfacial Area Concentration in Two-phase Flow

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Presentation Outline

- ✓ Introduction
- ✓ Formulation of Two-Fluid Model with Interfacial Area Transport Eq.
  - ✓ Two-Group Interfacial Area Transport Eq.
  - ✓ Two-Group Momentum Eq.
- ✓ Modeling of Sink and Source Terms in Interfacial Area Transport Eq.
  - ✓ Sink and Source Due to Bubble Breakup and Coalescence
  - ✓ Sink and Source Terms Due to Phase Change
  - ✓ Source Term Due to Wall Nucleation
- ✓ Database to Evaluate Interfacial Area Transport Eq.
  - ✓ Local Interfacial Area Measurement
  - ✓ Database for 8 X 8 Rod Bundle Geometry
- ✓ Benchmarking Interfacial Area Transport Eq.
  - ✓ Benchmarking 1-D IATE in Adiabatic Systems
  - ✓ Benchmarking 1-D IATE in Condensation Systems
- ✓ Future Directions
- ✓ Conclusions

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Introduction

The modeling philosophy of thermal-hydraulic system analysis codes treats interface structure using **flow regimes and transition criteria** that cannot dynamically represent the changes in interfacial structure (no time or length scale is incorporated into the transition criteria).

This leads to **instantaneous changes in flow regime**, which can not only induce non-physical oscillations in system behavior but can also hamper code accuracy and robustness.

To better represent the effects of interfacial structure and regime transition, the use of **a first order equation to characterize interfacial area transport** has been recommended (Ishii, 1975).

$$\frac{\partial a_i}{\partial t} + \nabla \cdot (a_i \boldsymbol{v}_i) = \Phi$$

a_i : interfacial area concentration

v_i : interfacial velocity

Φ : sink and source terms

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Formulation of Interfacial Area Transport Equation (Kocamustafaogullari and Ishii, 1995)

Boltzmann Transport Equation of Particles

$$\frac{\partial f}{\partial t} + \nabla \cdot (f\boldsymbol{v}) + \frac{\partial}{\partial V}\left(f\frac{dV}{dt}\right) = \sum_j S_j + S_{ph}$$

$f(V, \boldsymbol{x}, t)$: distribution function, V: volume, S_j and S_{ph}: particle source and sink rates per unit mixture volume due to particle interaction and phase change

Interfacial Area Transport Equation

$$\frac{\partial a_i}{\partial t} + \nabla \cdot (a_i \boldsymbol{v}_i) - \frac{2}{3}\left(\frac{a_i}{\alpha}\right)\left\{\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \boldsymbol{v}_g) - \eta_{ph}\right\} = \sum_j \Phi_j + \Phi_{ph}$$

η_{ph}: rate of volume generated by nucleation source per unit mixture volume, Φ_j and Φ_{ph}: interfacial area source and sink rates per unit mixture volume due to particle interaction and phase change

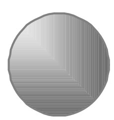
Development of Two-group Interfacial Area Transport Equation (Ishii and Hibiki, 2005)

Fluid particle number density transport equation analogous to Boltzmann's transport equation → Interfacial Area Transport Eq.

Two-group approach

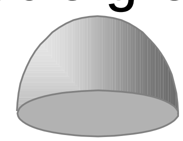
Group 1

Spherical/distorted bubble group



Group 2

Cap/slug/churn-turbulent bubble group



Maximum Distorted Bubble Size Limit →

$$D_{d,max} = 4\sqrt{\frac{\sigma}{g\Delta\rho}}$$

Two-group Interfacial Area Transport Equation (Ishii and Kim, 2004; Ishii and Hibiki, 2005)

Two-group Void Fraction Transport Equation

$$\frac{\partial\left(\alpha_{gk}\rho_g\right)}{\partial t}+\nabla\cdot\left(\alpha_{gk}\rho_g\boldsymbol{v}_{gk}\right)=\Gamma_{gk}+(-1)^k\,\Delta\dot{m}_{12}$$

$$\Delta\dot{m}_{12}=\rho_g\left[\sum_j\eta_{j,2}+\chi\left(D_{c1}^*\right)^3\left\{\frac{\partial\alpha_{g1}}{\partial t}+\nabla\cdot\left(\alpha_{g1}\boldsymbol{v}_{g1}\right)-\eta_{ph1}\right\}\right],\ \ D_{c1}^*\equiv\frac{D_{crit}}{D_{Sm1}}$$

Two-group Interfacial Area Transport Equation

$$\frac{\partial a_{i1}}{\partial t}+\nabla\cdot\left(a_{i1}\boldsymbol{v}_{i1}\right)=\left\{\frac{2}{3}-\chi\left(D_{c1}^*\right)^2\right\}\frac{a_{i1}}{\alpha_{g1}}\left[\frac{\partial\alpha_{g1}}{\partial t}+\nabla\cdot\left(\alpha_{g1}\boldsymbol{v}_{g1}\right)-\eta_{ph1}\right]+\sum_j\phi_{j,1}+\phi_{ph1}$$

$$\frac{\partial a_{i2}}{\partial t}+\nabla\cdot\left(a_{i2}\boldsymbol{v}_{i2}\right)=\frac{2}{3}\frac{a_{i2}}{\alpha_{g2}}\left[\frac{\partial\alpha_{g2}}{\partial t}+\nabla\cdot\left(\alpha_{g2}\boldsymbol{v}_{g2}\right)-\eta_{ph2}\right]$$
$$+\chi\left(D_{c1}^*\right)^2\frac{a_{i1}}{\alpha_{g1}}\left[\frac{\partial\alpha_{g1}}{\partial t}+\nabla\cdot\left(\alpha_{g1}\boldsymbol{v}_{g1}\right)-\eta_{ph1}\right]+\sum_j\phi_{j,2}+\phi_{ph2}$$

Two-group Momentum Equation
(Sun et al., 2003)

Two-group Momentum Equation

$$\frac{\partial\left(\alpha_{g1}\rho_g \boldsymbol{v}_{g1}\right)}{\partial t}+\nabla\cdot\left(\alpha_{g1}\rho_g \boldsymbol{v}_{g1}\boldsymbol{v}_{g1}\right)=-\alpha_{g1}\nabla p_{g1}+\nabla\cdot\left[\alpha_1\left(\boldsymbol{\mathcal{T}}_{g1}^{\mu}+\boldsymbol{\mathcal{T}}_{g1}^{T}\right)\right]+\alpha_{g1}\rho_g\boldsymbol{g}$$
$$+\left(\Gamma_{g1}-\Delta\dot{m}_{12}\right)\boldsymbol{v}_{gi1}-\nabla\alpha_1\cdot\boldsymbol{\mathcal{T}}_{gi1}+\boldsymbol{M}_{ig1}$$

$$\frac{\partial\left(\alpha_{g2}\rho_g \boldsymbol{v}_{g2}\right)}{\partial t}+\nabla\cdot\left(\alpha_{g2}\rho_g \boldsymbol{v}_{g2}\boldsymbol{v}_{g2}\right)=-\alpha_2\nabla p_{g2}+\nabla\cdot\left[\alpha_2\left(\boldsymbol{\mathcal{T}}_{g2}^{\mu}+\boldsymbol{\mathcal{T}}_{g2}^{T}\right)\right]+\alpha_{g2}\rho_g\boldsymbol{g}$$
$$+\left(\Gamma_{g2}+\Delta\dot{m}_{12}\right)\boldsymbol{v}_{gi2}-\nabla\alpha_2\cdot\boldsymbol{\mathcal{T}}_{gi2}+\boldsymbol{M}_{ig2}$$

$$\frac{\partial\left[\left(1-\alpha_g\right)\rho_f \boldsymbol{v}_f\right]}{\partial t}+\nabla\cdot\left[\left(1-\alpha_g\right)\rho_f \boldsymbol{v}_f\boldsymbol{v}_f\right]=-\left(1-\alpha_g\right)\nabla p_f+\nabla\cdot\left[\left(1-\alpha_g\right)\left(\boldsymbol{\mathcal{T}}_f^{\mu}+\boldsymbol{\mathcal{T}}_f^{T}\right)\right]$$
$$+\left(1-\alpha_g\right)\rho_f\boldsymbol{g}+\Gamma_f\boldsymbol{v}_{fi}+\boldsymbol{M}_{if}-\nabla\left(1-\alpha_g\right)\cdot\boldsymbol{\mathcal{T}}_{fi}$$

One-dimensional One-group Interfacial Area Transport Equation

Bubbly Flow Regime

2-G Interfacial Area Transport Eq. → 1-G Interfacial Area Transport Eq.

One-dimensional Interfacial Area Transport Equation

$$\frac{\partial \langle a_i \rangle}{\partial t} + \frac{\partial}{\partial z}\left(\langle a_i \rangle \langle\langle v_{iz} \rangle\rangle_a \right) = \langle \Phi_{HE} \rangle + \langle \Phi_{WE} \rangle + \langle \Phi_{BB} \rangle + \langle \Phi_{VT} \rangle - \langle \Phi_{BC} \rangle - \langle \Phi_{CD} \rangle$$

HE: bulk liquid boiling, WE: bubble nucleation from active cavities,
BB: bubble breakup, VT: void transport, BC: bubble coalescence, CD: condensation

$$\Phi_{WE} = \Phi_{WE}\left(N_n, f, D_d\right)$$

N_n: active nucleation site density, f : bubble generation frequency,
D_d: bubble departure size

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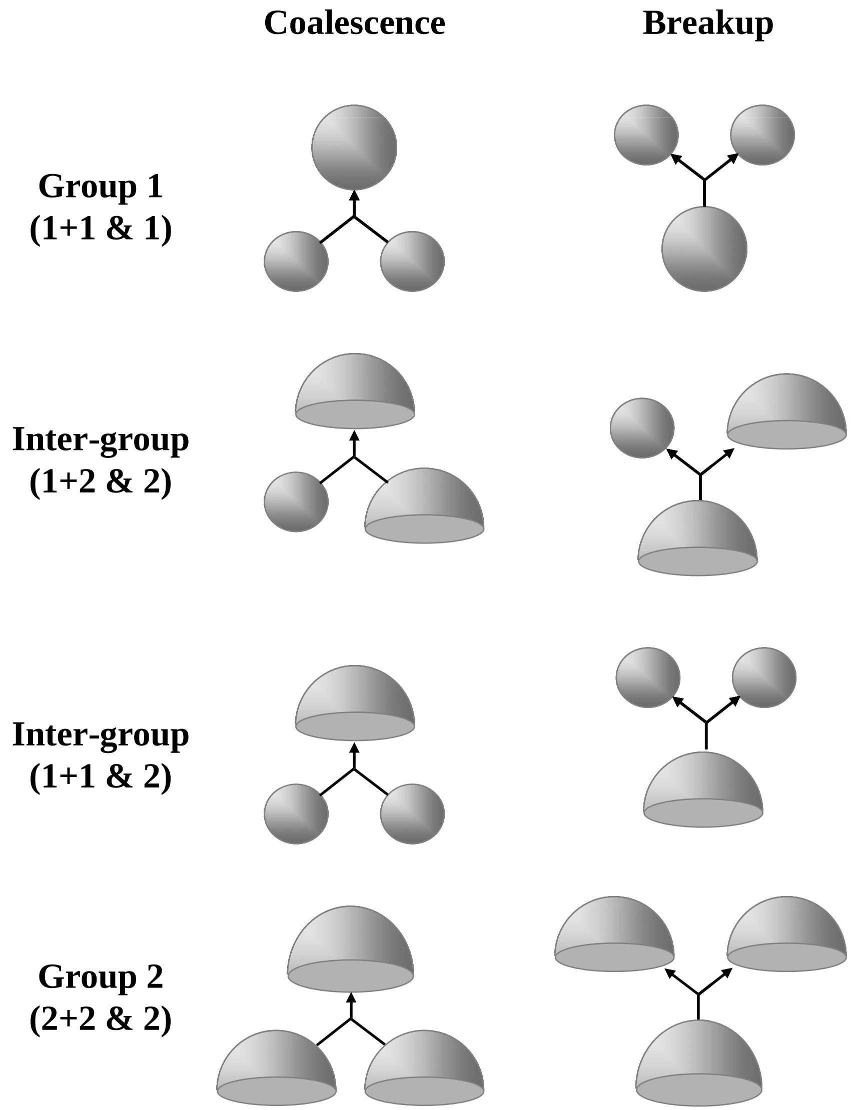
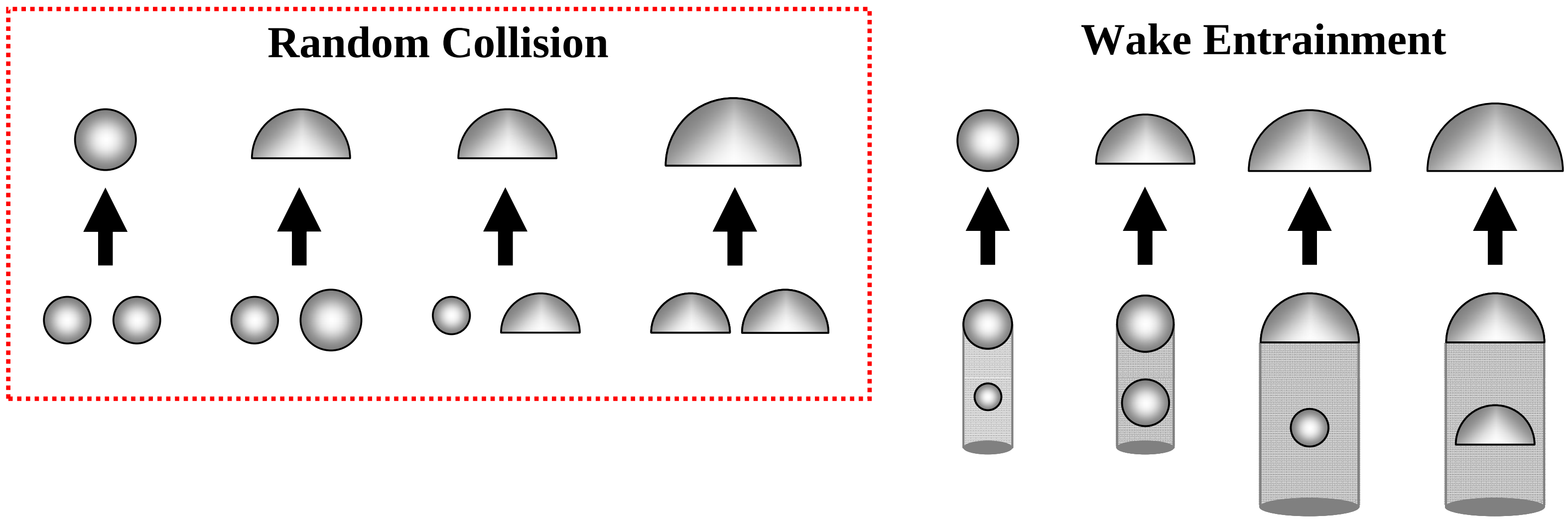
Classification of Possible Interactions of Two-group Bubbles (Hibiki and Ishii, 2000)

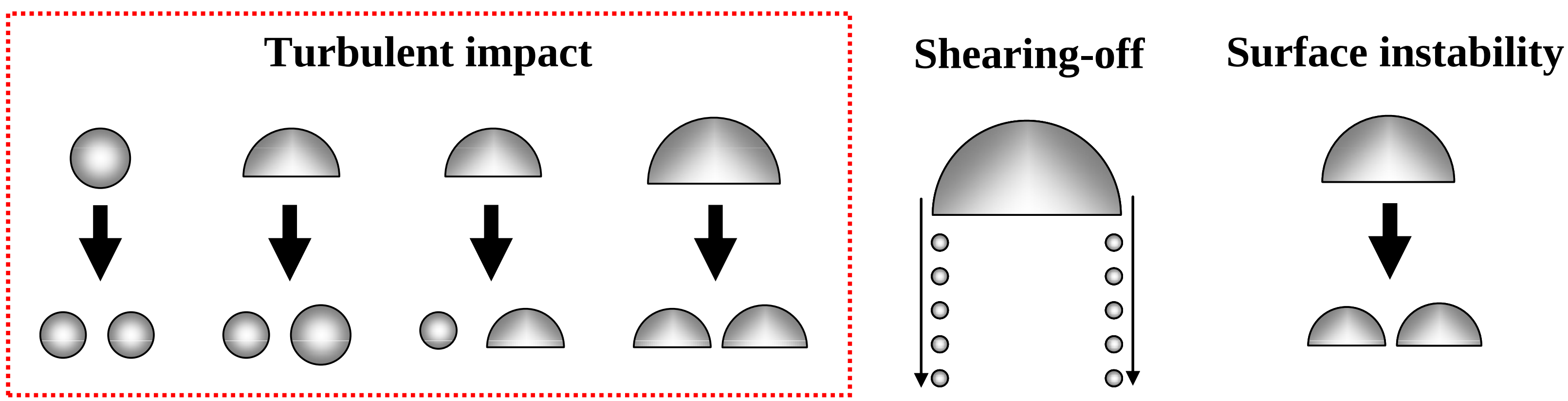


Bubble Coalescence & Breakup Mechanism (Kocamustafaogullari and Ishii, 1995)

Coalescence Mechanisms



Breakup Mechanisms



Modeling of Bubble Coalescence (Hibiki and Ishii, 2000)

Probable Coalescence Mechanism → **Bubble random collision induced by turbulence in a liquid phase**

Bubble Coalescence Rate = Bubble Collision Frequency x Coalescence Efficiency

Bubble Collision Frequency ←
(1) Turbulence is isotropic,
(2) Bubble size lies in the inertial subrange.

Coalescence Efficiency ← Coalescence efficiency is an exponential function of time required for bubble coalescence given by liquid-film-thinning model and a contact time for two bubbles given by dimensional consideration.

Sink Term of Interfacial Area Concentration Due to Bubble Coalescence (Hibiki and Ishii, 2000)

Bubble Collision Frequency

$$f_C = \frac{\gamma_C \alpha \varepsilon^{1/3}}{D_b^{2/3}\left(\alpha_{C,\max} - \alpha\right)}$$

Coalescence Efficiency

$$\lambda_C = \exp\left(-\frac{t_C}{\tau_C}\right) = \exp\left(-\frac{K_C \rho_f^{1/2} D_b^{5/6} \varepsilon^{1/3}}{\sigma^{1/2}}\right)$$

Rate of IAC Change

K_c=1.29

$$\Phi_C = \frac{1}{3\psi}\left(\frac{\alpha}{a_i}\right)^2 \phi_C = \frac{1}{3\psi}\left(\frac{\alpha}{a_i}\right)^2 f_C n_b \lambda_C$$

$$= \frac{\Gamma_C \alpha^2 \varepsilon^{1/3}}{D_b^{5/3}\left(\alpha_{C,\max} - \alpha\right)} \exp\left(-\frac{K_C \rho_f^{1/2} D_b^{5/6} \varepsilon^{1/3}}{\sigma^{1/2}}\right)$$

Modeling of Bubble Breakup (Hibiki and Ishii, 2000)

Probable Breakup Mechanism → **Bubble-eddy random collision induced by turbulence in a liquid phase**

Bubble Breakup Rate = Bubble-Eddy Collision Frequency x Breakup Efficiency

Bubble-Eddy Collision Frequency ←

(1) Turbulence is isotropic,

(2) Eddy size lies in the inertial subrange.

(3) Eddy with size from cD_b to D_b can break up bubble with size of D_b.

Breakup Efficiency ←

Breakup efficiency is an exponential function of average energy of a single eddy and average energy required for bubble breakup

Source Term of Interfacial Area Concentration Due to Bubble Breakup (Hibiki and Ishii, 2000)

Bubble-Eddy Collision Frequency

$$f_B = \frac{\gamma_B \alpha \varepsilon^{1/3}}{D_b^{2/3}\left(\alpha_{B,\max} - \alpha\right)}$$

Breakup Efficiency

$$\lambda_B = \exp\left(-\frac{E_B}{e}\right) = \exp\left(-\frac{K_B \sigma}{\rho_f D_b^{5/3} \varepsilon^{2/3}}\right)$$

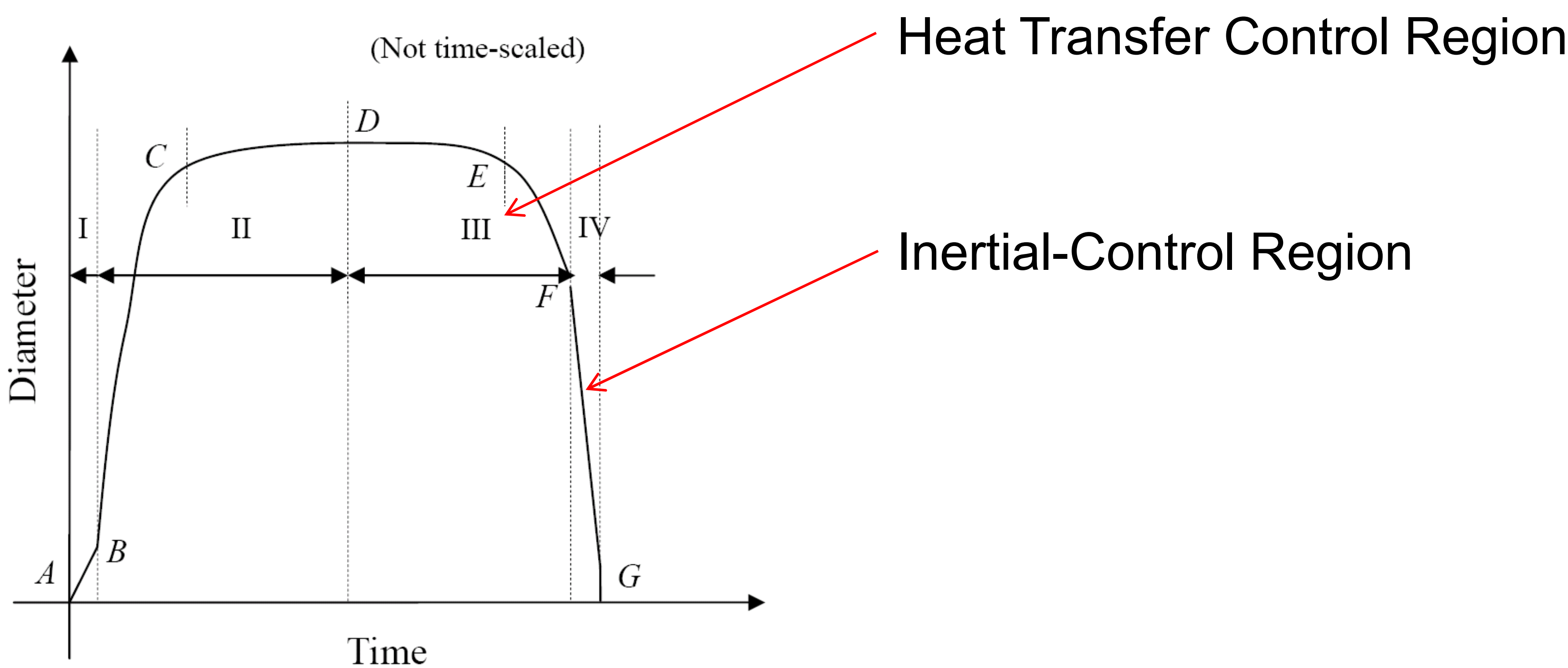
Rate of IAC Change

K_B=1.59

$$\Phi_B = \frac{1}{3\psi}\left(\frac{\alpha}{a_i}\right)^2 \phi_B = \frac{1}{3\psi}\left(\frac{\alpha}{a_i}\right)^2 f_B n_e \lambda_B$$

$$= \frac{\Gamma_B \alpha (1-\alpha) \varepsilon^{1/3}}{D_b^{5/3}\left(\alpha_{B,\max} - \alpha\right)} \exp\left(-\frac{K_B \sigma}{\rho_f D_b^{5/3} \varepsilon^{2/3}}\right)$$

Sink Term of Interfacial Area Concentration Due to Bubble Condensation (Park et al., 2007)



$$\Phi_{CD} = \Phi_{HC} + \Phi_{IC} = \pi n_b \left\{ 4\left(1 - P_c\right)\alpha_t N_{Nuc} N_{Ja} + \frac{D_B^2}{t_c} \right\},$$

Modeling of Wall Nucleation Term

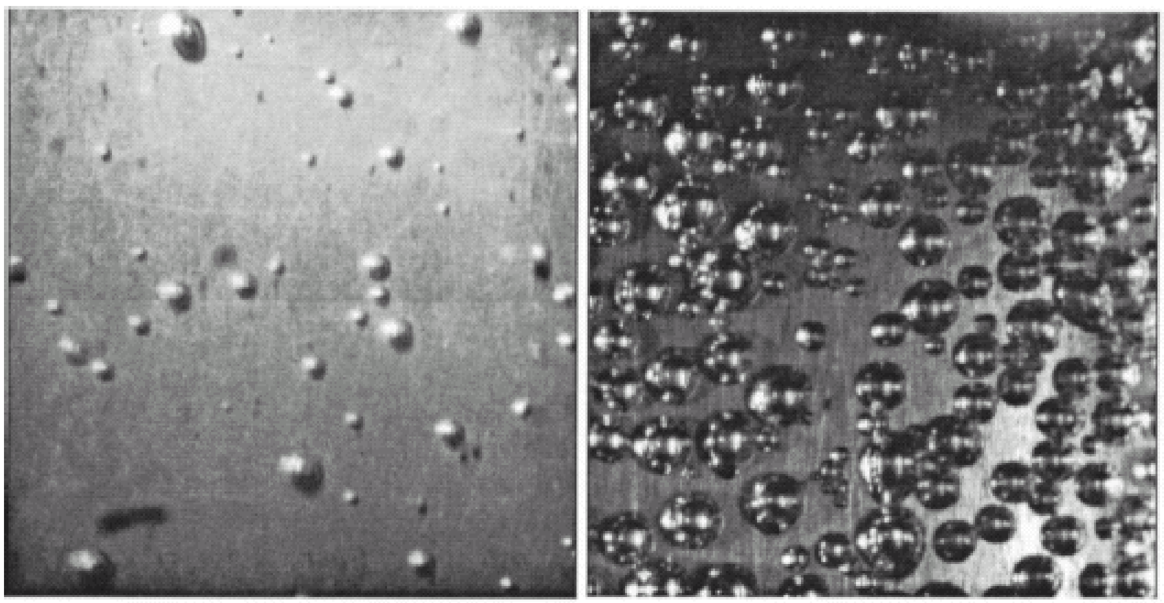
Wall Nucleation Source Term

$$\phi_{WE} = \pi D_d^2 \frac{N_n f \xi_H}{A_c}, \ \ \xi_H : \text{heated perimeter}, A_c : \text{cross-sectional area}$$

Key Models to Estimate Wall Nucleation Source Term

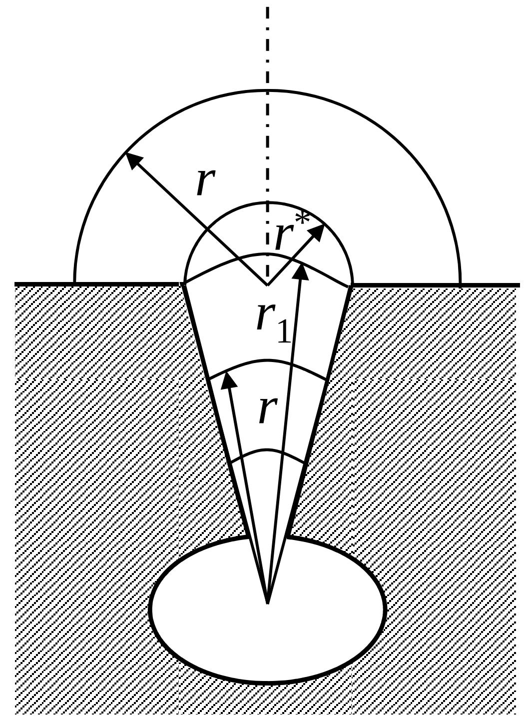
- Active Nucleation Site Density, N_n
- Bubble Departure Diameter, D_d
- Bubble Departure Frequency, f

Active Nucleation Site Density



(a) (b)

Fig. 16 Comparison of heater surface during nucleate boiling, (a) $\phi_s = 30$ deg and (b) $\phi_s = 90$ deg



Active nucleation site density images by Basu et al. (2002).

Active Nucleation Site Density (Hibiki and Ishii, 2003)

Knowledge of Size and Cone Angle Distributions of Cavities → Model

$$N_n = \overline{N_n}\left\{1-\exp\left(-\frac{\theta^2}{8\mu^2}\right)\right\}\left[\exp\left\{f\left(\rho^+\right)\frac{\lambda}{R_c}\right\}-1\right],$$

$\overline{N_n}$=4.72$\times$10^5 sites/m^2, μ=0.722 radian, λ=2.50$\times$10^{-6} m, θ: contact angle,

$$f\left(\rho^+\right) = \text{-}0.01064 + 0.48246\rho^+ - 0.22712\rho^{+2} + 0.05468\rho^{+3}, \rho^+ \equiv \log\left(\rho^*\right),$$

$$\rho^* \equiv \Delta\rho/\rho_g$$

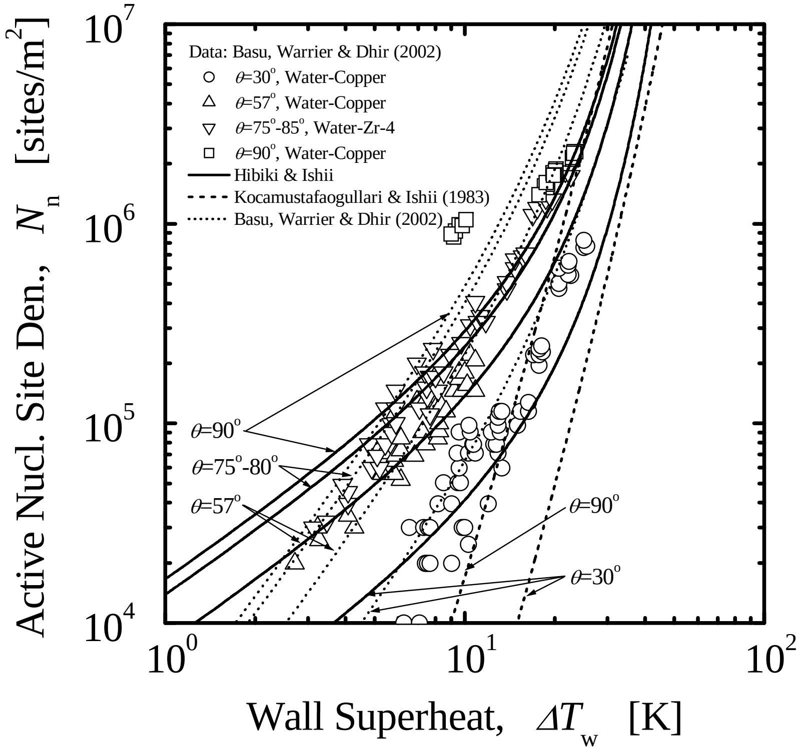
$$R_c = \frac{2\sigma\left\{1+\left(\rho_g/\rho_f\right)\right\}/p_f}{\exp\left\{i_{fg}\left(T_g - T_{sat}\right)/\left(RT_gT_{sat}\right)\right\}-1},$$

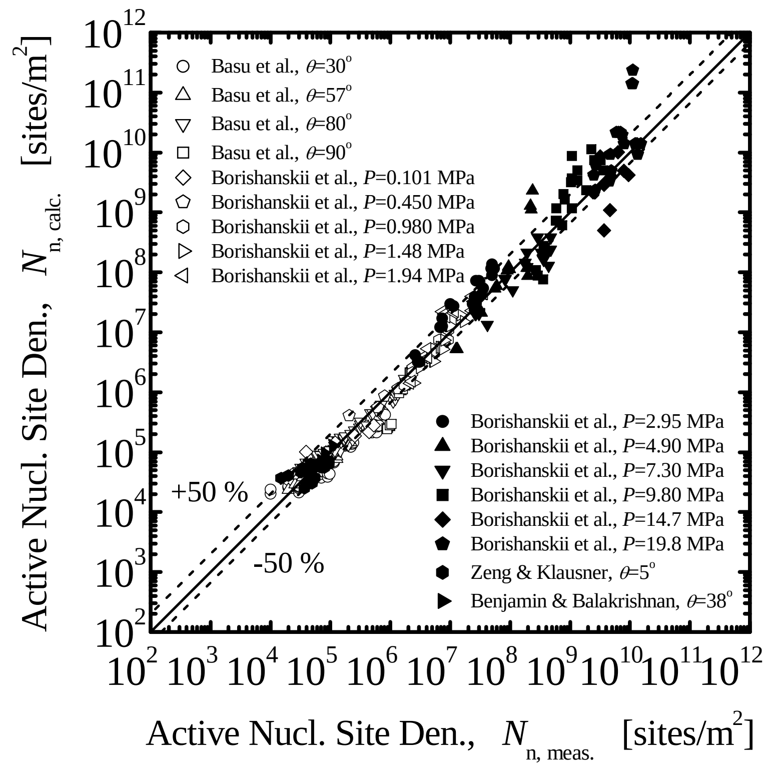
T_g : gas temperature, T_{sat}: saturation temperature, i_{fg}: latent heat,

R: gas constant based on a molecular weight. For example, the value

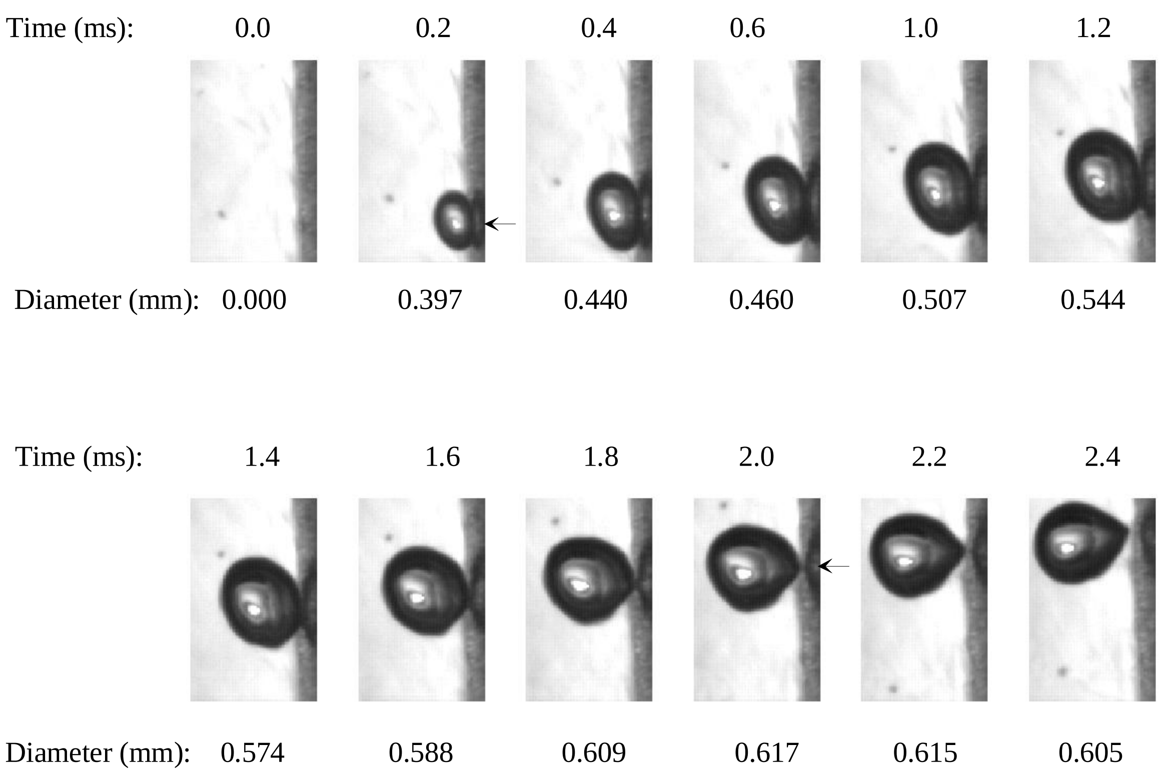
of for water vapor is 462 J/(kg K)(=8.31 J/(mol K)/(18.0 10-3 kg/mol))

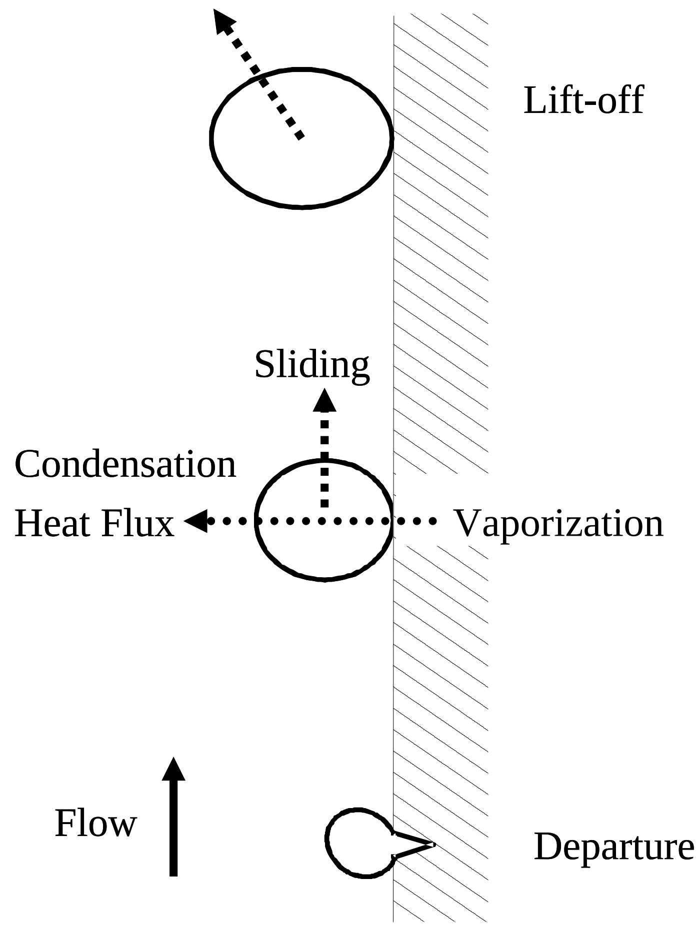
Active Nucleation Site Density (Hibiki and Ishii, 2003)





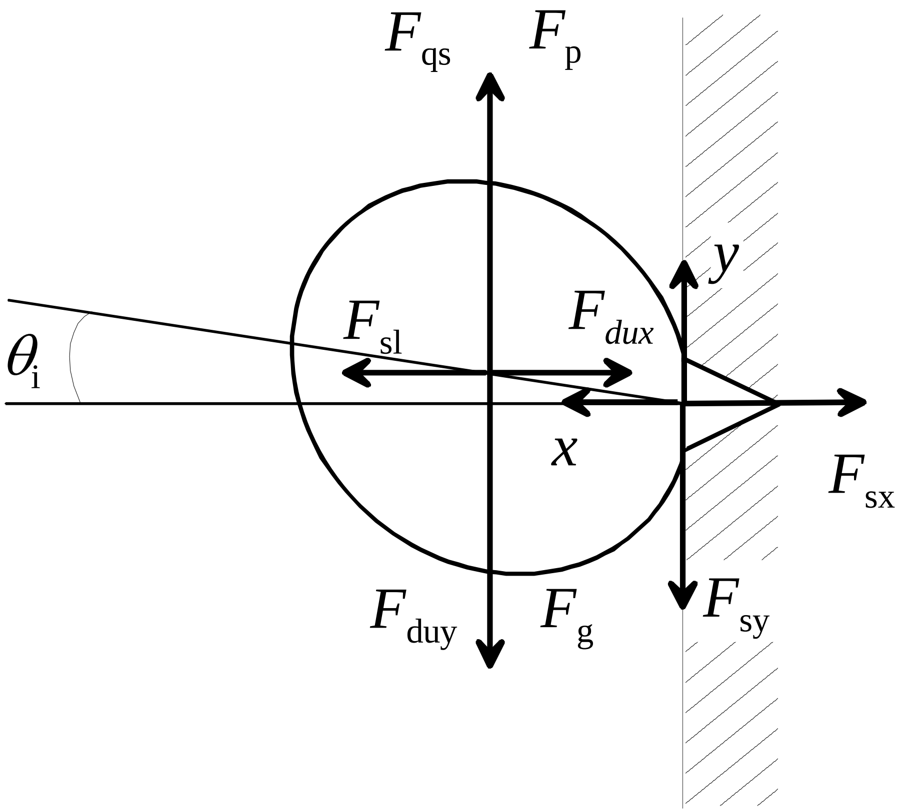
Bubble Departure Diameter





Bubble Departure Diameter (Situ et al., 2008)

Balance of Forces on Bubble at Nucleation Site → Model



F_{sx} : surface tension force at x-direction

F_{dux}: unsteady drag force (growth force) at x-direction

F_{sl} : shear lift force

F_{sy} : surface tension force at y-direction

F_{duy} : unsteady drag force at y-direction

F_p : pressure force

F_g : gravity force

F_{qs} : quasi-steady force

Bubble Departure Diameter (Situ et al., 2008)

$$\sum F_y = F_{sy} + F_{duy} + F_p + F_g + F_{qs}.$$

Surface Tension Force

$$F_{sy} = 0$$

Unsteady Drag Force

$$F_{duy} = -\frac{44b^4\alpha_f^2}{3\pi} N_{Jae}^4 \, sin\,\theta_i$$

Pressure and Gravity Forces

$$F_p + F_b = -\frac{4}{3}\pi\left(\rho_f - \rho_g\right) g r_b^3$$

Quasi-Steady Force

$$\frac{F_{qs}}{6\pi\rho_f\nu_f v_r r_b} = \frac{2}{3} + \left[\left(\frac{12}{N_{Reb}}\right)^n + 0.796^n\right]^{-1/n}$$

Bubble Departure Frequency (Situ et al., 2008)

Non-Dimensional Analysis → Correlation

$$N_{fd} = 4.06 N_{qNB}^{0.803}.$$

Non-Dimensional Bubble Departure Frequency

$$N_{fd} \equiv \frac{f D_d^2}{\alpha_f},$$

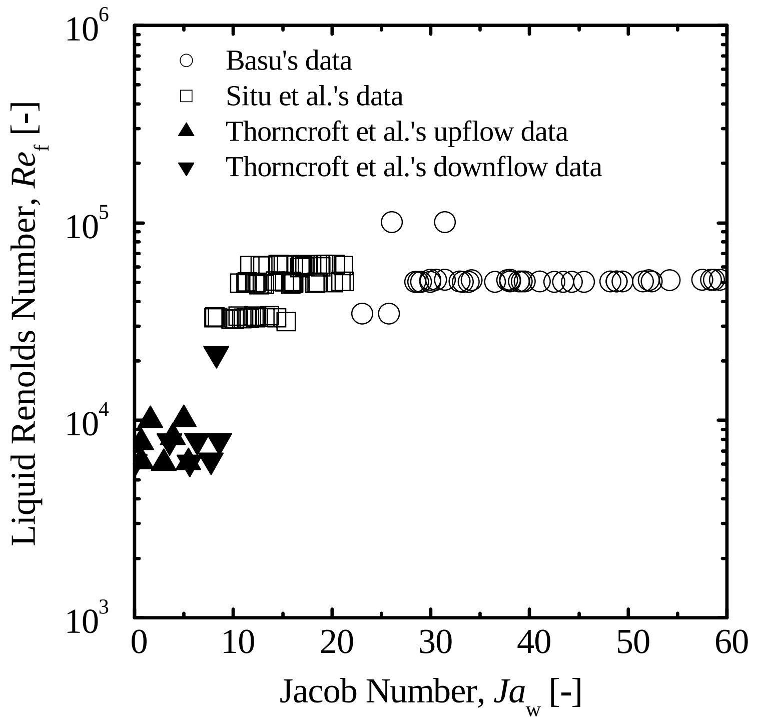
Non-Dimensional Heat Flux Representing Nucleate Boiling Heat Transfer

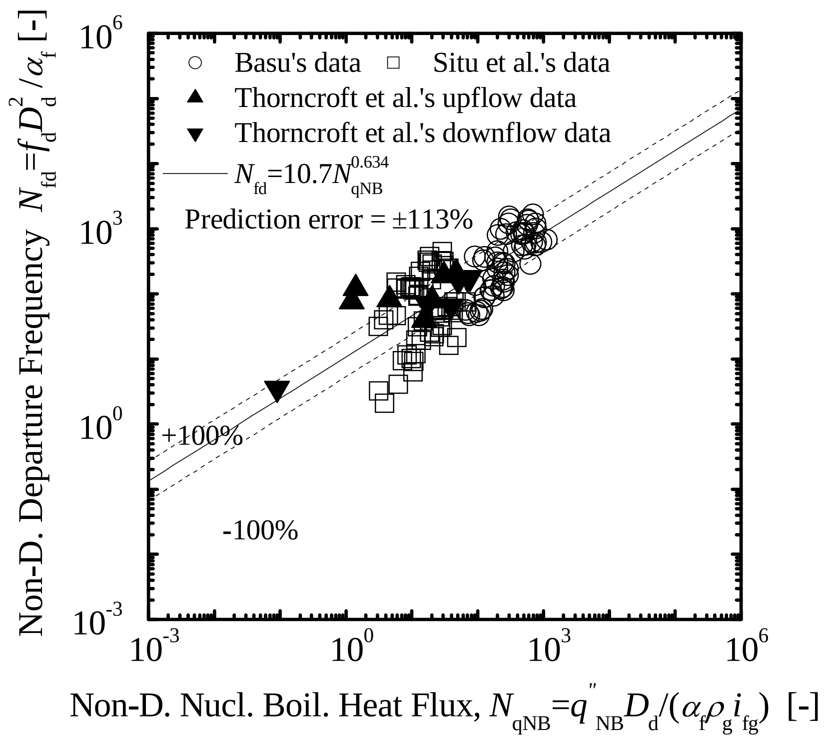
$$N_{qNB} \equiv \frac{q''_{qNB} D_d}{\alpha_f \rho_g i_{fg}},$$

D_b: bubble departure diameter,

q''_{qNB} : nucleate boiling heat flux calculated by using Chen's correlation (1966)

Bubble Departure Frequency (Situ et al., 2008)





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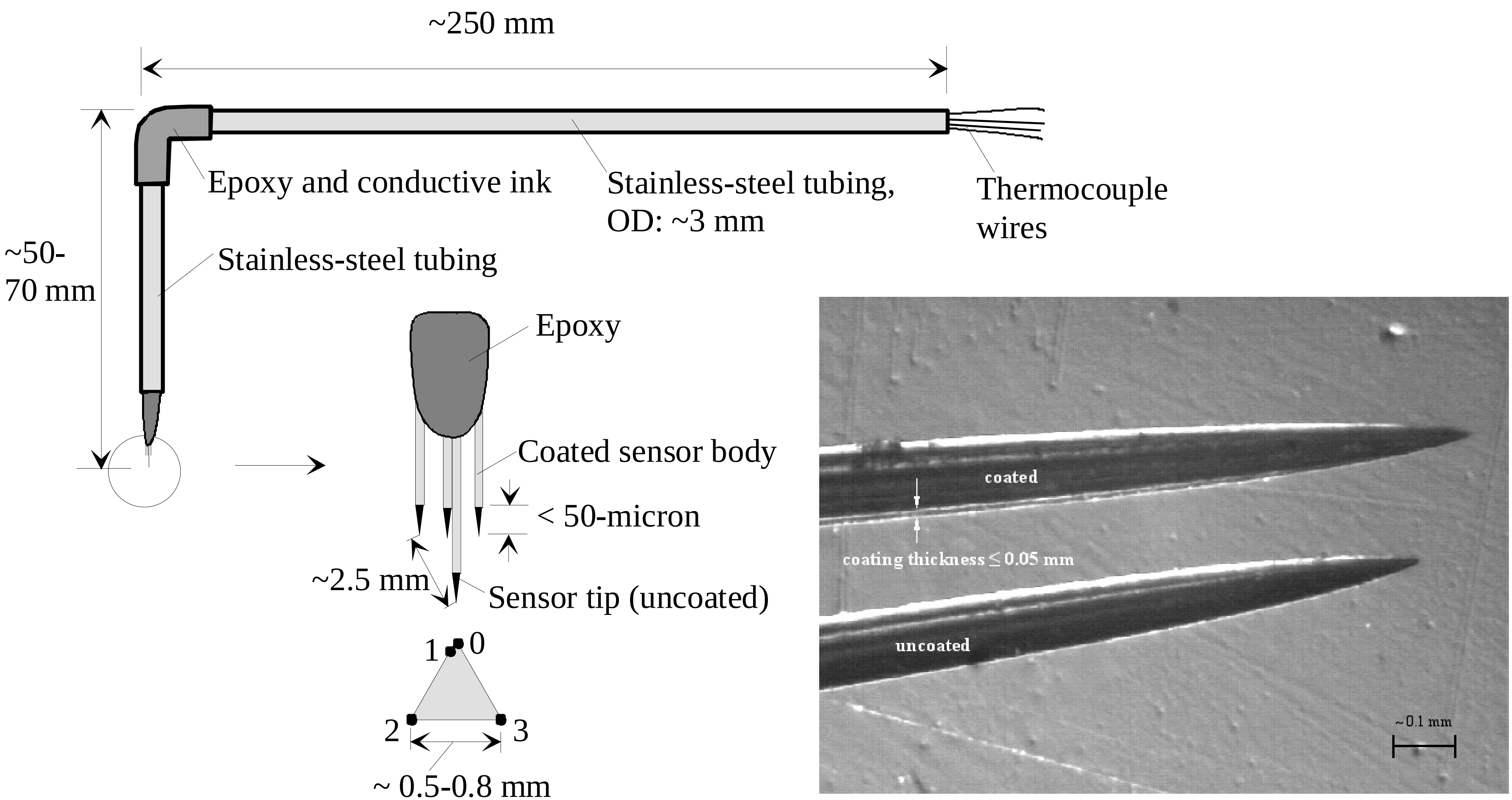
Local Interfacial Structure Characterization

- Instrument: Multi-sensor Conductivity Probe
- Measured Variables (Local)
  - Void fraction
  - Interfacial area concentration
  - Interfacial velocity
  - Bubble number frequency and bubble chord length

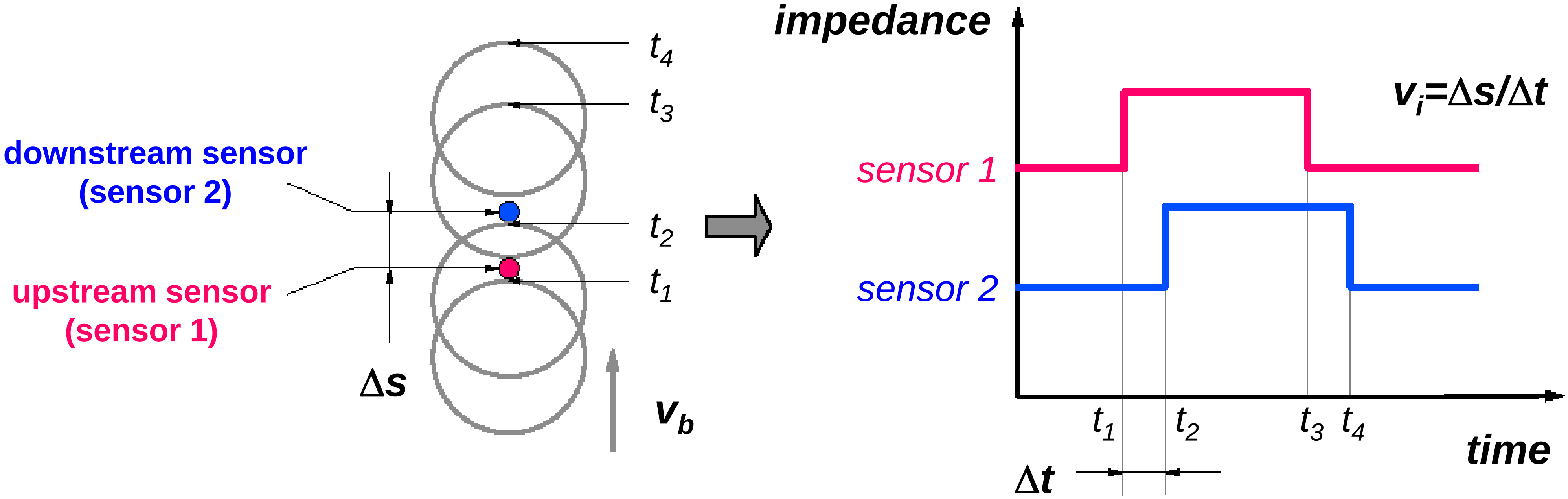
$$\overline{a}_i^t = \frac{1}{\Delta T} \sum_j \frac{1}{v_{nij}}$$

- Transverse Distribution of These Variables
- Measurements for Two Bubble Groups Separately
  - Group 1: Spherical and distorted small bubbles
  - Group 2: Taylor and churn-turbulent large bubbles

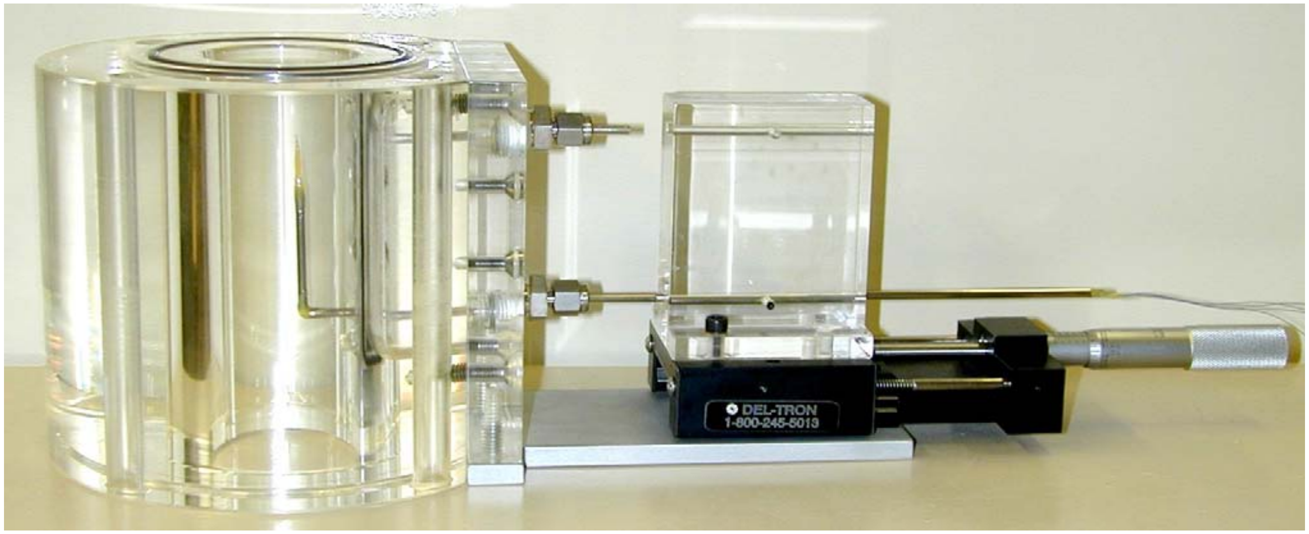
Multi-Sensor Conductivity Probe

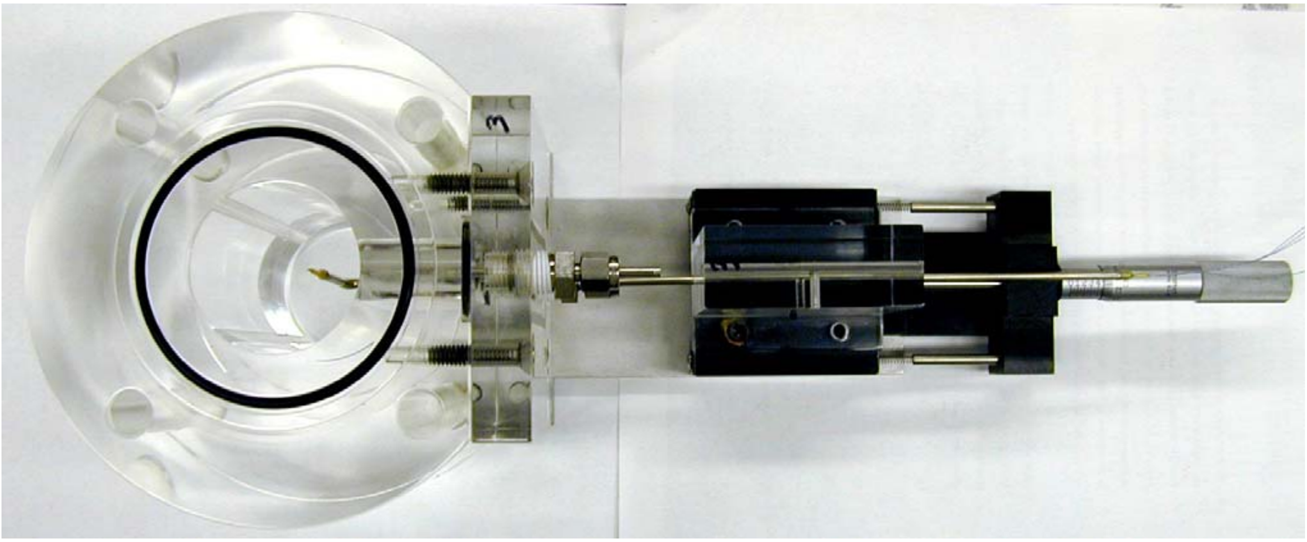


Interfacial Area Measurement (Cont'd)



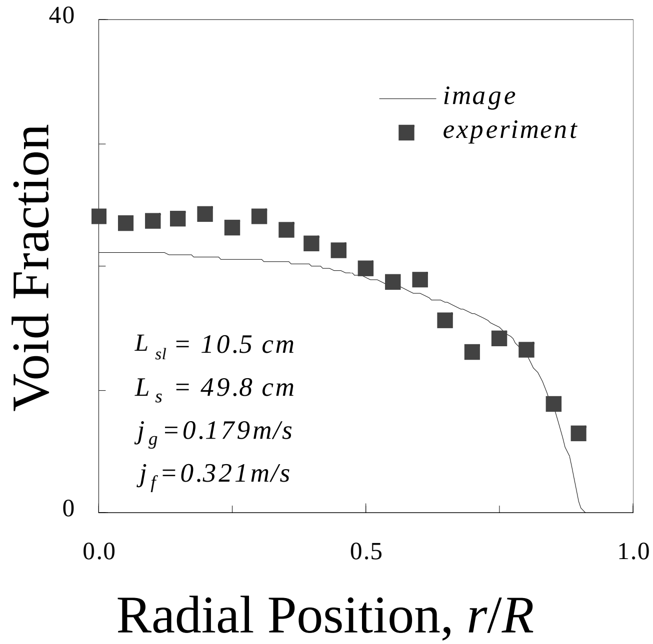
Conductivity Probe Port

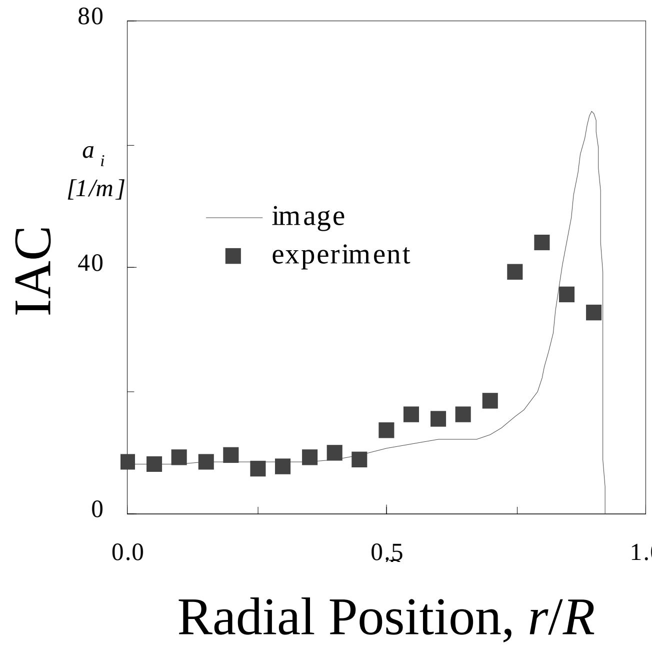




Benchmark with Image Analysis

(50.8 mm *ID* Pipe Upward Flow: $\langle j_f \rangle = 0.321$ and $\langle j_g \rangle = 0.179$ m/s)





Database to Evaluate Interfacial Area Transport Equation -Adiabatic Two-phase Flow-

Investigator	Geometry	Flow Direction	$\langle j_d \rangle$ [m/s]	$\langle j_c \rangle$ [m/s]	Dispersed Phase	Continuous Phase	Measured Bubble Category	Measurement Technique
Grossetete (1995)	38.1 mm vertical pipe	Upward	0.0895-0.181	0.877-1.75	Air	Water	G1	Probe
Hibiki et al. (1998)	50.8 mm vertical pipe	Upward	0.0147-0.0790	0.600-1.30	Air	Water	G1	Probe
Hibiki and Ishii (1999)	25.4 mm vertical pipe	Upward	0.0414-0.931	0.262-3.49	Air	Water	G1	Probe
Hibiki et al. (2001a)	50.8 mm vertical pipe	Upward	0.0275-3.90	0.491-5.00	Air	Water	G1, G2	Probe
Fu and Ishii (2003b)	48.3 mm vertical pipe	Upward	0.039-1.23	0.018-5.1	Air	Water	G1, G2	Probe
Hibiki et al. (2003a)	50.8 mm vertical pipe	Downward	0.00427-0.189	0.620-2.49	Air	Water	G1	Probe
Hibiki et al. (2003b)	ID: 19. 1 mm, OD:38.1 mm, D_H :19.1 mm, vertical annulus	Upward	0.0313-0.910	0.272-2.08	Air	Water	G1	Probe
Kim et al. (2003)	10 × 200 mm vertical confined channel	Upward	0.05-0.94	0.32-4.40	Air	Water	G1	Probe
Sun et al. (2003)	102 mm vertical pipe	Upward	0.048-0.502	0.048-0.502	Air	Water	G1, G2	Probe
Takamasa et al. (2003a)	9 mm pipe	Microgravity	0.0083-0.022	0.073-0.22	Nitrogen	Water	G1	Photographic
Takamasa et al. (2003b)	9 mm vertical pipe	Upward	0.013-0.052	0.58-1.0	Air	Water	G1	Photographic
Sun et al. (2004a)	10 × 200 mm vertical confined channel	Upward	0.39-2.01	0.32-2.84	Air	Water	G1, G2	Probe
Takamasa et al. (2004)	9 mm vertical pipe	Upward	0.00903-0.0101	0.154-0.529	Nitrogen	Water	G1	Photographic
Takamasa et al. (2004)	9 mm pipe	Microgravity	0.00871-0.0103	0.156-0.440	Nitrogen	Water	G1	Photographic
Hibiki et al. (2005)	25.4 mm vertical pipe	Downward	0.0177-0.487	1.25-3.11	Air	Water	G1	Probe
Vasavada et al. (2007)	25.4 mm pipe	Equidensity liquids	0.012-0.112	0.118-0.742	Therminol 59	Water	G1, G2	Probe
Hibiki et al. (2007)	1.02 mm vertical pipe	Upward	0.0741-0.472	1.02-4.89	Nitrogen	Water	G1	Photographic
Jeong et al. (2008)	ID:19.1mm, OD:38.1 mm, D_H :19.1 mm, vertical annulus	Upward	0.041-5.43	0.240-3.34	Air	Water	G1, G2	Probe

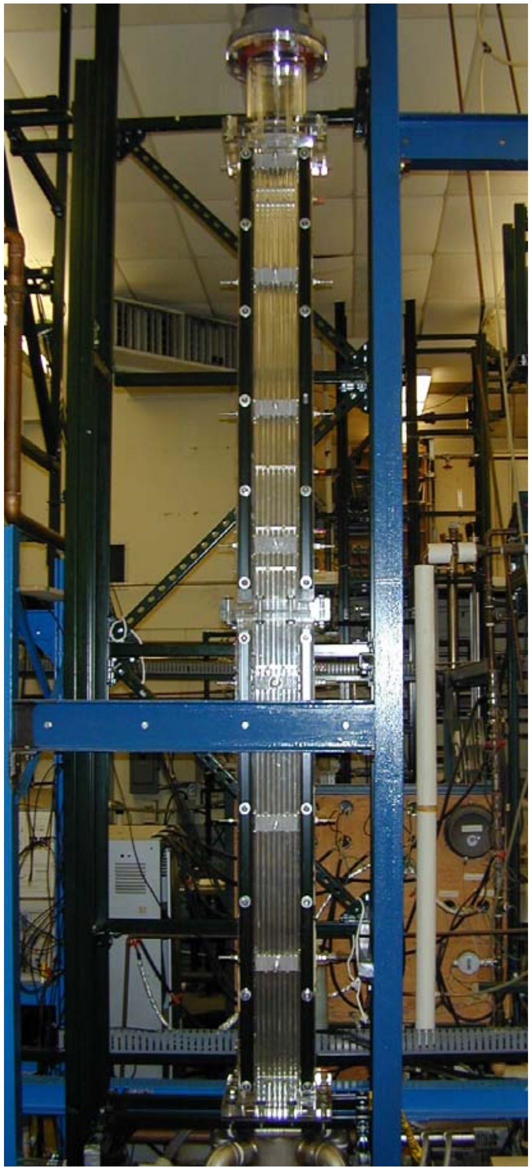
Database to Evaluate Interfacial Area Transport Equation -Boiling Two-phase Flow-

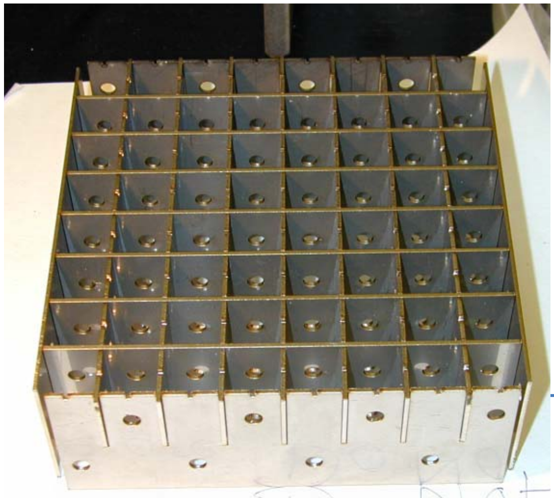
Investigators	Geometry	Fluid	p [MPa]	ρ_f [kg/m^3]	ρ_g [kg/m^3]	μ_f [mPa·s]	μ_g [mPa·s]	σ [mN/m]	G [kg/m^{2}s]	q'' [kW/m^2]	ΔT_{in} [°C]	$\langle j_g \rangle$ [m/s]	$\langle j_f \rangle$ [m/s]	Measurement Technique
Zeitoun (1994)	ID:25.4mm, OD:50.8mm, D_H :25.4mm, vertical upward annulus	Water	0.117 – 0.168	947 – 955	0.684 – 0.959	0.243 – 0.270	0.0124 – 0.0128	56.0 – 58.1	151 - 412	287 - 706	11.6 - 31.1	N/A	N/A	Photographic
Bartel et al. (2001)	ID:19.1mm, OD:38.1mm, D_H :19.1mm, Vertical upward annulus	Water	0.100	958	0.590	0.283	0.0123	59.0	470 - 1953	105 - 193	N/A	0.0009 - 0.0306	2.038 - 0.490	Probe
Situ et al. (2004)	ID:19.1mm, OD:38.1mm, D_H :19.1mm, vertical upward annulus	Water	0.110 - 0.128	953 – 956	0.646 – 0.744	0.263 – 0.275	0.0124 – 0.0125	57.6 – 58.5	475 - 1184	98 - 150	8.30 - 13.1	0.0002 - 0.1615	0.496 - 1.240	Probe
Lee et al. (2008)	ID:19.1mm, OD:38.1mm, D_H :19.1mm, vertical upward annulus	Water	0.110 – 0.131	953 – 957	0.646 – 0.760	0.261 – 0.275	0.0123 – 0.0125	57.5 – 58.5	478 - 1917	50 - 200	8.00 - 14.6	0.0015 - 0.2010	0.500 - 2.008	Probe

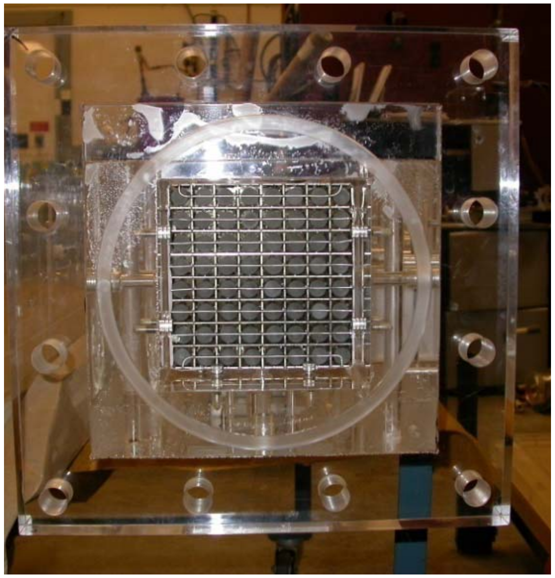
Summary of Interfacial Area Database

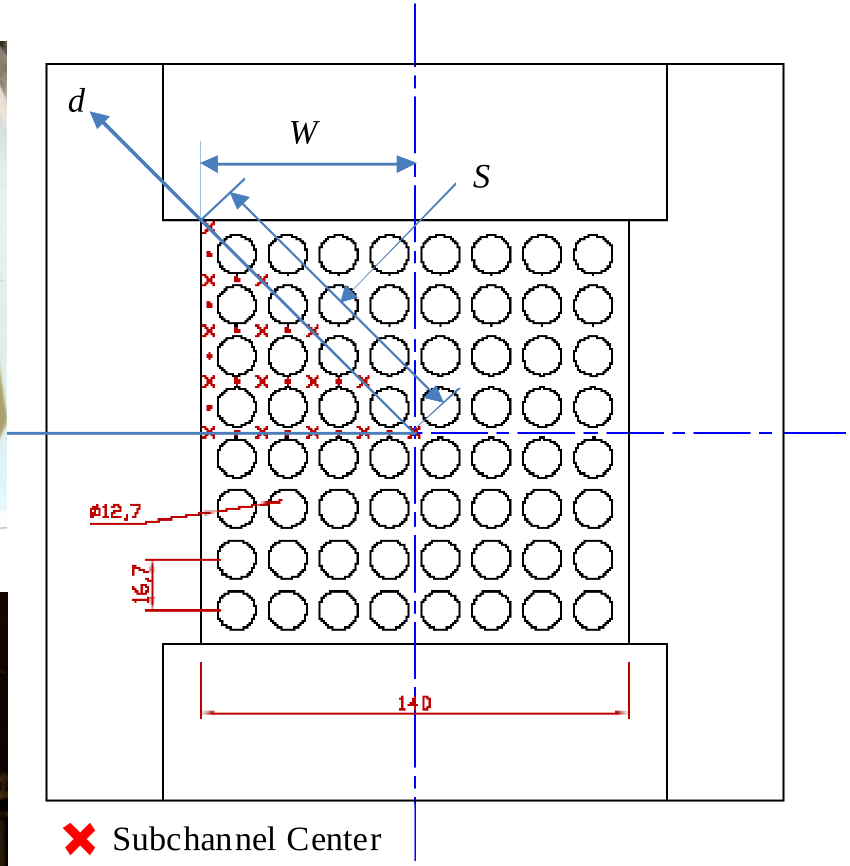
- Test Section Geometry: Round pipe, Confined channel, Annulus and Rod Bundle
- Test Section Size: 1 mm to 102 mm
- Flow Regime: Bubbly, Cap-bubbly, Slug and Churn-turbulent Flows,
- Flow Condition: $\langle j_g \rangle$ up to 10 m/s, $\langle j_f \rangle$ from -3.1 m/s to 5.0 m/s
- Thermal Condition: Adiabatic and Diabatic Flows
- Gravity Condition: Normal and Micro Gravity Conditions
- Pressure Condition: Atmospheric Pressure

Database for 8 X 8 Rod Bundle Geometry

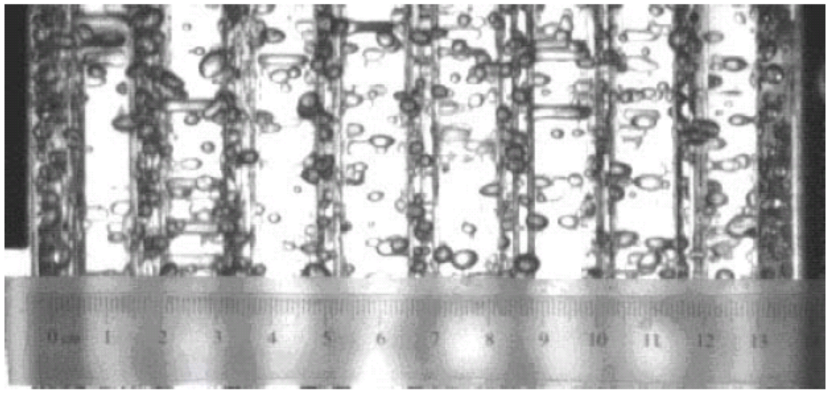






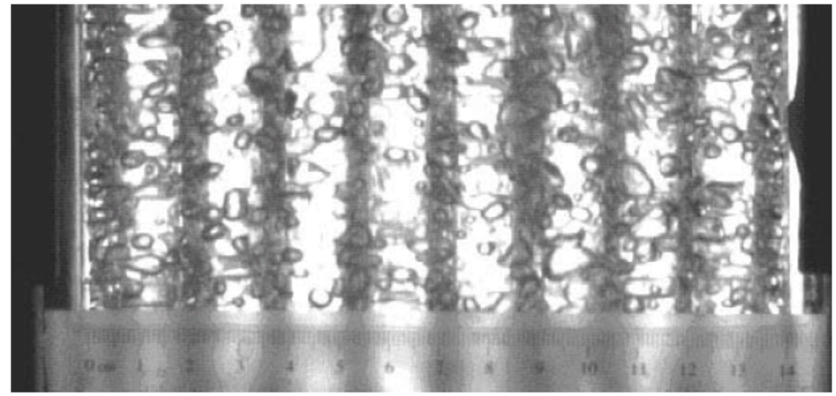


Database for 8 X 8 Rod Bundle Geometry



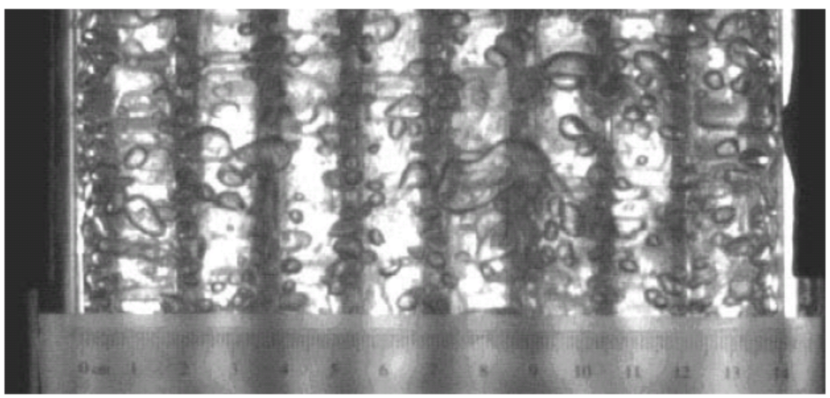
(a) bubbly flow

$\langle j_g \rangle = 0.02$ m/s, $\langle j_f \rangle = 0.20$ m/s.



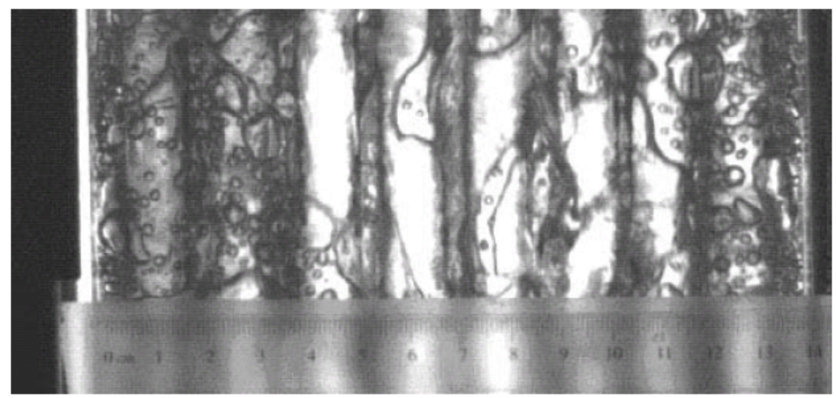
(b) cap bubbly flow

$\langle j_g \rangle = 0.14$ m/s, $\langle j_f \rangle = 0.20$ m/s.



(c) Cap turbulent flow

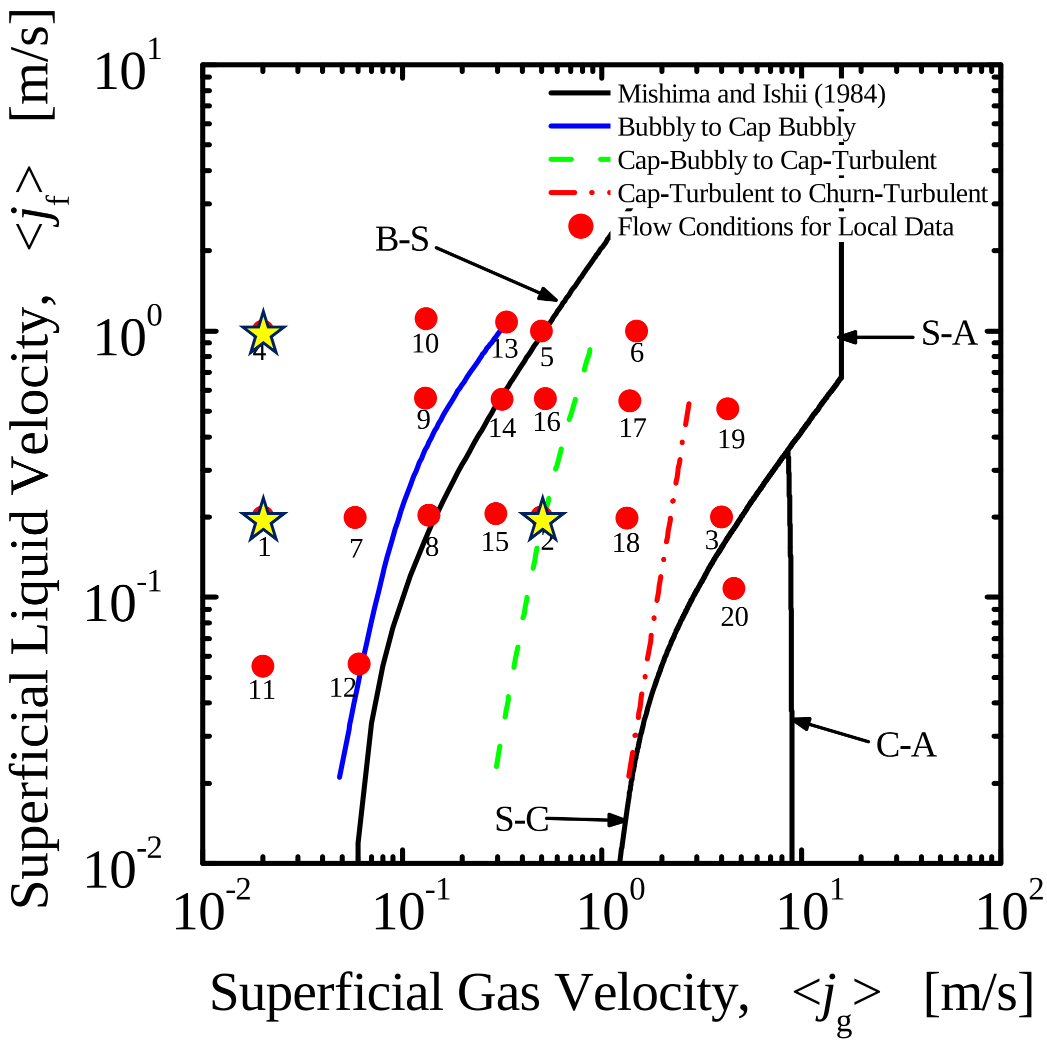
$\langle j_g \rangle = 0.80$ m/s, $\langle j_f \rangle = 0.21$ m/s.



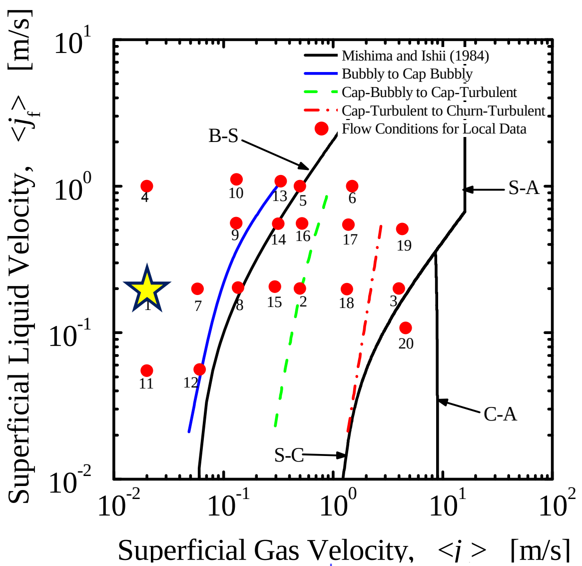
(d) Churn turbulent flow

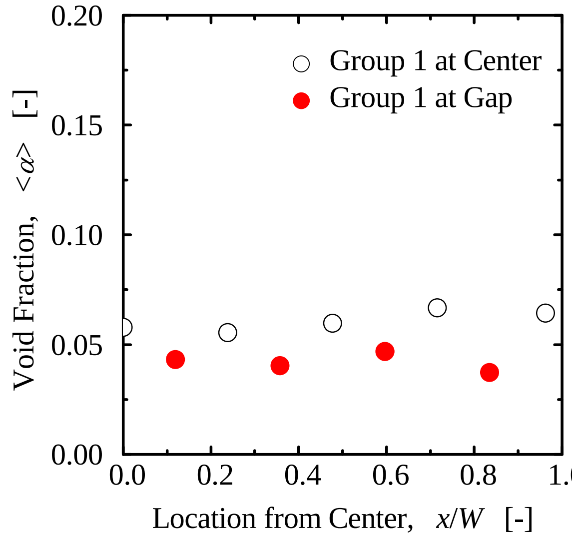
$\langle j_g \rangle = 8.80$ m/s, $\langle j_f \rangle = 0.20$ m/s.

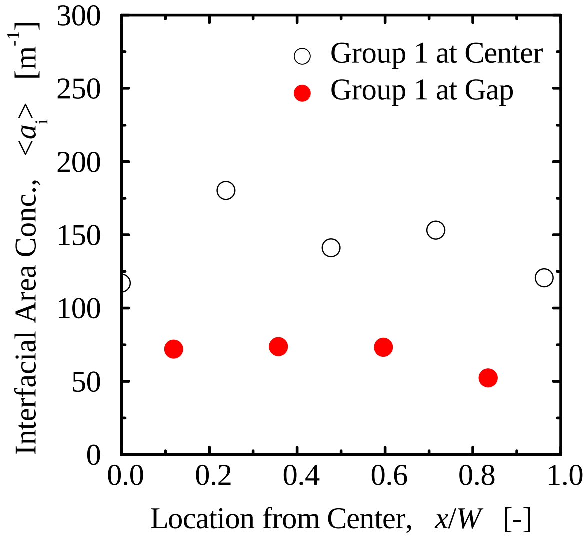
Database for 8 X 8 Rod Bundle Geometry

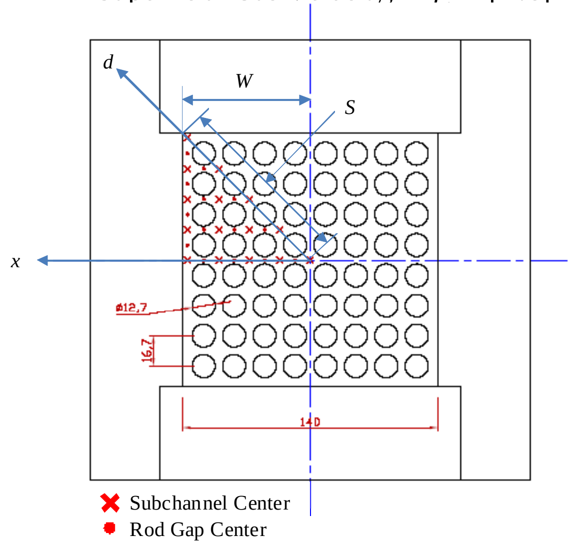


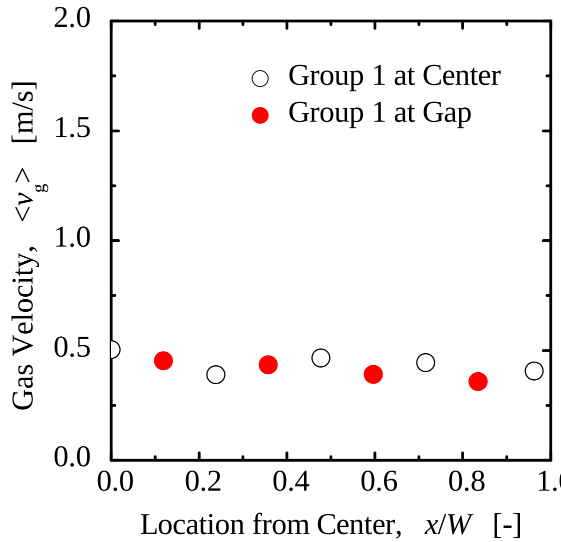
Local Data for 8 X 8 Rod Bundle Geometry at z/D=200 ($\langle j_f \rangle$ = 0.2 m/s and $\langle j_g \rangle$ = 0.02 m/s)

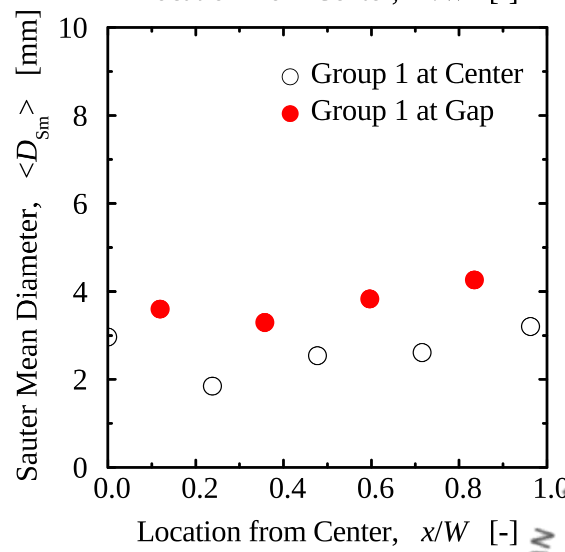




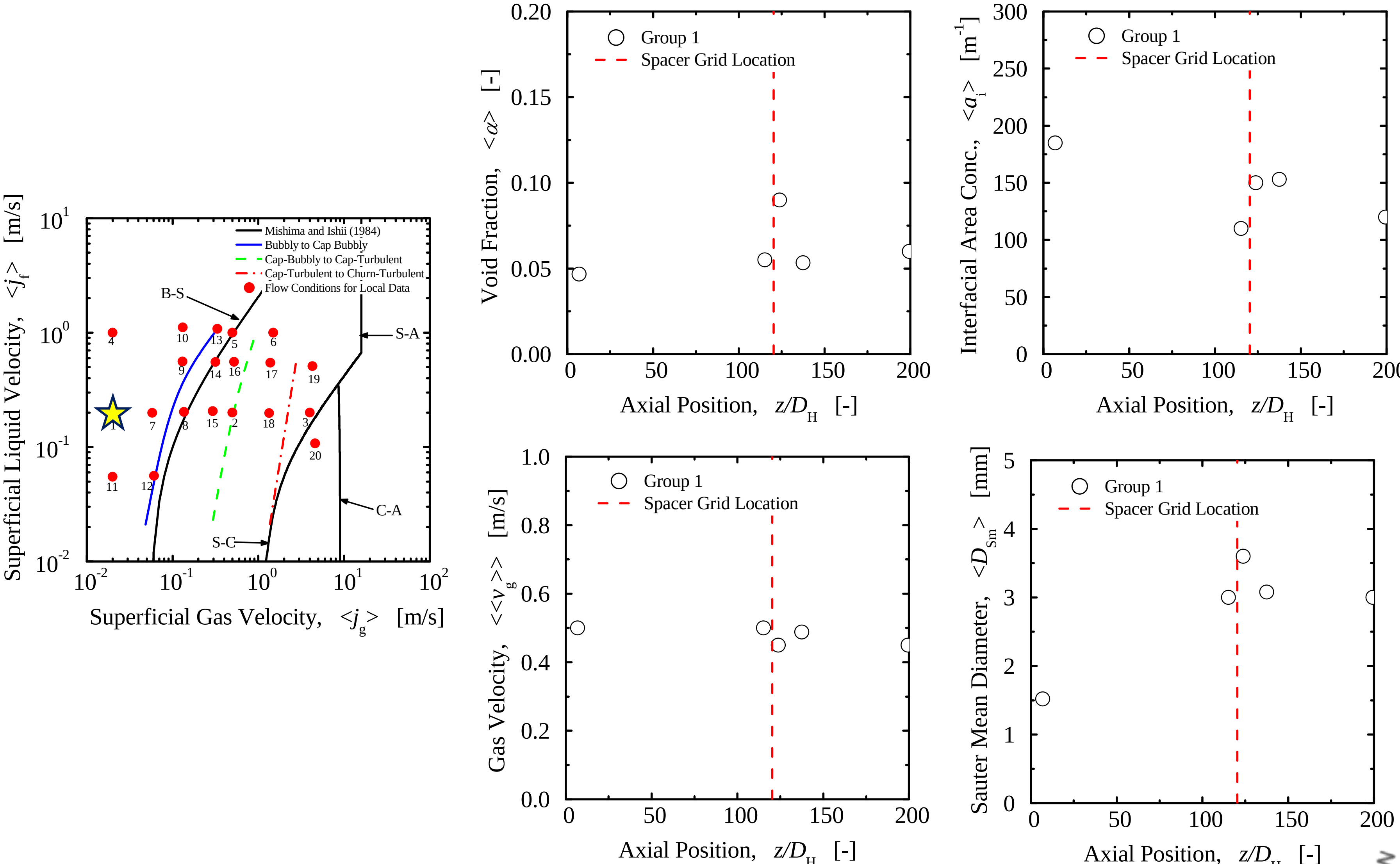




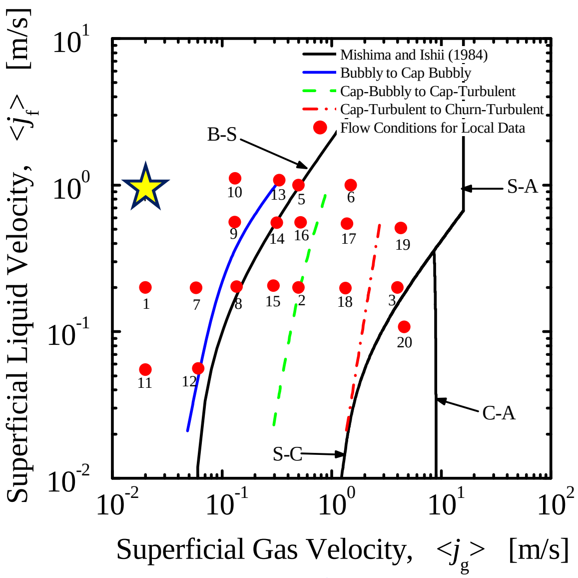


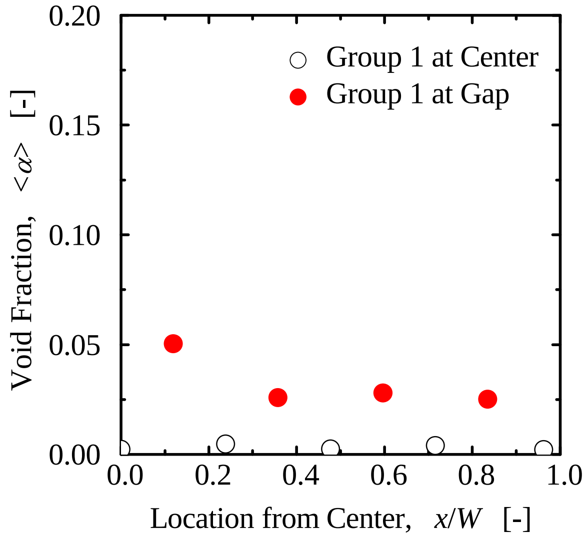


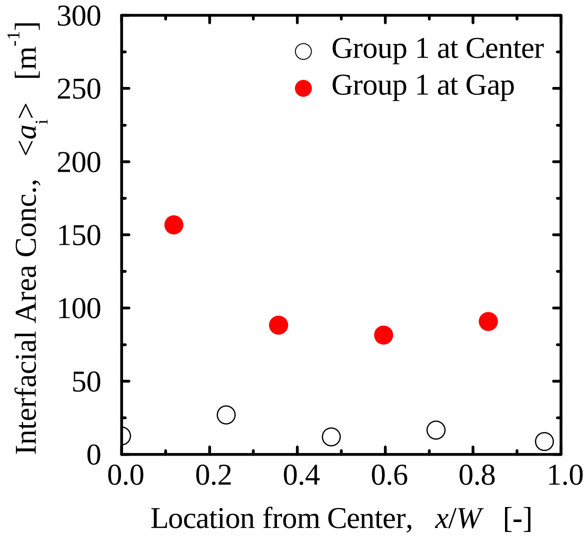
1-D Data for 8 X 8 Rod Bundle Geometry
($\langle j_f \rangle$ = 0.2 m/s and $\langle j_g \rangle$ = 0.02 m/s)

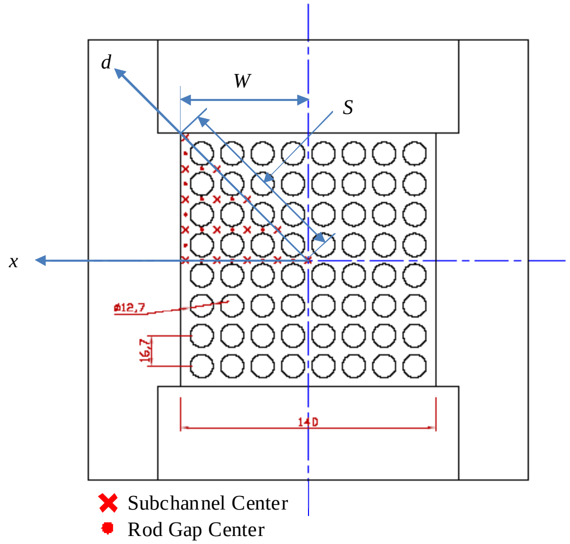


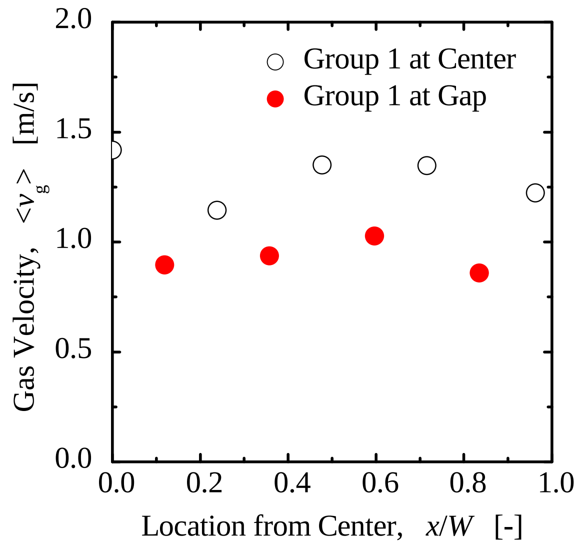
Local Data for 8 X 8 Rod Bundle Geometry at z/D=200
(<j_f> = 1.0 m/s and <j_g> = 0.02 m/s)

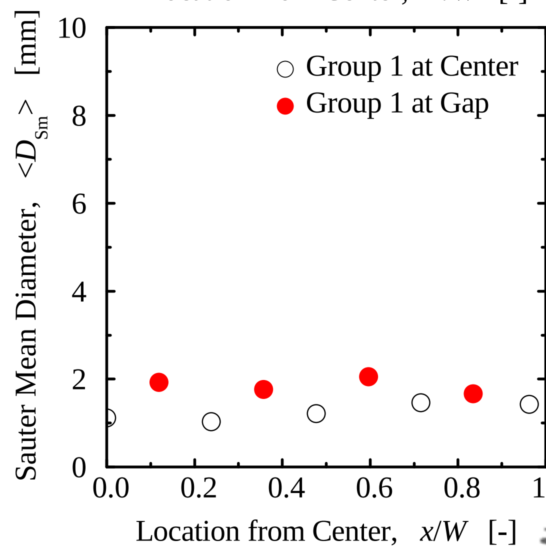




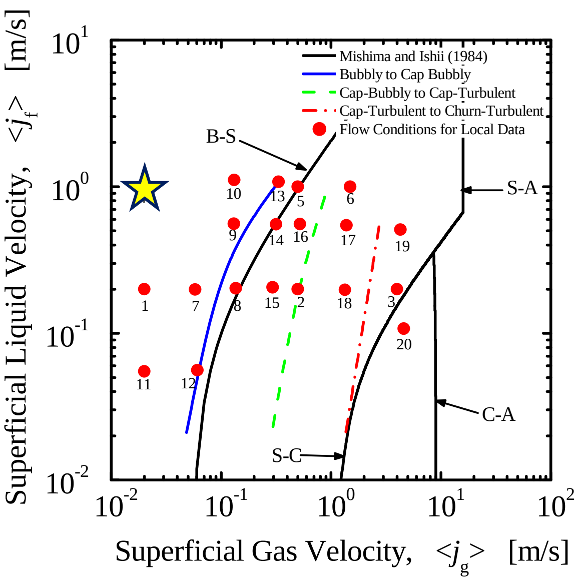


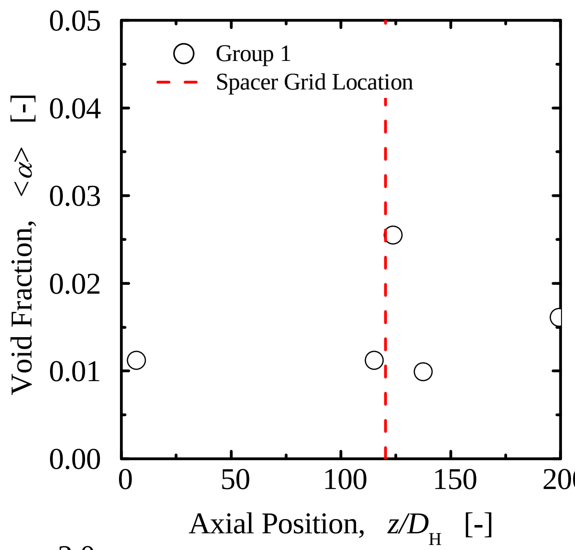


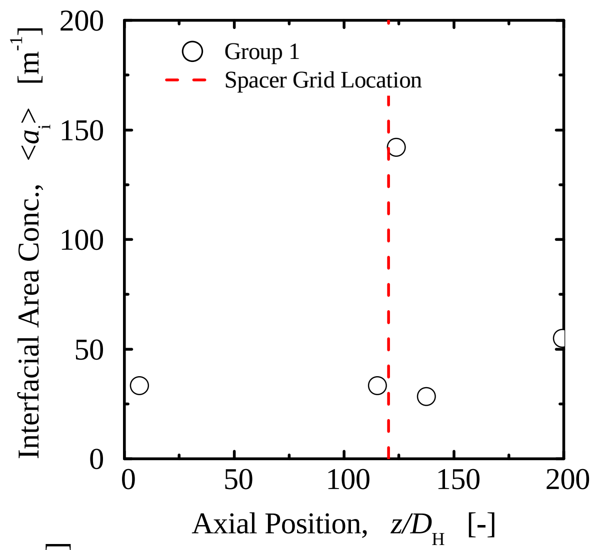


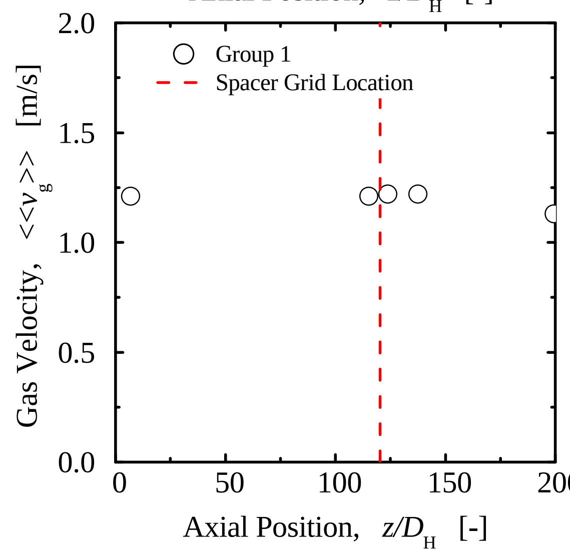


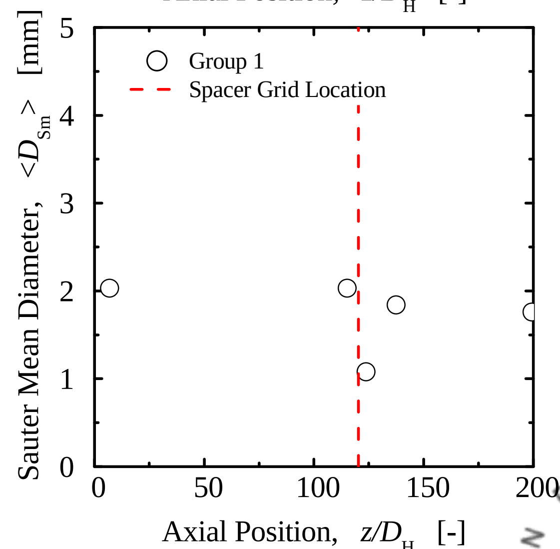
1-D Data for 8 X 8 Rod Bundle Geometry
(<j_f> = 1.0 m/s and <j_g> = 0.02 m/s)



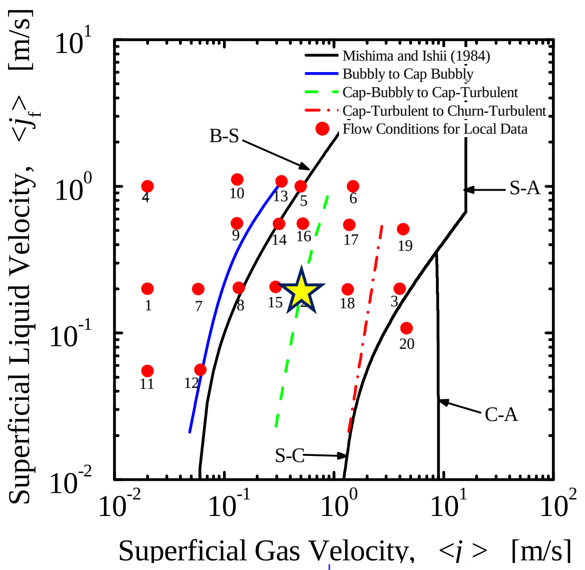


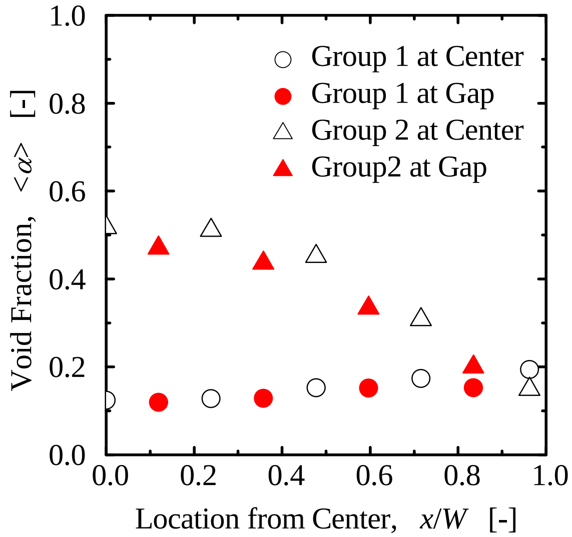


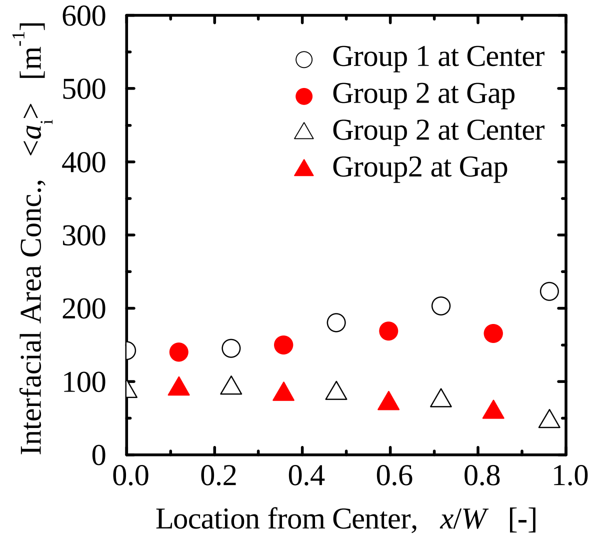


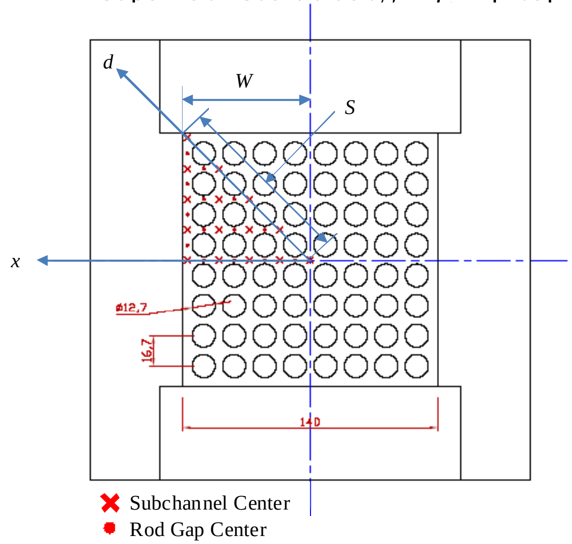


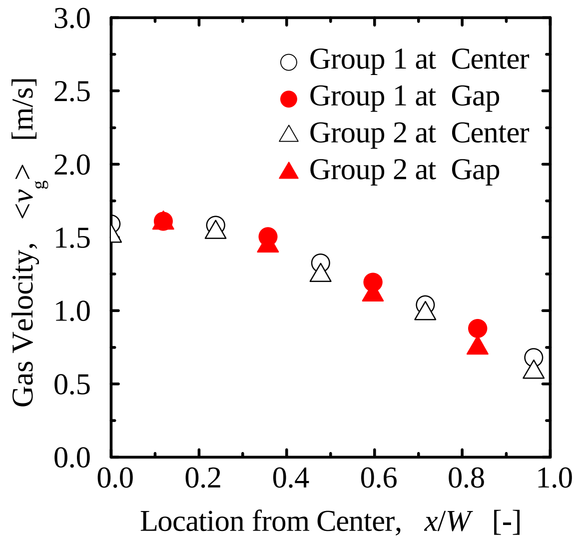
Local Data for 8 X 8 Rod Bundle Geometry at z/D=200 ($\langle j_f \rangle$ = 0.2 m/s and $\langle j_g \rangle$ = 0.5 m/s)

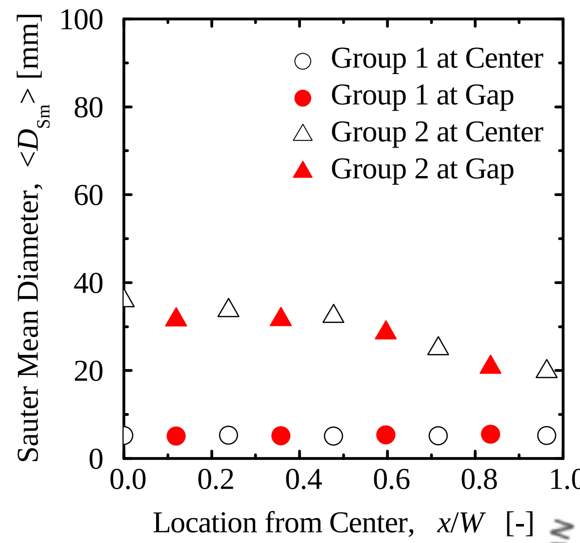




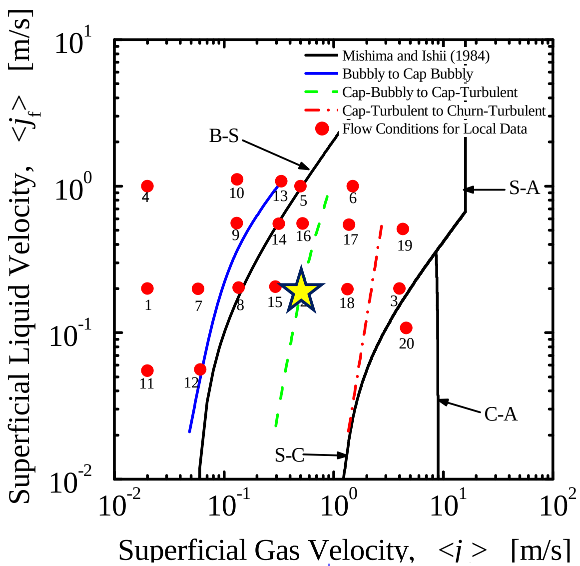


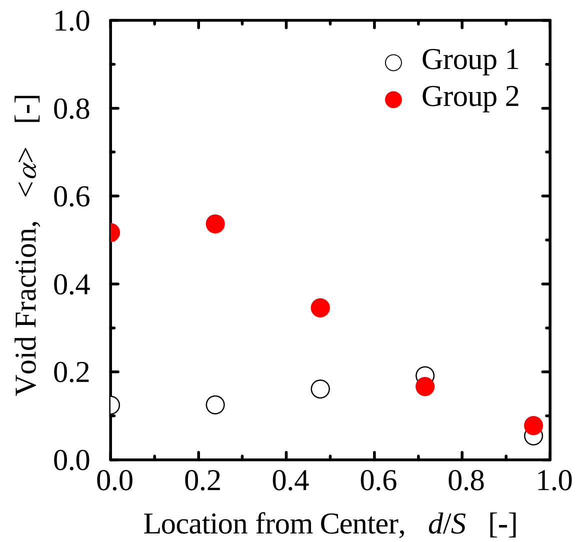


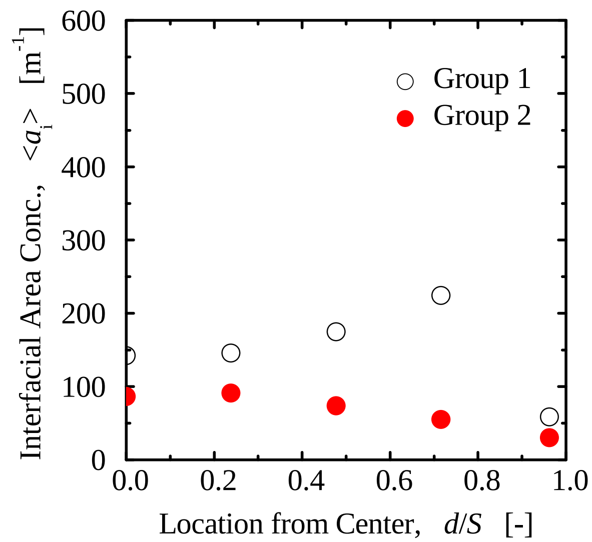


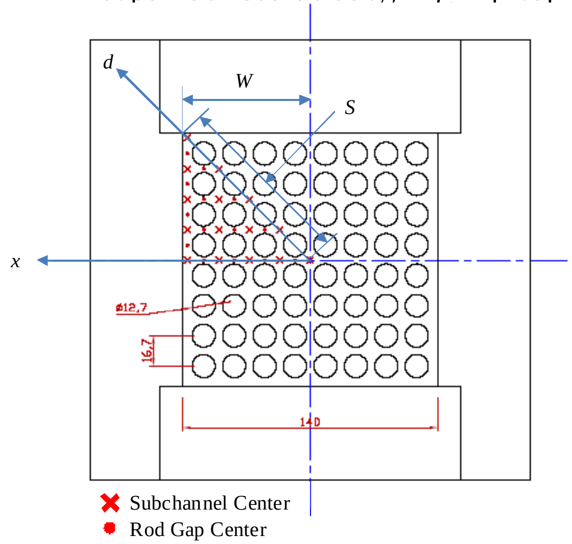


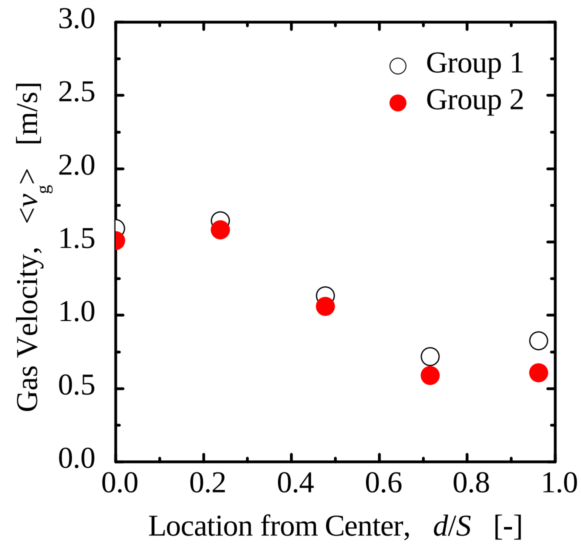
Local Data for 8 X 8 Rod Bundle Geometry at z/D=200
($\langle j_f \rangle$ = 0.2 m/s and $\langle j_g \rangle$ = 0.5 m/s)

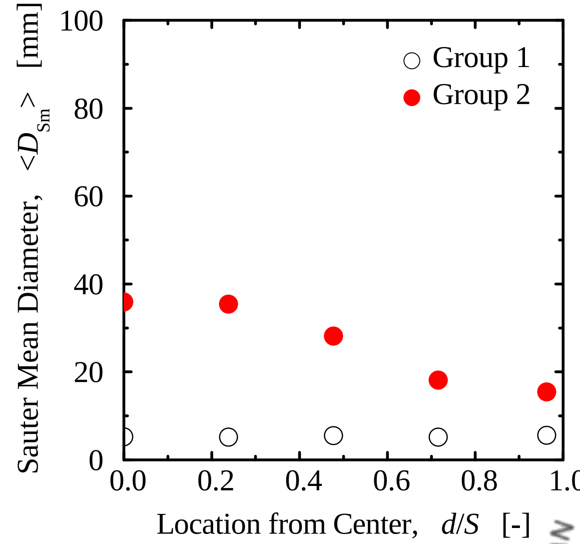




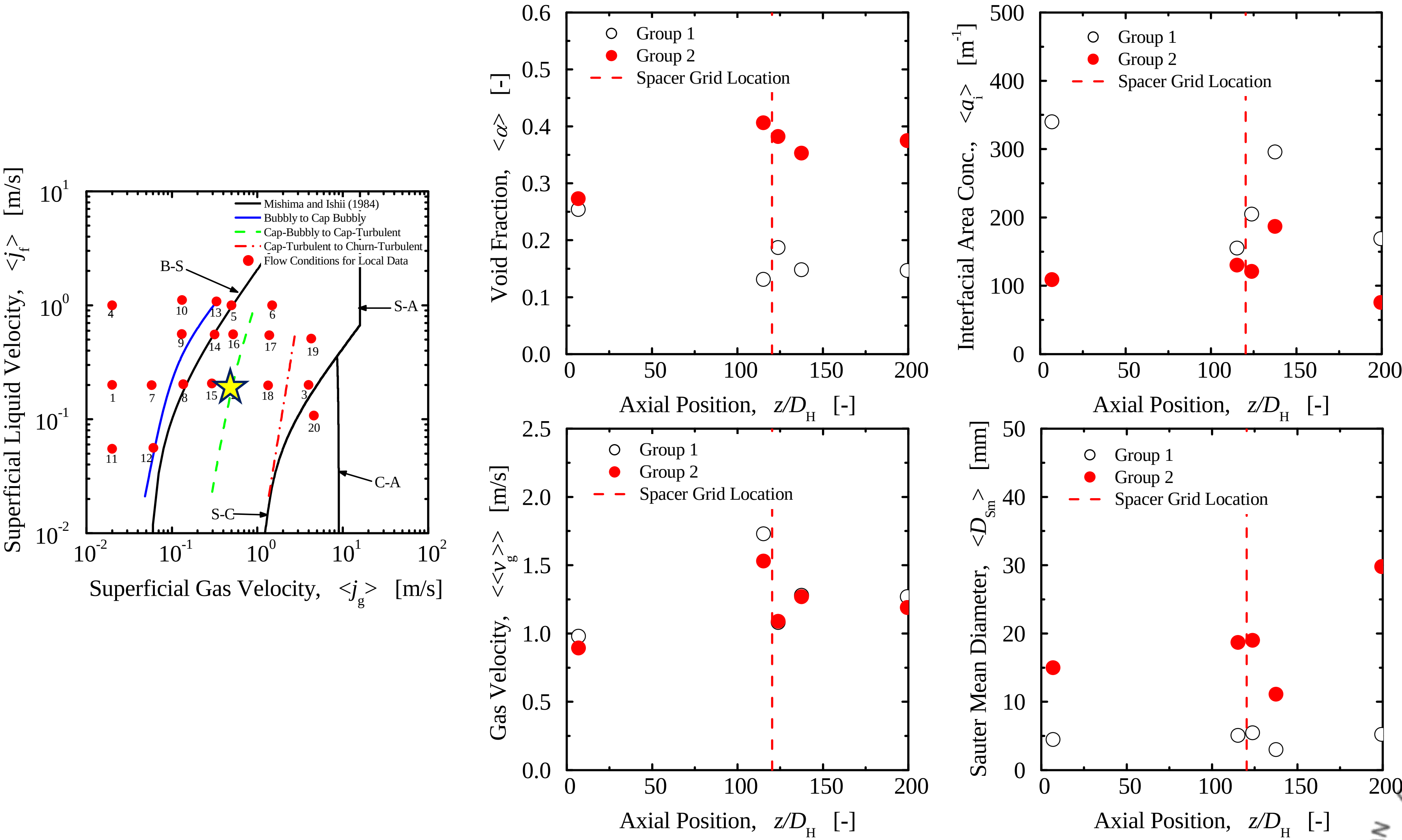






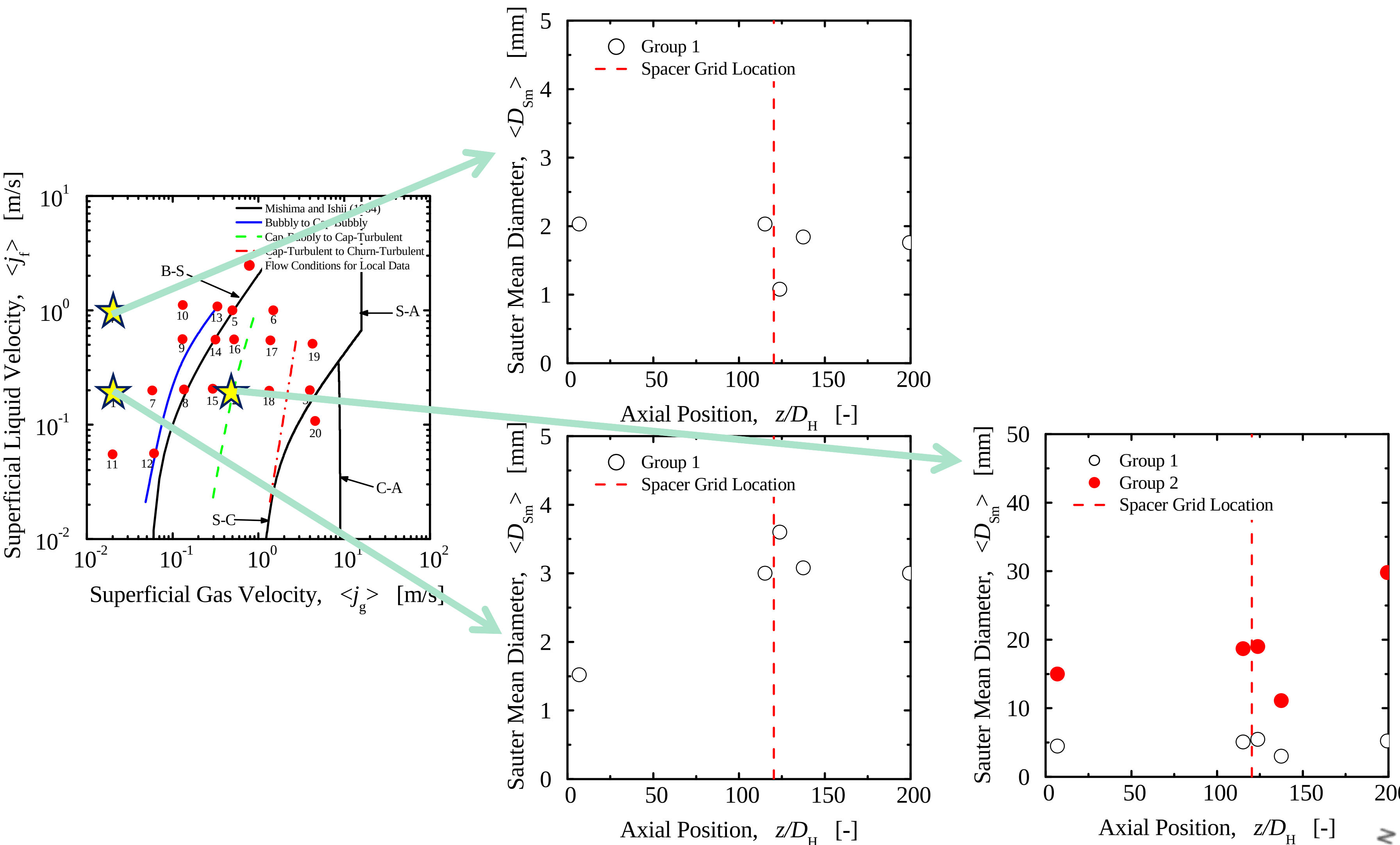


1-D Data for 8 X 8 Rod Bundle Geometry
($\langle j_f \rangle$ = 0.2 m/s and $\langle j_g \rangle$ = 0.5 m/s)



Thermal-Hydraulics and Reactor Safety Laboratory, School of Nuclear Engineering, Purdue University

1-D Data for 8 X 8 Rod Bundle Geometry



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- ✓ Introduction
- ✓ Formulation of Two-Fluid Model with Interfacial Area Transport Eq.
  - ✓ Two-Group Interfacial Area Transport Eq.
  - ✓ Two-Group Momentum Eq.
- ✓ Modeling of Sink and Source Terms in Interfacial Area Transport Eq.
  - ✓ Sink and Source Due to Bubble Breakup and Coalescence
  - ✓ Sink and Source Terms Due to Phase Change
  - ✓ Source Term Due to Wall Nucleation
- ✓ Database to Evaluate Interfacial Area Transport Eq.
  - ✓ Local Interfacial Area Measurement
  - ✓ Database for 8 X 8 Rod Bundle Geometry
- ✓ Benchmarking Interfacial Area Transport Eq.
  - ✓ Benchmarking 1-D IATE in Adiabatic Systems
  - ✓ Benchmarking 1-D IATE in Condensation Systems
- ✓ Future Directions
- ✓ Conclusions

Benchmarking One-Dimensional Interfacial Area Transport Equation

One-Dimensional One-Group IATE under Steady Bubbly Flow Conditions

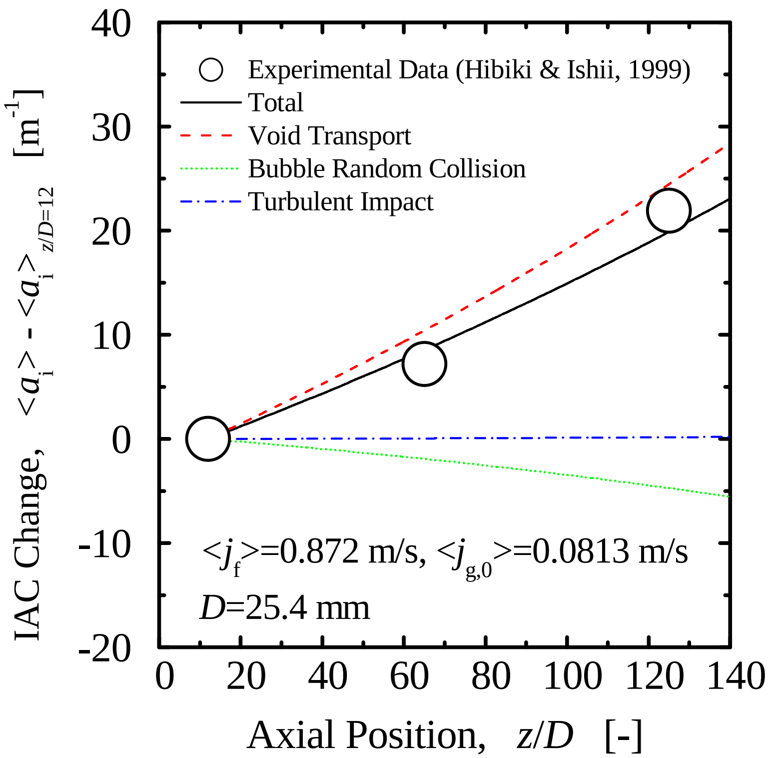
$$\frac{\partial}{\partial z}\langle a_i\rangle\langle\langle v_i\rangle\rangle_a = \langle \Phi_{TI}\rangle - \langle \Phi_{RC}\rangle + \frac{2\langle a_i\rangle}{3\langle\alpha\rangle}\frac{\partial}{\partial z}\langle\alpha\rangle\langle\langle v_g\rangle\rangle$$

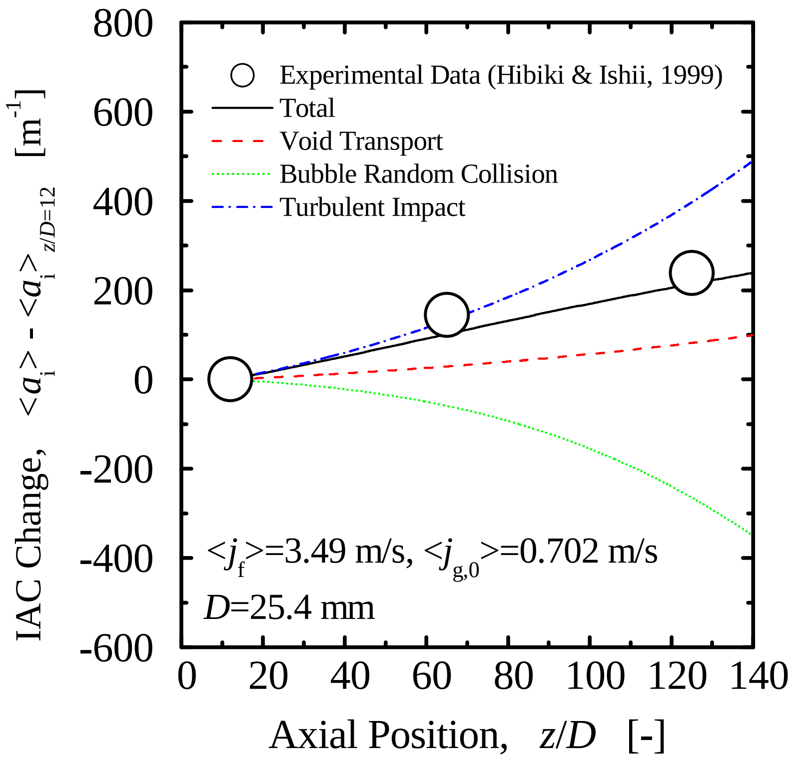
Sink and Source Terms

$$\Phi_{RC} = \frac{\Gamma_{RC}\langle\alpha\rangle^2\langle\varepsilon\rangle^{1/3}}{\langle D_b\rangle^{5/3}\left(\alpha_{RC,max}-\langle\alpha\rangle\right)}\exp\left(-\frac{K_{RC}\rho_f^{1/2}\langle D_b\rangle^{5/6}\langle\varepsilon\rangle^{1/3}}{\sigma^{1/2}}\right)$$

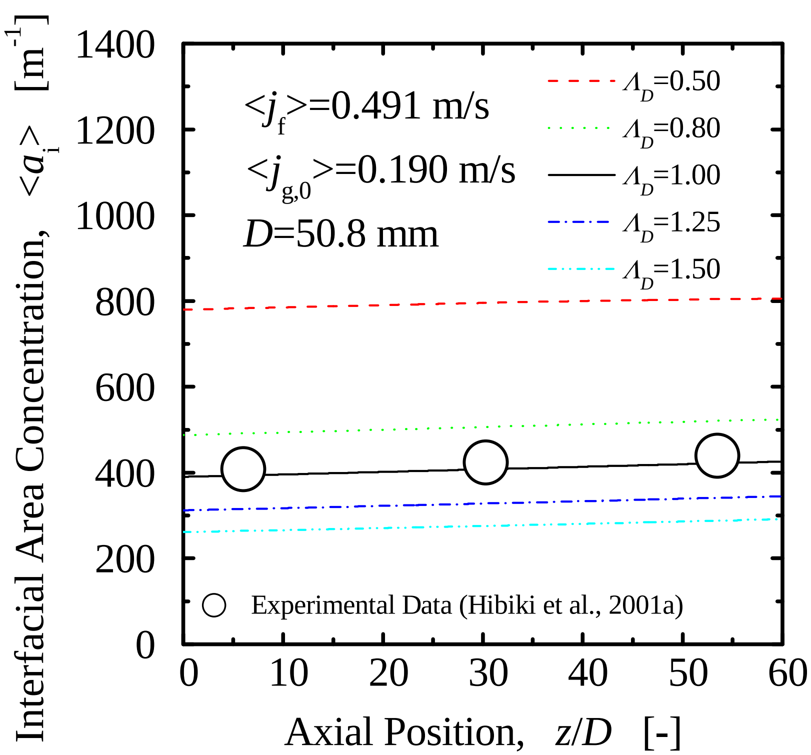
$$\Phi_{TI} = \frac{\Gamma_{TI}\langle\alpha\rangle\left(1-\langle\alpha\rangle\right)\langle\varepsilon\rangle^{1/3}}{\langle D_b\rangle^{5/3}\left(\alpha_{TI,max}-\langle\alpha\rangle\right)}\exp\left(-\frac{K_{TI}\sigma}{\rho_f\langle D_b\rangle^{5/3}\langle\varepsilon\rangle^{2/3}}\right)$$

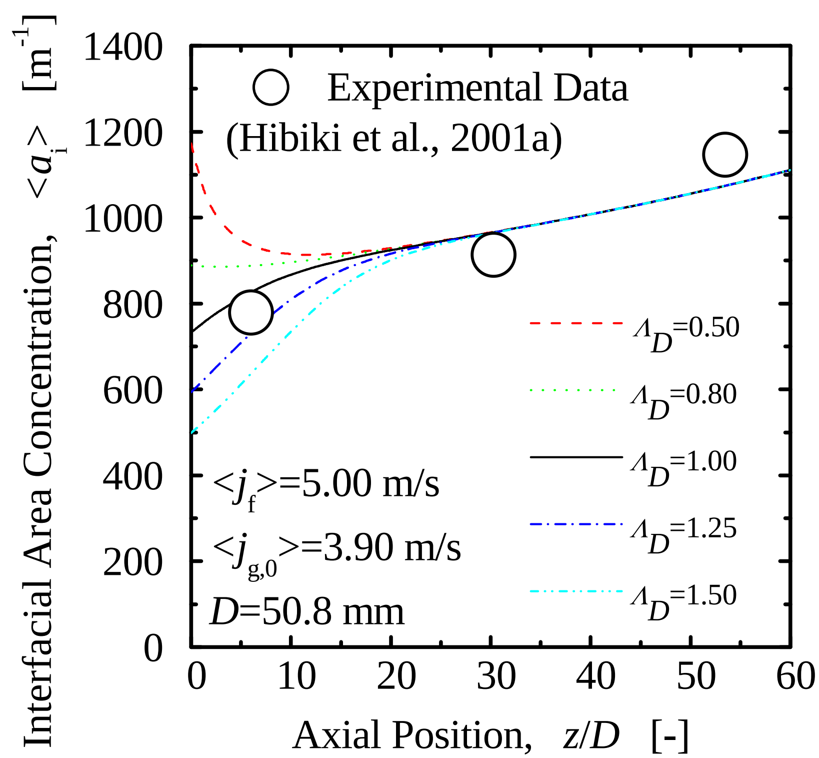
Benchmarking One-Dimensional Interfacial Area Transport Equation (Hibiki and Ishii, 2002)





Benchmarking Interfacial Area Transport Equation -Sensitivity Analysis- (Hibiki and Ishii, 2002)





$$\Lambda_D \equiv \frac{\langle D_{b,0,set} \rangle}{\langle D_{b,0} \rangle}$$

$D_{b,0,set}$: initial bubble diameter utilized for computation,

$D_{b,0}$: initial bubble diameter observed in the experiment

Benchmarking One-Dimensional Interfacial Area Transport Equation

One-Dimensional One-Group IATE under Steady Bubbly Flow Conditions with Condensation

$$\frac{\partial}{\partial z}\langle a_i\rangle\left\langle\left\langle v_i\right\rangle\right\rangle_a = \left\langle\Phi_{TI}\right\rangle - \left\langle\Phi_{RC}\right\rangle - \left\langle\Phi_{CD}\right\rangle + \frac{2\langle a_i\rangle}{3\langle\alpha\rangle}\frac{\partial}{\partial z}\langle\alpha\rangle\left\langle\left\langle v_g\right\rangle\right\rangle$$

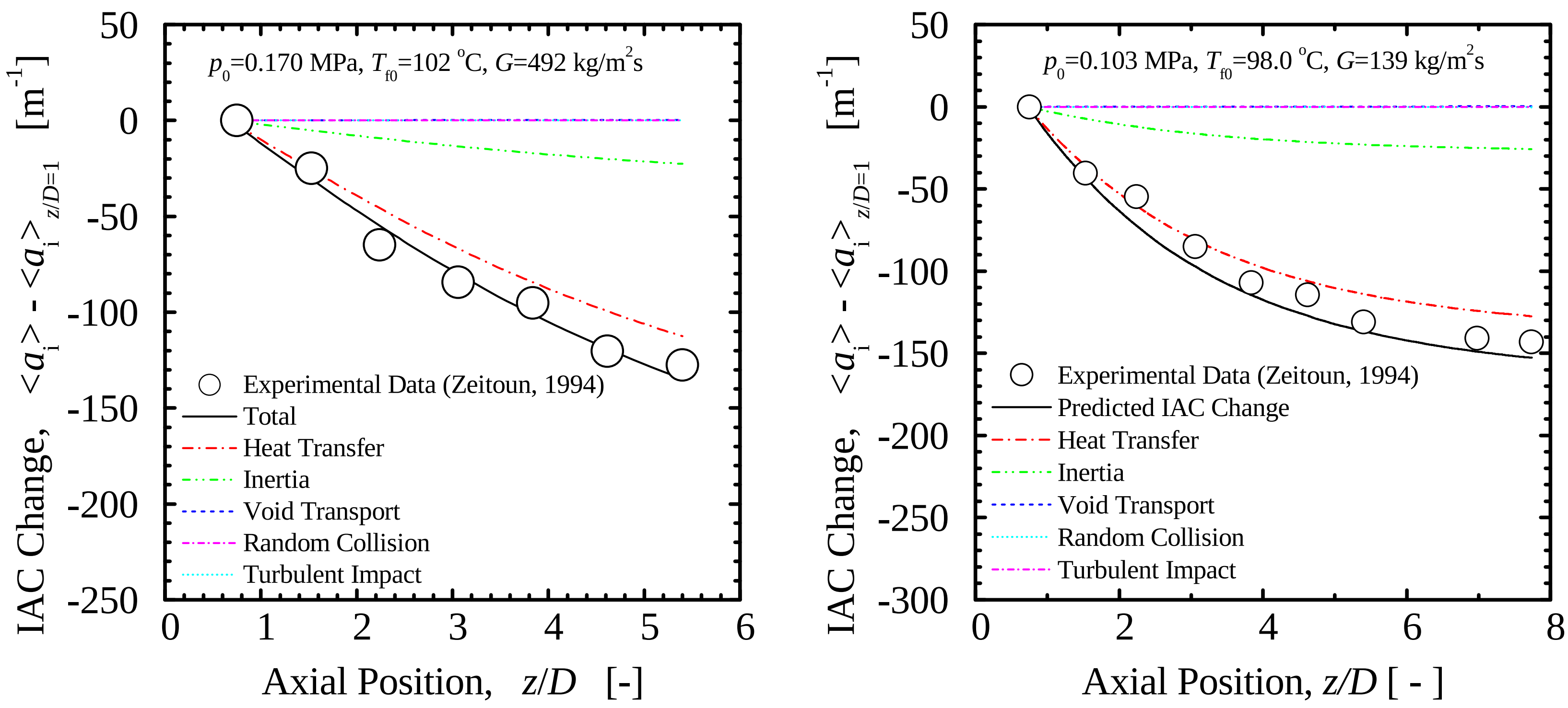
Sink and Source Terms

$$\left\langle\Phi_{RC}\right\rangle = \frac{\Gamma_{RC}\langle\alpha\rangle^2\langle\varepsilon\rangle^{1/3}}{\langle D_b\rangle^{5/3}\left(\alpha_{RC,max}-\langle\alpha\rangle\right)}\exp\left(-\frac{K_{RC}\rho_f^{1/2}\langle D_b\rangle^{5/6}\langle\varepsilon\rangle^{1/3}}{\sigma^{1/2}}\right)$$

$$\left\langle\Phi_{TI}\right\rangle = \frac{\Gamma_{TI}\langle\alpha\rangle\left(1-\langle\alpha\rangle\right)\langle\varepsilon\rangle^{1/3}}{\langle D_b\rangle^{5/3}\left(\alpha_{TI,max}-\langle\alpha\rangle\right)}\exp\left(-\frac{K_{TI}\sigma}{\rho_f\langle D_b\rangle^{5/3}\langle\varepsilon\rangle^{2/3}}\right)$$

$$\left\langle\Phi_{CD}\right\rangle = \left\langle\Phi_{HC}\right\rangle + \left\langle\Phi_{IC}\right\rangle = \pi\langle n_b\rangle\left\{4\left(1-P_c\right)\alpha_t N_{Nuc}N_{Ja} + \frac{\langle D_B\rangle^2}{t_c}\right\}$$

Benchmarking One-Dimensional Interfacial Area Transport Equation



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- ✓ Future Directions
- ✓ Conclusions

Future Direction
Formulation of Interfacial Area Transport Equation

Formulation of Interfacial Area Transport Equation		
1975	Ishii	Basic concept of necessity of interfacial area transport equation
1995	Kocamustafaogullari and Ishii	Foundation of interfacial area transport equation
2003c	Hibiki et al.	Formulation of one-dimensional interfacial area transport equation in subcooled boiling flow
2003a	Sun et al.	Formulation of modified two-fluid model for two-gas momentum equations
2004	Ishii and Kim	Formulation of two-group interfacial area transport equation
Future work		• Extension of interfacial area transport equation to churn-turbulent-to-annular flow transition • Extension of interfacial area transport equation to annular and annular-mist flow regimes

Future Direction
Development of Measurement Techniques

Development of Measurement Techniques		
1986	Kataoka et al.	Mathematical foundation of interfacial area concentration to be measured by local probe technique
1992	Revankar and Ishii	Demonstration of double-sensor probe technique
1993	Revankar and Ishii	Demonstration of multi-sensor probe technique
1998	Hibiki et al.	Development of improved double-sensor probe technique
1998	Hibiki et al.	Application of hot-film anemometry to liquid velocity measurement
1999	Wu and Ishii	Monte Carlo simulation of double-sensor probe technique
2000	Kim et al.	Development of improved multi-sensor probe technique
2004c	Sun et al.	Application of laser Doppler anemometer to liquid velocity measurement
Future work		• Improvement of local probe technique to be applicable to highly three-dimensional flow • Application of film thickness probe to measure annular flow characteristics • Application of droplet measurement technique to measure annular-mist flow characteristics

Future Direction
Database Construction

Database Construction		
1998	Hibiki et al.	Upward bubbly flow in vertical pipe (gas and liquid phases)
1999	Hibiki and Ishii	Upward bubbly flow in vertical pipe (gas and liquid phases)
2001	Bartel et al.	Upward boiling bubbly flow in vertical annulus
2001a	Hibiki et al.	Upward bubbly flow in vertical pipe (gas and liquid phases)
2002	Sun et al.	Upward bubbly flow in vertical large diameter pipe
2003a	Hibiki et al.	Downward bubbly flow in vertical pipe
2003b	Hibiki et al.	Upward bubbly flow in vertical annulus
2003	Kim et al.	Upward bubbly flow in confined channel
2003b	Sun et al.	Upward cap-turbulent and transition to slug flows in vertical large diameter pipe
2003	Takamasa et al.	Bubbly flow in pipe under microgravity conditions
2004	Situ et al.	Upward boiling bubbly flow in vertical annulus
2004a	Sun et al.	Upward cap-turbulent and churn-turbulent flows in confined channel
2005	Situ et al.	Bubble lift-off and departure diameters
2007	Hazuku et al.	Upward annular flow in vertical pipe
2007	Hibiki et al.	Upward bubbly flow in vertical mini-channel
2008	Jeong et al.	Upward cap-turbulent and churn-turbulent flows in vertical annulus
2008	Situ et al.	Bubble departure frequency
Future work		• Development of extensive slug, churn-turbulent and annular flow data • Development of extensive data at elevated pressure • Development of extensive data in various flow channels (geometry, orientation and size) • Development of extensive wall nucleation data (active nucleation site density, bubble departure size and frequency) • Development of extensive condensation and boiling data

Future Direction
Sink and Source Term Modeling

Sink and source term modeling		
1983	Kocamustafaogullari and Ishii	Active nucleation site density
1989	Riznic and Ishii	Flashing source term
1998	Wu et al.	One-group model in pipe
2000a	Hibiki and Ishii	One-group model in pipe
2000b	Hibiki and Ishii	Two-group model in pipe
2001b	Hibiki et al.	One-group model in small-diameter pipe
2003a	Fu and Ishii	Two-group model in pipe
2003	Hibiki and Ishii	Active nucleation site density
2004b	Sun et al.	Two-group model in confined channel
2005	Situ et al.	Bubble lift-off diameter
2007	Park et al.	Condensation sink term
2008	Situ et al.	Bubble departure diameter
2008	Situ et al.	Bubble departure frequency
Future work		• Improvement of two-group model • Improvement of bubble departure diameter model • Improvement of bubble departure frequency model • Development of bulk boiling source model

Future Direction
Implementation into CFD Codes

Implementation into CFD code	
Future work	• Implementation of interfacial area transport equation into CFD code • Benchmarking CFD code against data showing fully 3-D behavior

Future Direction
Modeling of Interfacial Forces and Turbulence Models

Interfacial Force Models

- Lift Force Model
  - Tomiyama et al. (2002)
  - Hibiki and Ishii (2007)
- Wall Lubrication Force Model
  - Antal et al. (1991)
  - Tomiyama (1998)
- Turbulence Dispersion Force Model
  - Lahey et al. (1993)
  - Burns et al. (2004)

Turbulence Models

- Zero-Equation Model
  - Sato et al. (1981)
- One-Equation Model
  - Kataoka and Serizawa (1995)
- Two-Equation Model
  - Lopez de Bertodano et al. (1994)

Presentation Outline

- ✓ Introduction
- ✓ Formulation of Two-Fluid Model with Interfacial Area Transport Eq.
  - ✓ Two-Group Interfacial Area Transport Eq.
  - ✓ Two-Group Momentum Eq.
- ✓ Modeling of Sink and Source Terms in Interfacial Area Transport Eq.
  - ✓ Sink and Source Due to Bubble Breakup and Coalescence
  - ✓ Sink and Source Terms Due to Phase Change
  - ✓ Source Term Due to Wall Nucleation
- ✓ Database to Evaluate Interfacial Area Transport Eq.
  - ✓ Local Interfacial Area Measurement
  - ✓ Database for 8 X 8 Rod Bundle Geometry
- ✓ Benchmarking Interfacial Area Transport Eq.
  - ✓ Benchmarking 1-D IATE in Adiabatic Systems
  - ✓ Benchmarking 1-D IATE in Condensation Systems
- ✓ Future Directions
- ✓ Conclusions

Conclusions

In relation to the modeling of the interfacial transfer terms in the two-fluid model, the concept of the interfacial area transport equation has been proposed to develop a constitutive relation for the interfacial area concentration. The changes in the two-phase flow structure can be predicted mechanistically by introducing the interfacial area transport equation.

(1) The basic concept of the interfacial area transport equation and its formulation have been briefly explained.

(2) Available models of interfacial area sink and source terms and existing databases have been reviewed.

(3) Newly obtained data for 8 X 8 rod bundle geometry has been presented.

(4) The interfacial area transport equation has been benchmarked using adiabatic bubbly flow and condensation bubbly flow data

(5) Future direction for this research has been also suggested.