

# COMPUTATIONAL NUCLEAR THERMAL HYDRAULICS

*Cho, Hyoung Kyu*

*Department of Nuclear Engineering  
Seoul National University*

# **TWO-FLUID MODEL: CONSTITUTIVE RELATIONS**

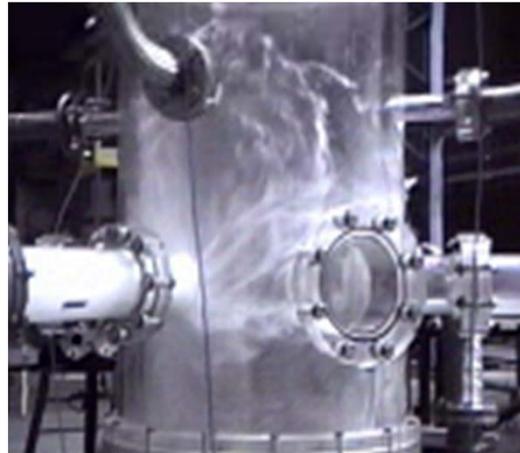
# Nuclear Thermal-hydraulics

## 열유체 분야

### 원자로 열수력학 Nuclear Thermal-hydraulics

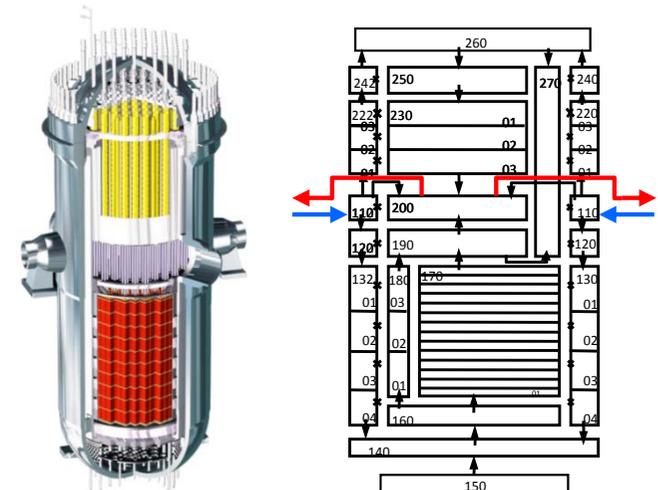
- 원자로 운전 조건: 고온, 고압 (150 bars, 325°C)
  - 사고 조건 (ex: 대형 냉각재 상실사고)
    - ⇒ 수십 초 만에 대기압으로 감소
    - ⇒ **상 변화 (phase change)**: 핵연료봉 온도 증가
    - ⇒ 안전계통 가동: 고온 핵연료봉과 비상냉각 간
- 2상 유동 열전달 (two-phase flow)**

- 2상 유동 ⇒ 상 변화, 고온, 고압, 대형 배관
- 2상 유동 해석 기술
  - ⇒ 원자로 안전성 평가의 핵심 기술



### 원자로 안전해석 기술 Nuclear Reactor Safety Analysis

- 사고 시 열수력 거동 예측을 통한 안전성 입증
- 2-유체 모델 (Two-fluid model)
  - ⇒ 각 상에 대한 N.S. 방정식 사용
  - ⇒ 계면전달항 (interfacial transfer terms)
  - ⇒ 실험을 통한 경험적 모델링에 의존
- 원자로 안전해석
  - ⇒ 원자로 전체의 과도 2상 유동 해석
  - ⇒ 1차원 해석: 보수성이 검증된 생성항 모델
  - ⇒ 방대한 V&V
  - ⇒ 2상 유동 CFD 활용 증가, 적용 한계



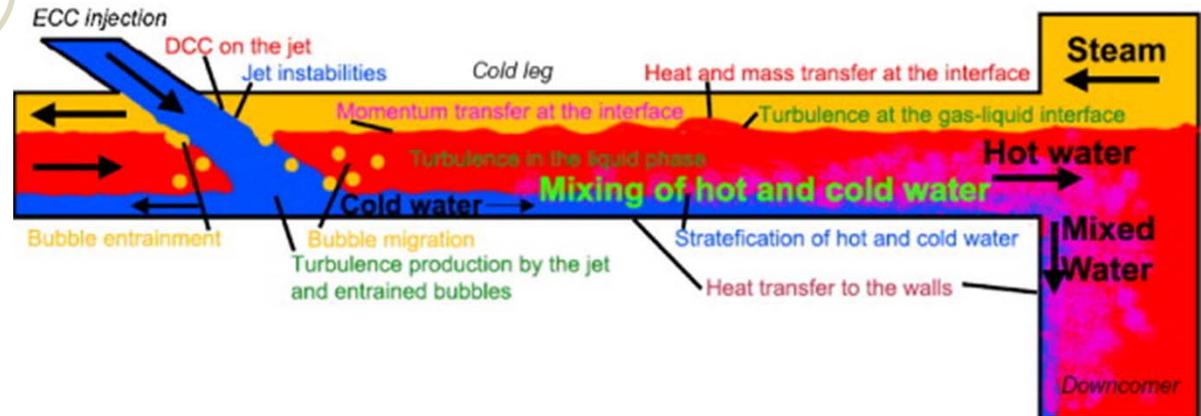
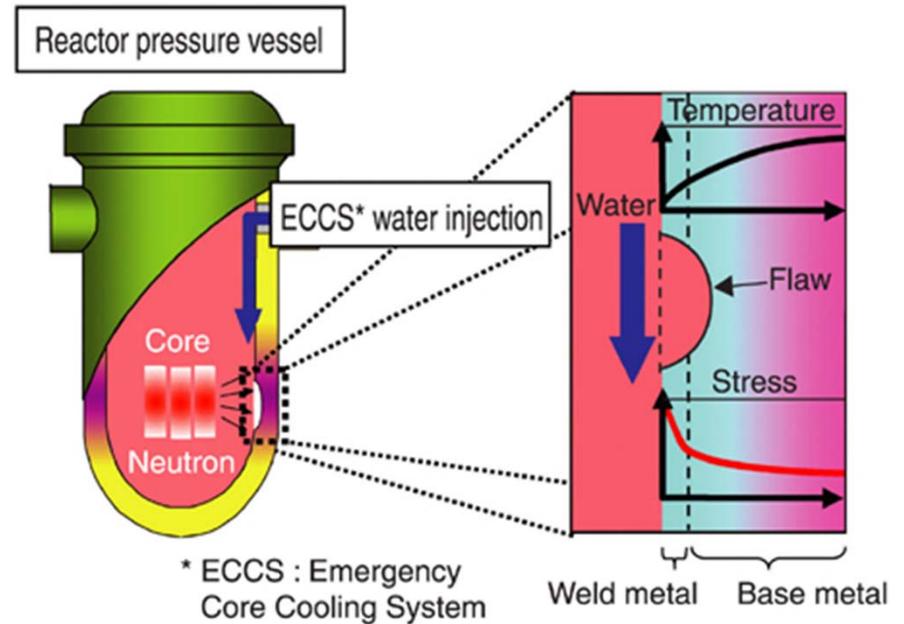
# Need for Extension of CFD Capability to Two-phase Flow

	NRS problem	Maturity of present CFD tools
1	<b>DNB, dry out and CHF investigations</b>	M
2	Subcooled boiling	M
3	<b>Two-phase pressurized thermal shock</b>	M
4	Direct contact condensation: steam discharge in a pool	M
5	Pool heat exchangers: thermal stratification and mixing problems	H
6	Corrosion Erosion deposition	L
7	<b>Containment thermal-hydraulics</b>	H
8	Two-phase flow in valves, safety valves	L
9	ECC bypass and downcomer penetration during refill	L
10	<b>Two phase flow features in BWR cores</b>	M
11	Atmospheric transport of aerosols outside containment	M
12	DBA reflooding	M
13	Reflooding of a debris bed	L
14	Steam generator tube vibration	L
15	Upper plenum injection	L
16	Local 3-D effects in singular geometries	L
17	Phase distribution in inlet and outlet headers of steam generators	L
18	Condensation induced waterhammer	L
19	Components with complex geometry	L
20	<b>Pipe Flow with Cavitation</b>	M
21	<b>External reactor pressure vessel cooling</b>	M
22	Behaviour of gas-liquid interfaces	M
23	Two-phase pump behaviour	L
24	Pipe Break-In vessel mechanical load	M
25	<b>Specific features in Passive reactors</b>	M

# Need for Extension of CFD Capability to Two-phase Flow

## Pressurized Thermal Shock 가압열충격

- 원전 계속운전을 위한 주요 현안
- 증기 응축
- 노심냉각수 및 응축수 간의 열혼합
- 열성층 형성 여부
- EDF (프랑스): 계속운전 인허가를 위해 2상유동 CFD 결과 활용



# Need for Extension of CFD Capability to Two-phase Flow

## Passive Safety System 피동 안전 계통

- 자연 순환에 의한 피동 냉각
- 중력에 의한 안전주입

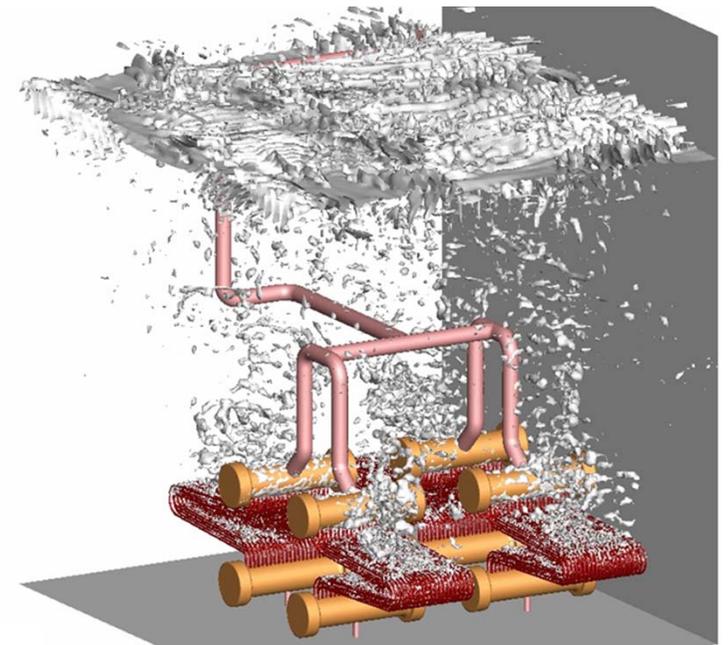
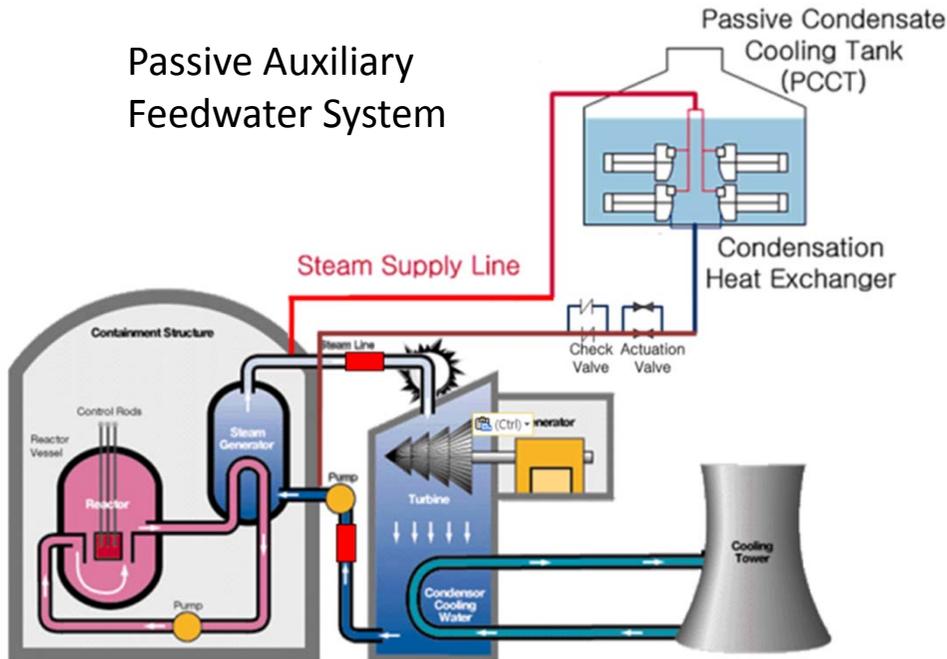
## Small Modular Reactor 소형모듈형원자로

- 피동 냉각 계통
- 자연순환 냉각

- 작은 구동력
- 열전달 성능 예측의 불확실성



## Passive Auxiliary Feedwater System



# Need for Extension of CFD Capability to Two-phase Flow

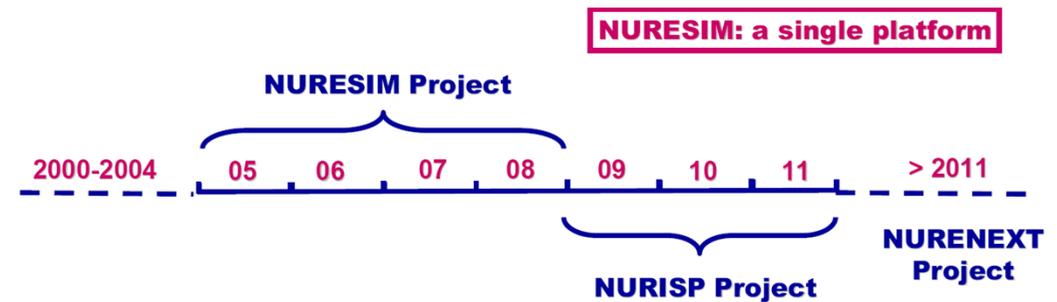
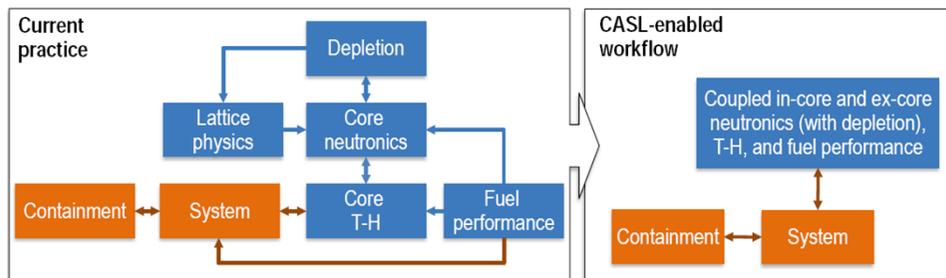
US

- CASL (The Consortium for Advanced Simulation of Light Water Reactors)
- CFD-BWR (ANL): based on STAR-CD
- NPHASE (RPI): inhouse multiphase flow code

EU

- NEPTUNE project (EDF, CEA, AREVA, IRSN)
  - ✓ DNB, PTS, TH in BWR, Reflood during LOCA
- Multi-physics, multi-scale platform

Power up-rates  
Lifetime extension  
Higher burn-up



- **NURESIM Project: basis towards the target with first significant possibilities**
- **NURISP: consolidation + extension**
- **NURENEXT: confirmation + rationalization + further extension**

# Difficulties in Two-phase Flow Simulation for Nuclear Reactor Safety

## □ 원자로 내 2상 유동 해석의 어려움

- 혼합체 모델, 2-유체 모델 (mixture model, two-fluid model)  
 ⇔ Interface tracking method (VOF, Level set)
- 2-유체 모델: 각 상에 대한 N.S. 방정식 사용

3차원 2유체 모델: 2 + 6 + 2

$$\frac{\partial}{\partial t}(\alpha_k \rho_k) + \nabla \cdot (\alpha_k \rho_k \underline{u}_k) = \Omega_k \quad \alpha_g : \text{기포율, 제어체적 내의 기체 체적 비}$$

$$\frac{\partial}{\partial t}(\alpha_k \rho_k \underline{u}_k) + \nabla \cdot (\alpha_k \rho_k \underline{u}_k \underline{u}_k) = -\alpha_k \nabla P + \nabla \cdot [\alpha_k (\underline{\tau}_k + \underline{\tau}_k^T)] + \alpha_k \rho_k \underline{g}$$

$$+ u_{ki} \Omega_k + M_{ik} + M_{ik}^{ND}$$

Interfacial  
area

Interfacial  
drag force

Interfacial  
non-drag force

- Virtual mass
- Lift
- Wall lubrication
- Turbulent dispersion

생성항을 위한 다양한 모델이 요구됨 ⇒ 실험에 의존

# Difficulties in Two-phase Flow Simulation for Nuclear Reactor Safety

## □ 원자로 내 2상 유동 해석의 어려움

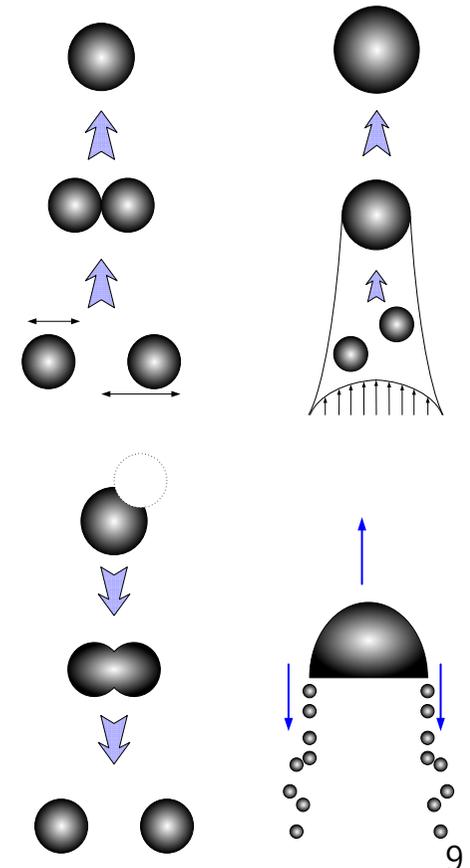
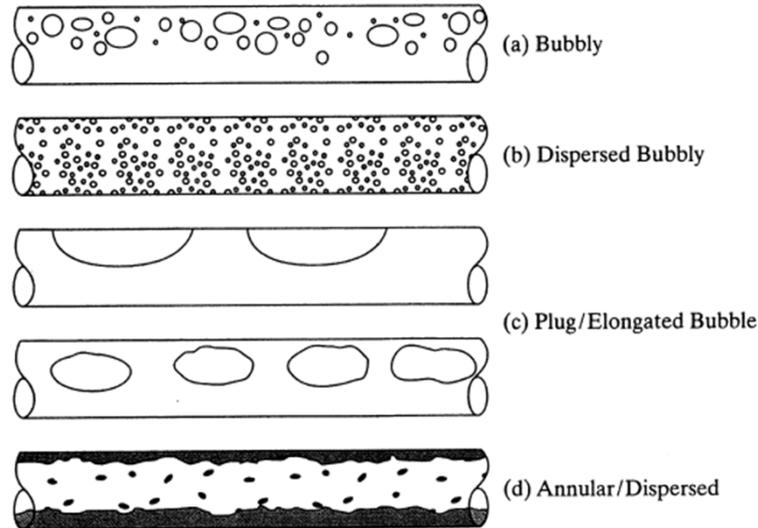
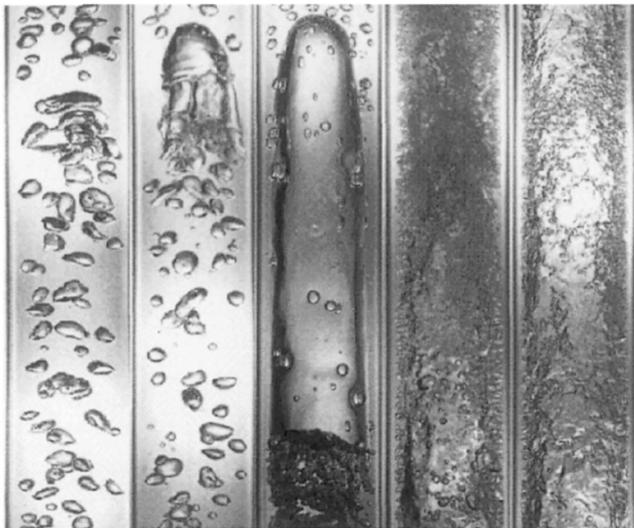
- 수치 불안정성

- ✓ 상간의 밀도차이: 1580 배 (대기압)
- ✓ 급격한 압력 변화: 150 기압 → 대기압 (30초)

- 계면 면적 (interfacial area)

- ✓ 유동 조건에 따라 계면 형상 변화
- ✓ 계면면적 수송 방정식: 기포 유동으로 적용이 제한됨.

생성항: 계면면적 × 구동력

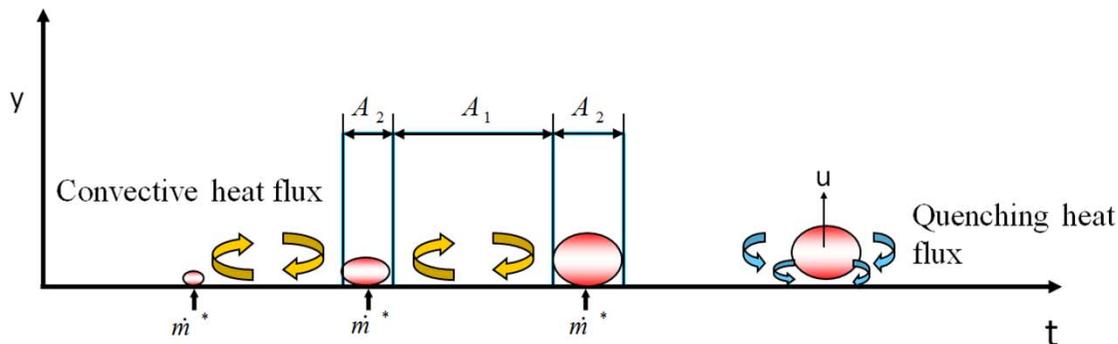
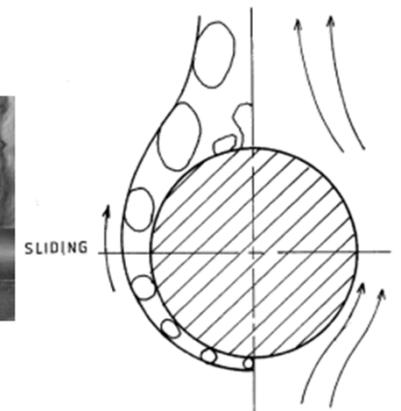
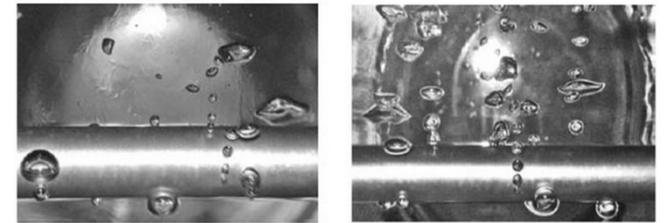
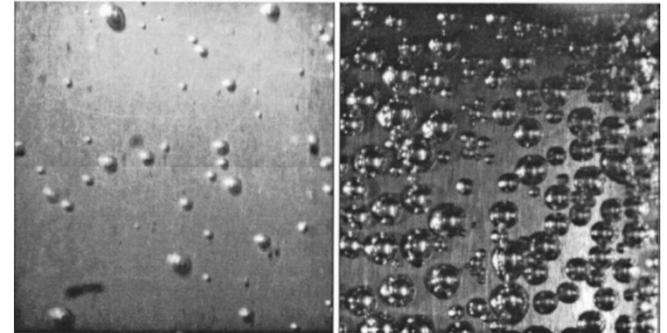


# Difficulties in Two-phase Flow Simulation for Nuclear Reactor Safety

## □ 원자로 내 2상 유동 해석의 어려움

### • 벽면 비등

- ✓ 가열벽 표면 특성의 효과
  - 단위 면적당 기포 생성 지점 (nucleation site density)
- ✓ 기포 경계층 내의 기포 거동의 효과
  - 기포 이탈 직경 (bubble departure diameter)
  - 기포 이탈 빈도 (bubble frequency)
- ✓ 유로 형상의 효과
  - 수평 평판형 가열면
  - 수평 원형 가열면
  - 수직 가열면
  - 가열면 방향의 효과



# Difficulties in Two-phase Flow Simulation for Nuclear Reactor Safety

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## □ 원자로 내 2상 유동 해석 연구 방향

- 형상의 복잡성 극복
  - ✓ 다중스케일 열수력 해석 (Multi-scale TH analysis)
- 적용성 확장
  - ✓ 모델 개발 및 검증이 수직 배관에 집중됨 (원자로 노심 모사)
  - ✓ 피동 계통 및 신규 안전기기 개발로 인한 적용성 확장 필요
  - ✓ 대형 배관에 대한 적용성 확장 필요: 고온관, 강수부 등
- 생성항의 정확도 향상
  - ✓ 범용성 확보의 어려움
  - ✓ 필요한 조건 및 형상에 대한 실험을 통해 생성항의 정확도 향상
  - ✓ Interface tracking method를 활용한 생성항 모델 개발

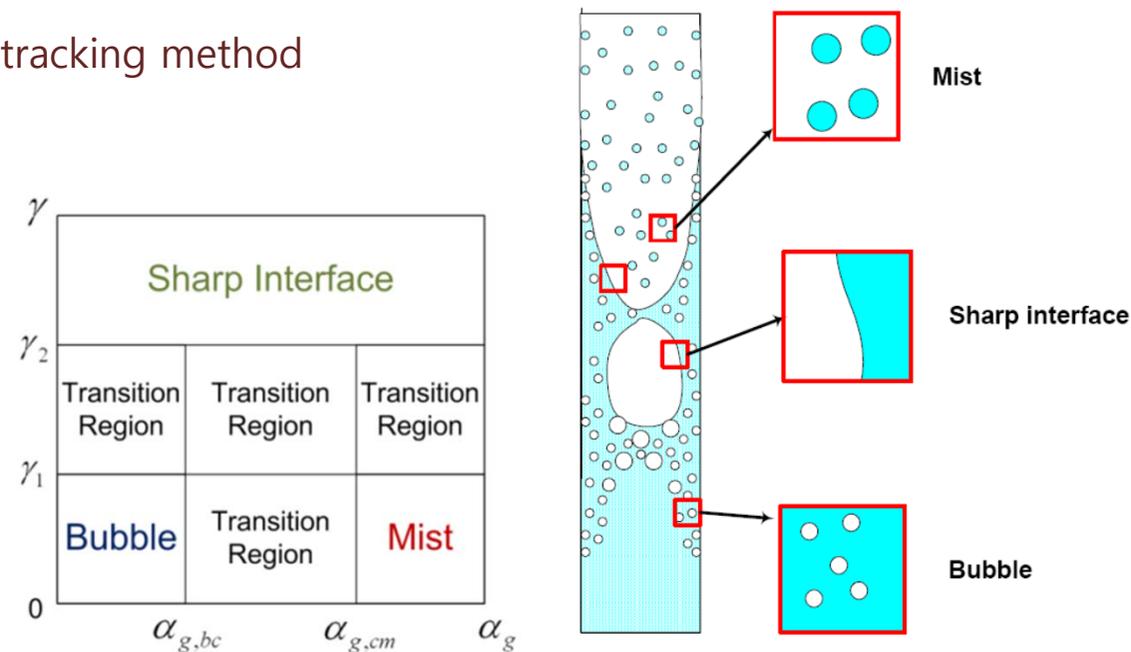
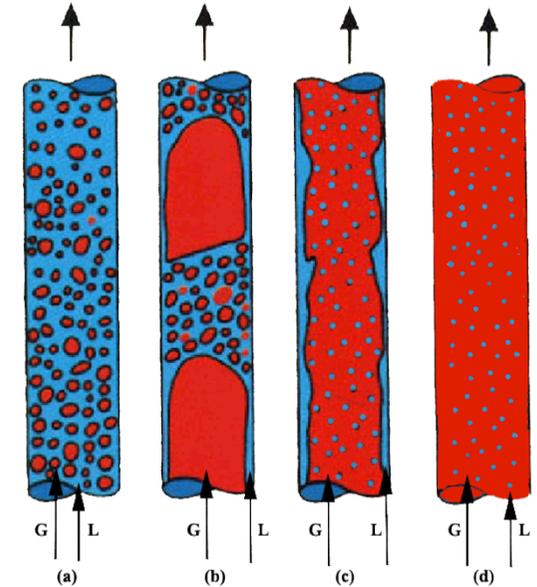
## □ 2-유체 모델 생성항 모델

- 계면 형상 모델 (Interface topology)
- 계면 면적 수송 방정식 (IAT: Interface area transport equation)
- 계면 비건인력 (Interfacial non-drag forces)
- 벽면 열분배 모델 (Wall heat partitioning model)
- 기포 기인 난류 (Bubble induced turbulence)

# Two-phase Flow Models

## □ 계면 형상 모델 (Interface topology)

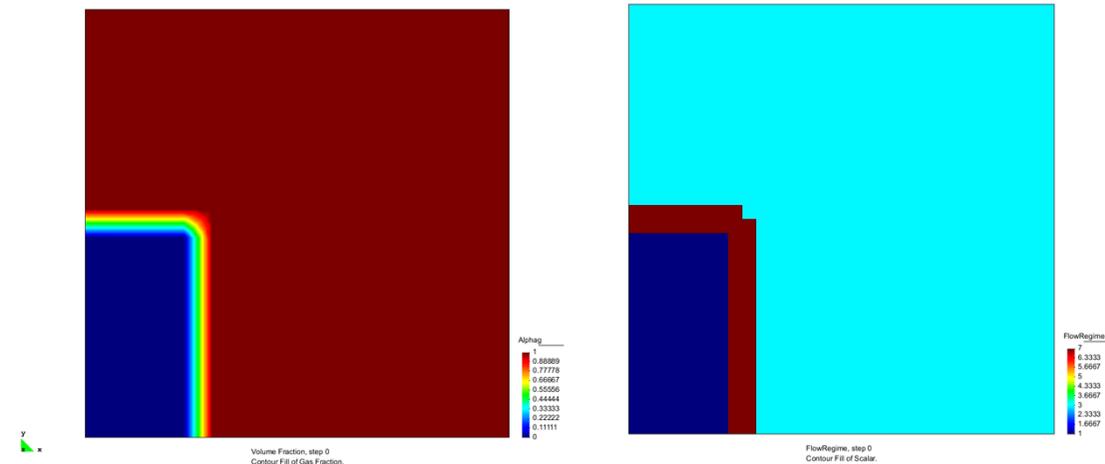
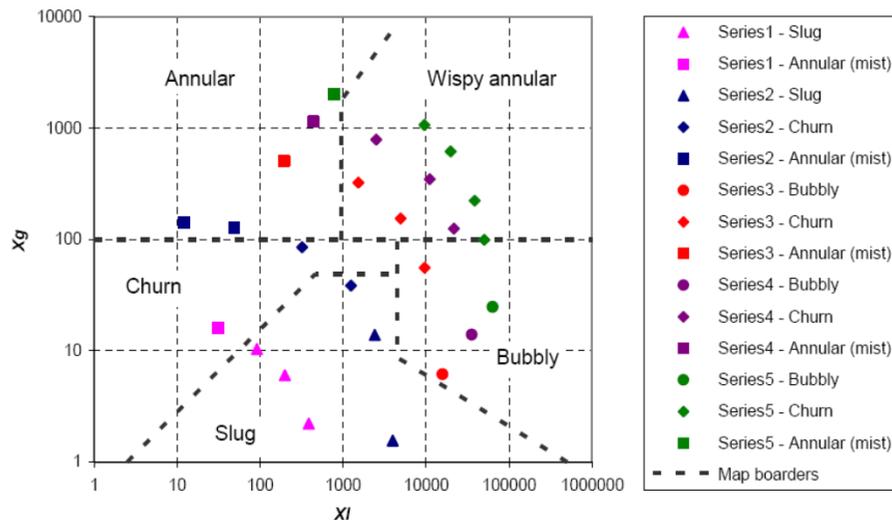
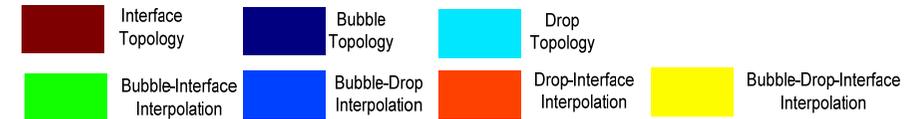
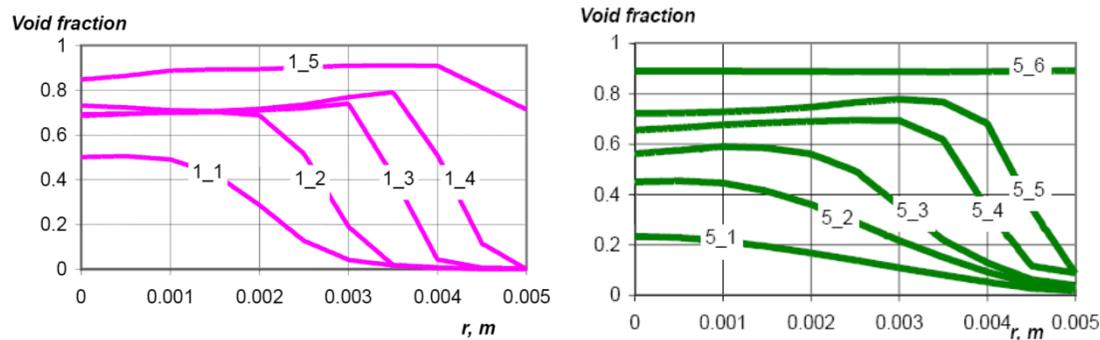
- BWR
  - ✓ 기포유동  $\Rightarrow$  슬러그유동  $\Rightarrow$  환상유동 (annular flow)
  - ✓ 다양한 유동 양식 예측을 위한 계면 형상 모델 필요
- CFD-BWR (ANL)
  - ✓ STAR-CD 기반 BWR 해석 모듈
  - ✓ Local inter-phase surface topology maps
- 기포, 액적, 분리유동 경계면
  - ✓ Interface recognition method  $\Leftrightarrow$  interface tracking method
- 계면 형상 천이 조건
  - ✓ 기포율 ( $\alpha$ ) 및 기포율 구배 ( $\nabla\alpha$ ) 기반
- 계면 형상에 따른 구성방정식
  - ✓ 계면면적/ 계면마찰계수
  - ✓ 계면열전달계수/ 계면비결인력 모델



# Two-phase Flow Models

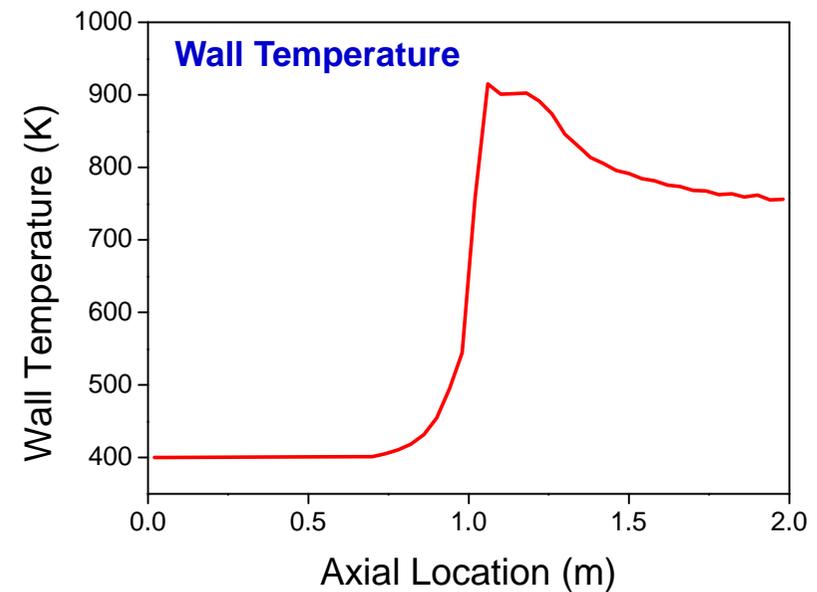
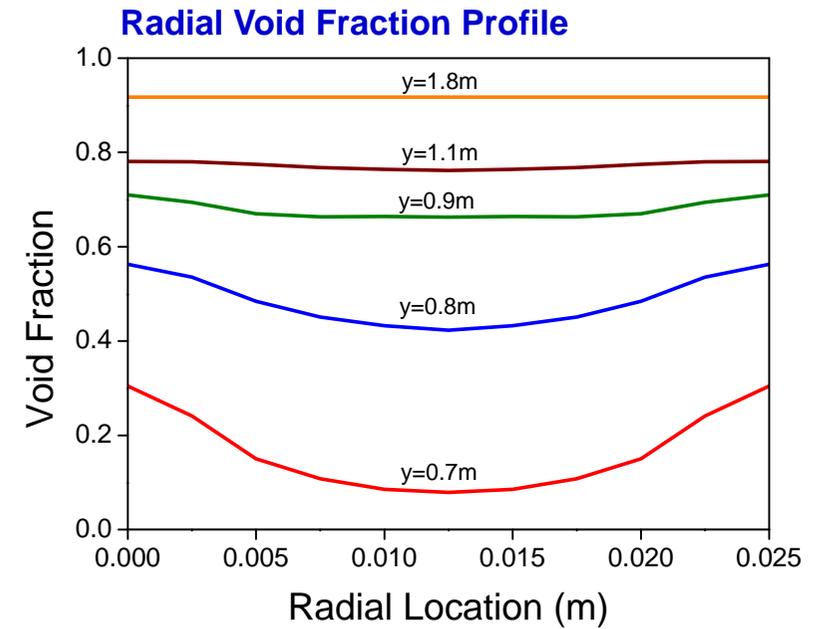
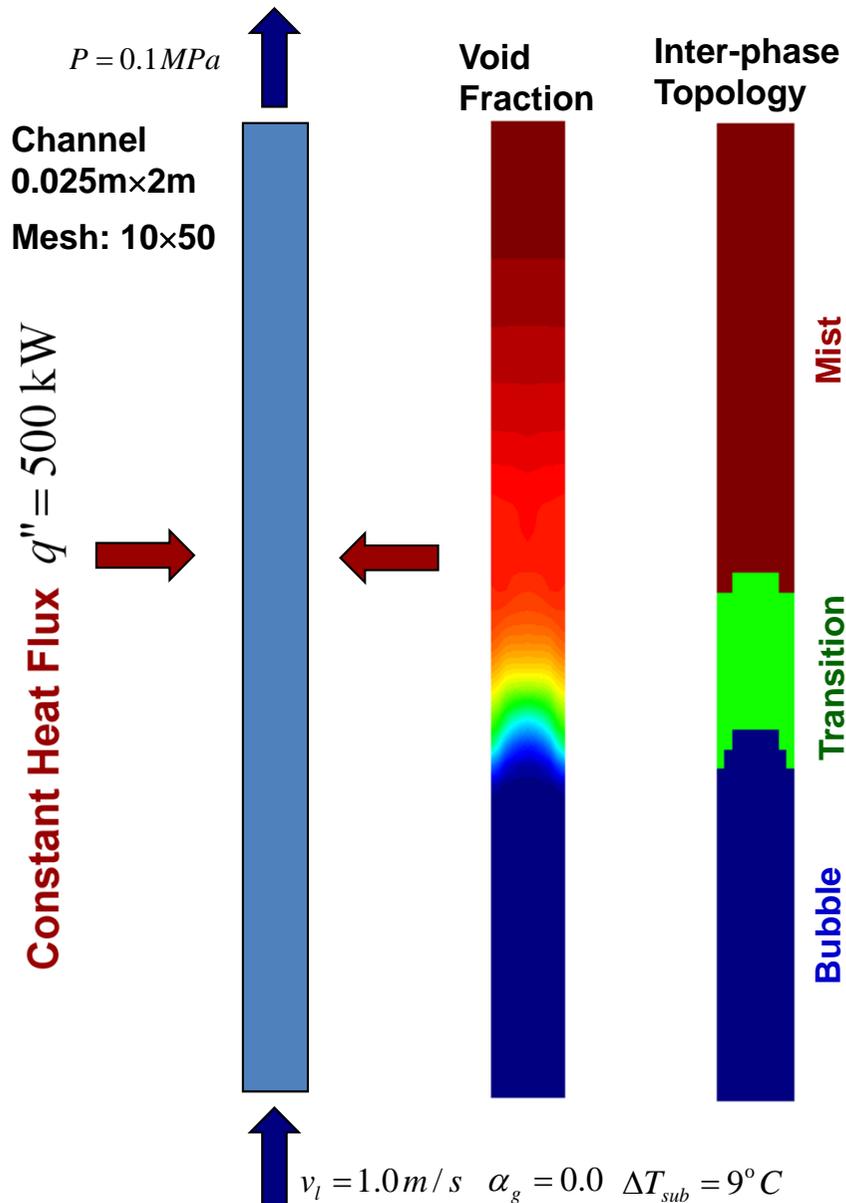
## □ 계면 형상 모델 (Interface topology)

- V&V: 수직 배관, 상향 물-증기 유동
  - ✓ 단열 조건 (포화 온도)
- 수평 배관, 가열 조건, 대형 배관 등의 적용성 검증 필요



# Two-phase Flow Models

## □ 계면 형상 모델 (Interface topology)



## □ 2-유체 모델 생성항 모델

- 계면 형상 모델 (Interface topology)
- 계면 면적 수송 방정식 (IAT: Interface area transport equation)
- 계면 비건인력 (Interfacial non-drag forces)
- 벽면 열분배 모델 (Wall heat partitioning model)
- 기포 기인 난류 (Bubble induced turbulence)

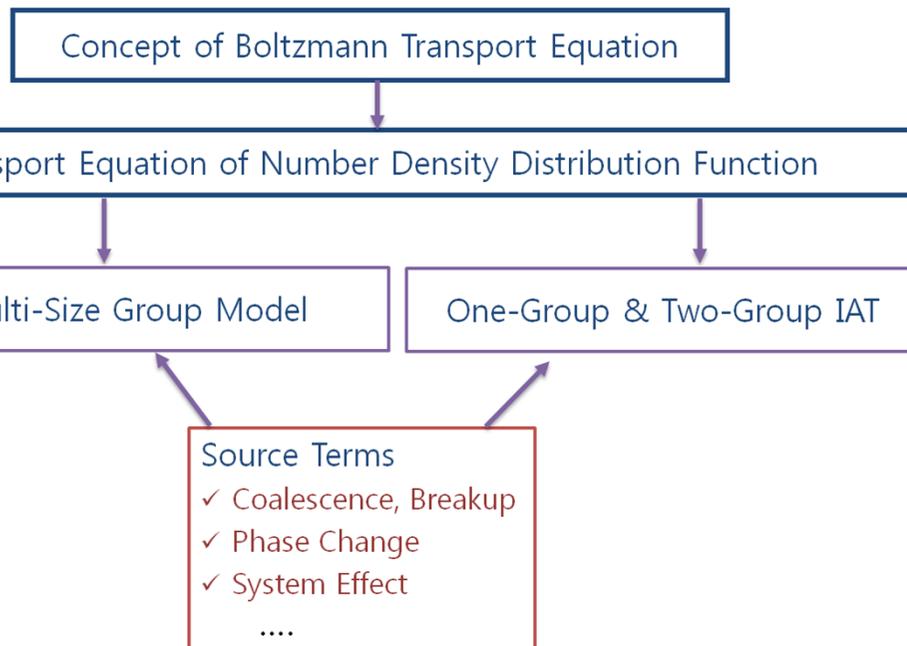
# Two-phase Flow Models

## □ 계면 면적 수송 방정식

- IAC (Interfacial Area Concentration)

- ✓ 계면 면적 밀도, 단위 체적 당 계면 면적
- ✓ 계면 전달항 ~ (IAC) X (구동력)
- ✓ 경험적 상관식/ 수송방정식

- IATE (Interfacial Area Transport Equation)



$$a_i = \frac{A_i}{\text{Unit Volume}} = \frac{A_i}{V_g / \alpha} = \frac{6\alpha}{d_{sm}}$$

$$\frac{\partial a_i}{\partial t} + \nabla \cdot (a_i V_g) = \frac{2}{3} \frac{a_i}{\alpha \rho_g} \left[ \Gamma_{ig} - \alpha \frac{d\rho_g}{dt} \right] + \frac{36\pi}{3} \left( \frac{\alpha}{a_i} \right)^2 \left( \boxed{\varphi_n^{CO}} + \boxed{\varphi_n^{BK}} \right) + \pi \boxed{d_{Bw}^2 \varphi_n^{NUC}}$$

## □ 계면 면적 수송 방정식

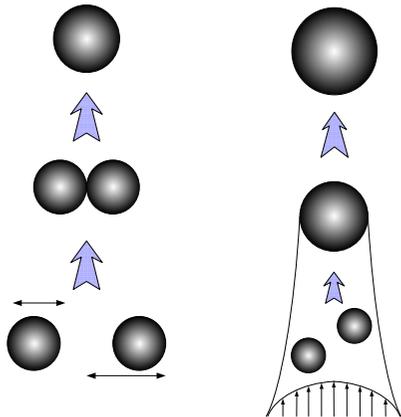
- 생성항

✓ 기포 병합 (coalescence), 기포 파열 (break-up), 벽면 비등 (nucleation)

$$\frac{\partial a_i}{\partial t} + \nabla \cdot (a_i V_g) = \frac{2}{3} \frac{a_i}{\alpha \rho_g} \left[ \Gamma_{ig} - \alpha \frac{d\rho_g}{dt} \right] + \frac{36\pi}{3} \left( \frac{\alpha}{a_i} \right)^2 \left( \boxed{\varphi_n^{CO}} + \boxed{\varphi_n^{BK}} \right) + \boxed{\pi d_{Bw}^2 \varphi_n^{NUC}}$$

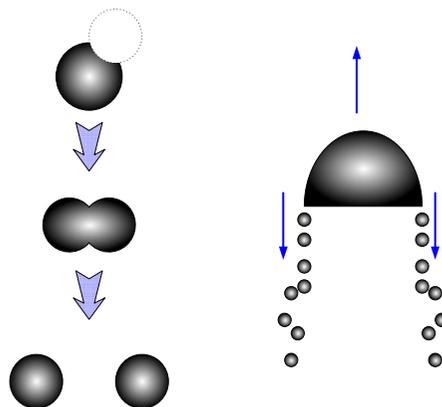
### ○ Bubble Coalescence

- Random Collision
- Wake Entrainment



### ○ Bubble Break-up

- Turbulence eddy impact
- Shearing off



$$\boxed{\pi d_{Bw}^2 \varphi_n^{NUC}}$$

$$\varphi_n^{NUC} = \frac{\boxed{n} \cdot \boxed{f} \cdot A_H}{V}$$

Bubble departure diameter  
Active nucleation site density  
Bubble departure frequency

## □ 계면 면적 수송 방정식

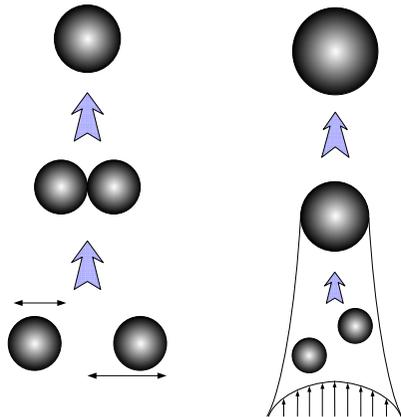
- 생성항

✓ 기포 병합 (coalescence), 기포 파열 (break-up), 벽면 비등 (nucleation)

$$\frac{\partial a_i}{\partial t} + \nabla \cdot (a_i V_g) = \frac{2}{3} \frac{a_i}{\alpha \rho_g} \left[ \Gamma_{ig} - \alpha \frac{d\rho_g}{dt} \right] + \frac{36\pi}{3} \left( \frac{\alpha}{a_i} \right)^2 \left( \phi_n^{CO} + \phi_n^{BK} \right) + \pi d_{Bw}^2 \phi_n^{NUC}$$

### ○ Bubble Coalescence

- Random Collision
- Wake Entrainment



$$\phi_{RC} = -\frac{1}{3\psi} \left( \frac{\alpha_g}{a_i} \right)^2 f_{RC} n_b \lambda_c$$

[Collision Frequency] X [Number] X [Coalescence Efficiency]

$$\phi_{WE} = -\frac{1}{3\psi} \left( \frac{\alpha_g}{a_i} \right)^2 f_{WE} n_b \lambda_c$$

[Collision Frequency] X [Number] X [Coalescence Efficiency]

## □ 계면 면적 수송 방정식

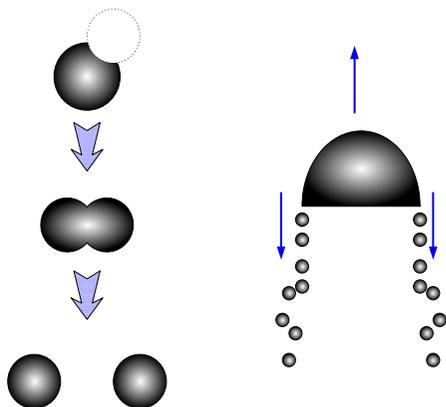
- 생성항

✓ 기포 병합 (coalescence), 기포 파열 (break-up), 벽면 비등 (nucleation)

$$\frac{\partial a_i}{\partial t} + \nabla \cdot (a_i V_g) = \frac{2}{3} \frac{a_i}{\alpha \rho_g} \left[ \Gamma_{ig} - \alpha \frac{d\rho_g}{dt} \right] + \frac{36\pi}{3} \left( \frac{\alpha}{a_i} \right)^2 \left( \phi_n^{CO} + \phi_n^{BK} \right) + \pi d_{Bw}^2 \phi_n^{NUC}$$

### ○ Bubble Break-up

- Turbulence eddy impact
- Shearing off



$$\phi_{TI} = \frac{1}{3\psi} \left( \frac{\alpha_g}{a_i} \right)^2 f_B n_e \lambda_B$$

[Collision Frequency] X [Eddy Number] X [Breakup Efficiency]

$$\phi_{TI} = \frac{\Gamma_{TI} \alpha (1 - \alpha) \varepsilon^{1/3}}{d_b^{5/3} (\alpha_{\max} - \alpha)} \exp\left( -\frac{K_B \sigma}{\rho_f d_b^{3/5} \varepsilon^{2/3}} \right)$$

$$\Gamma_{TI} = 0.0209 \quad K_B = 1.59$$

### □ 2-유체 모델 생성항 모델

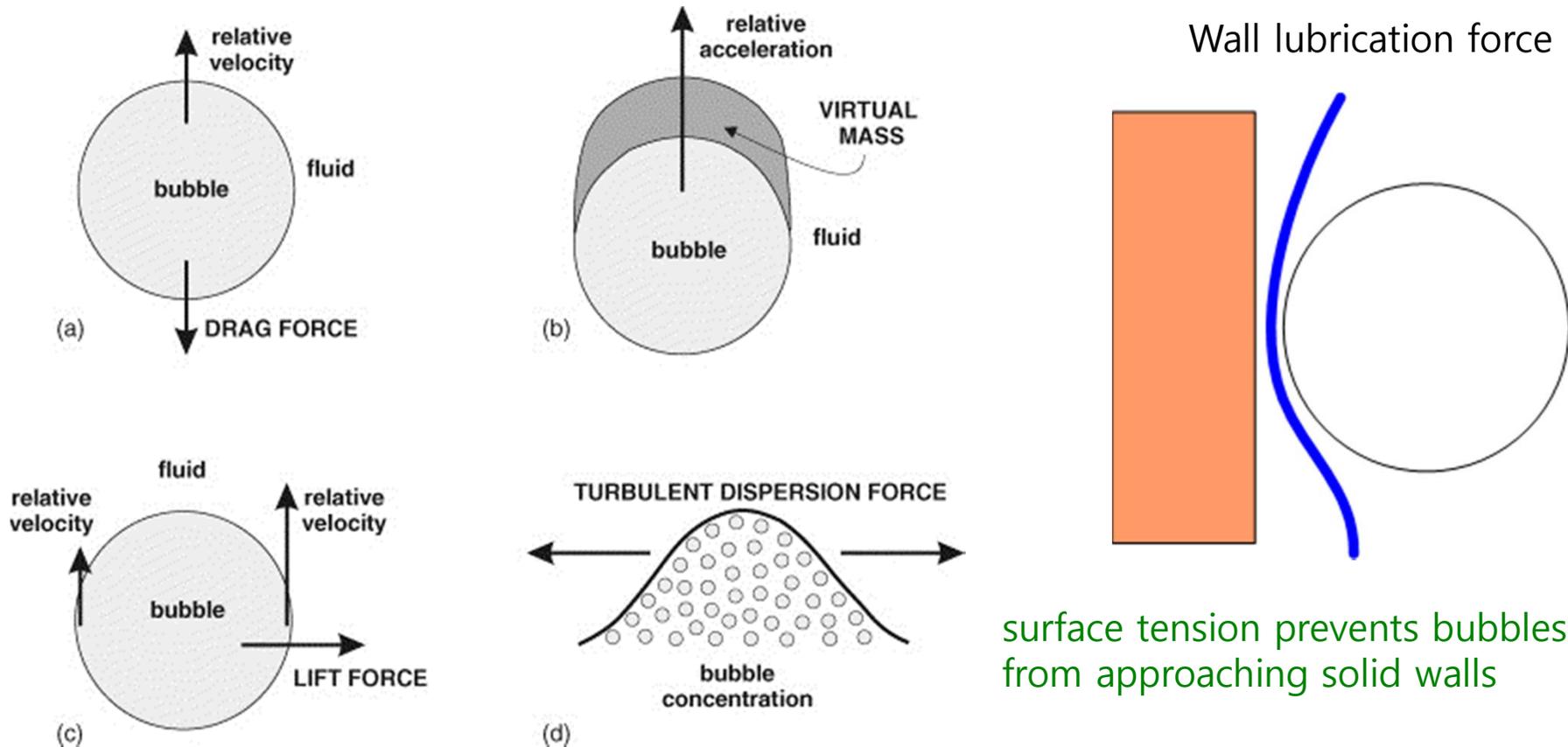
- 계면 형상 모델 (Interface topology)
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- 기포 기인 난류 (Bubble induced turbulence)

# Two-phase Flow Models

## □ 계면 견인력 (Interfacial non-drag force)

$$\underline{M}_{ig} = \Gamma_g \underline{u}_{gi} + \underline{M}_{drag,g} + \underline{M}_{vm,g} + \underline{M}_{lift,g} + \underline{M}_{td,g} + \underline{M}_{wl,g} \Rightarrow \text{Interfacial non-drag forces}$$

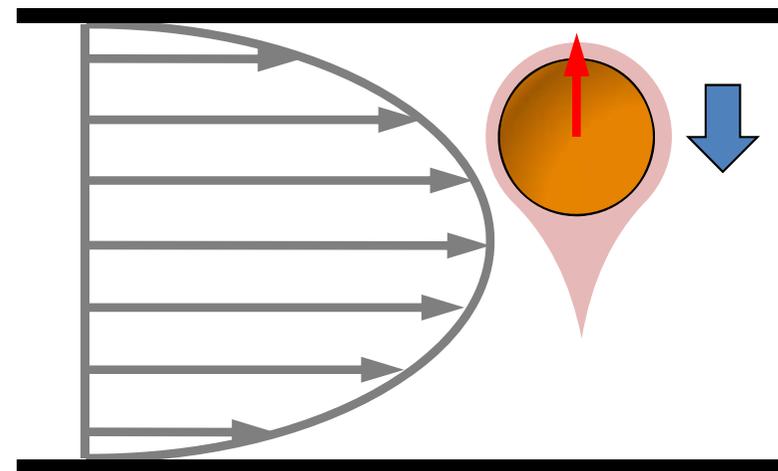
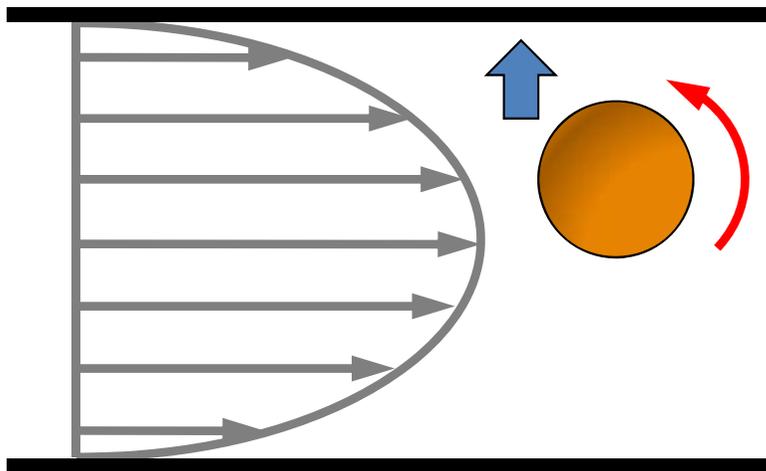
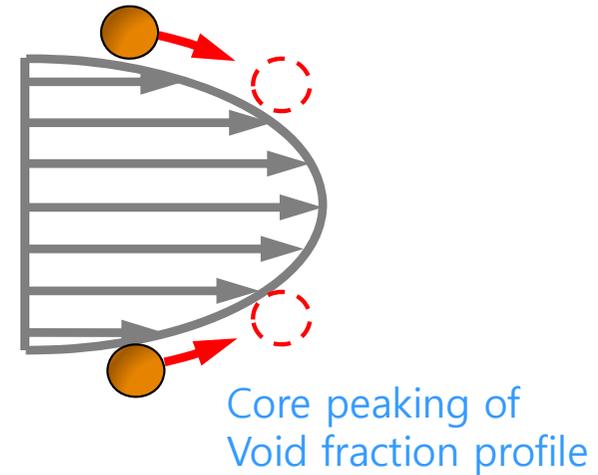
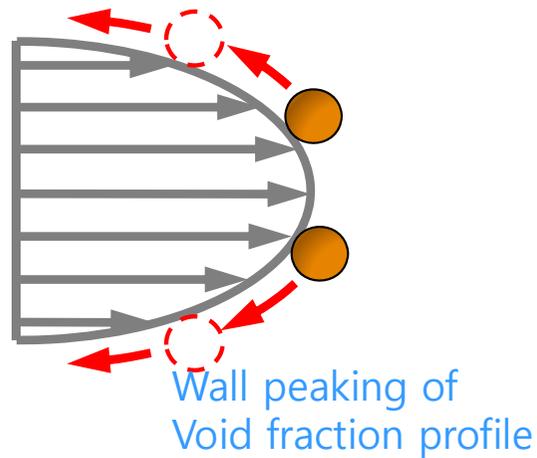
Interfacial momentum transfer terms



# Two-phase Flow Models

## □ 계면 견인력 (Interfacial non-drag force)

$$\underline{M}_{ig} = \Gamma_g \underline{u}_{gi} + \underline{M}_{drag,g} + \underline{M}_{vm,g} + \underline{M}_{lift,g} + \underline{M}_{td,g} + \underline{M}_{wl,g}$$



# Two-phase Flow Models

## □ 계면 견인력 (Interfacial non-drag force)

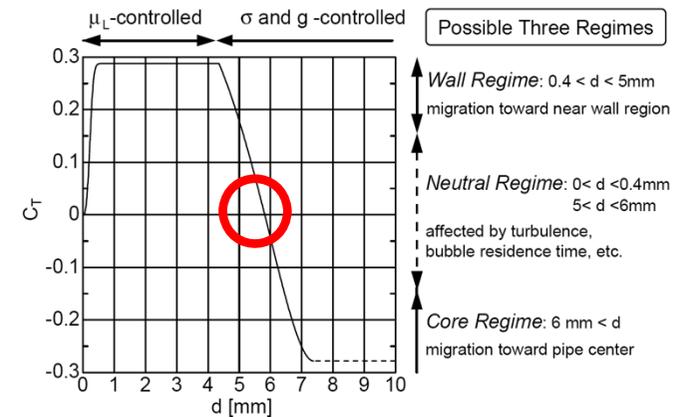
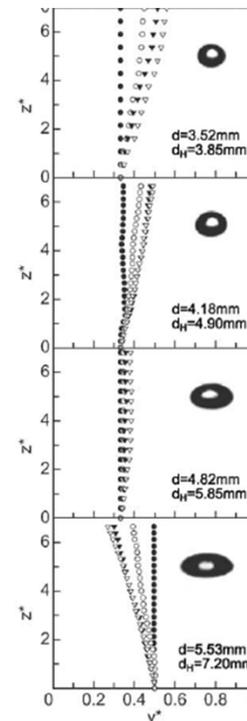
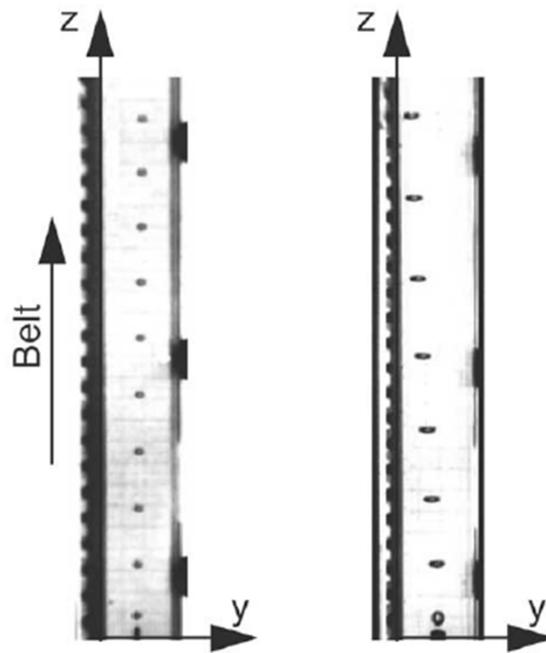
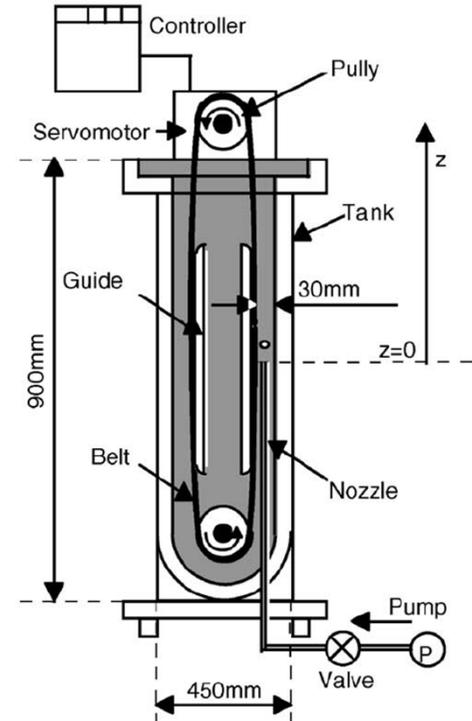
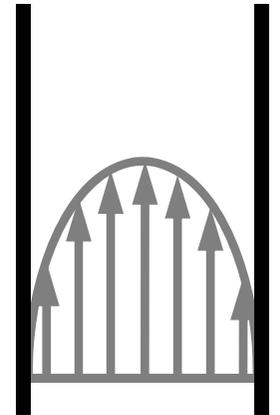
$$\underline{M}_{ig} = \Gamma_g \underline{u}_{gi} + \underline{M}_{drag,g} + \underline{M}_{vm,g} + \underline{M}_{lift,g} + \underline{M}_{td,g} + \underline{M}_{wl,g}$$

$$\underline{M}_{lift,g} = \alpha_g \rho_l C_{lift} (\underline{u}_g - \underline{u}_l) \otimes (\vec{\nabla} \otimes \underline{u}_l) = -\underline{M}_{lift,l}$$

Axial liquid velocity gradient



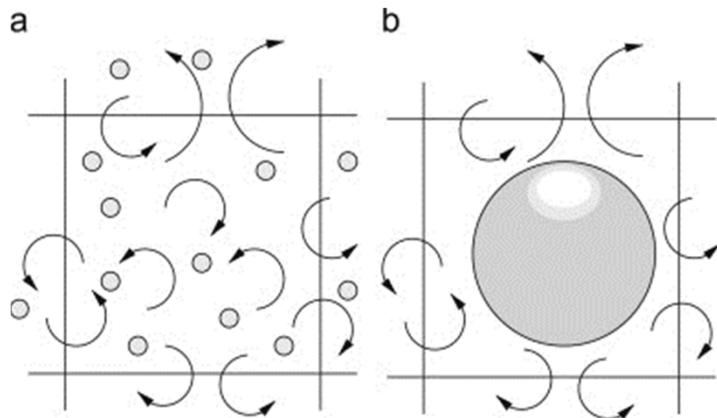
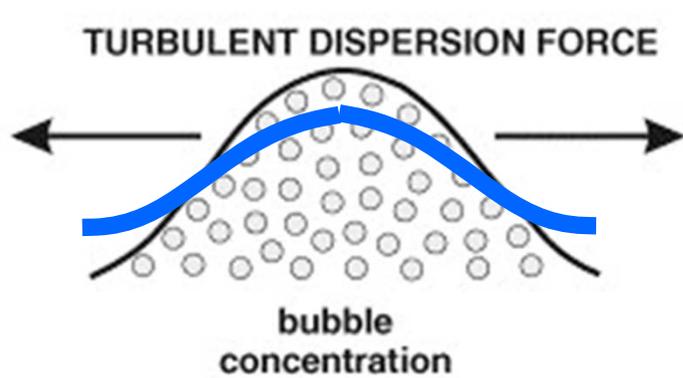
Lateral directional force acting on a bubble



# Two-phase Flow Models

## □ 계면 견인력 (Interfacial non-drag force)

$$\underline{M}_{ig} = \Gamma_g \underline{u}_{gi} + \underline{M}_{drag,g} + \underline{M}_{vm,g} + \underline{M}_{lift,g} + \underline{M}_{td,g} + \underline{M}_{wl,g}$$



$$\underline{M}_{td,g} = C_{TD} \rho_l k_l \nabla \alpha_g$$

Turbulent dispersion coefficient

Turbulent kinetic energy

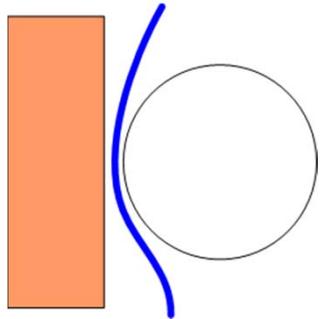
From turbulence model

Void fraction gradient

# Two-phase Flow Models

## □ 계면 견인력 (Interfacial non-drag force)

$$\underline{M}_{ig} = \Gamma_g \underline{u}_{gi} + \underline{M}_{drag,g} + \underline{M}_{vm,g} + \underline{M}_{lift,g} + \underline{M}_{td,g} + \underline{M}_{wl,g}$$



$$\underline{M}_{wl,g} = \frac{-\alpha_g \rho_l C_{wl} |\underline{u}_g - \underline{u}_l|^2}{D_b} \max\left(0, C_1 + C_2 \frac{D_b}{y_{wall}}\right) \vec{n}$$

Wall lubrication coefficient

Bubble diameter

$$C_1 = -0.01$$

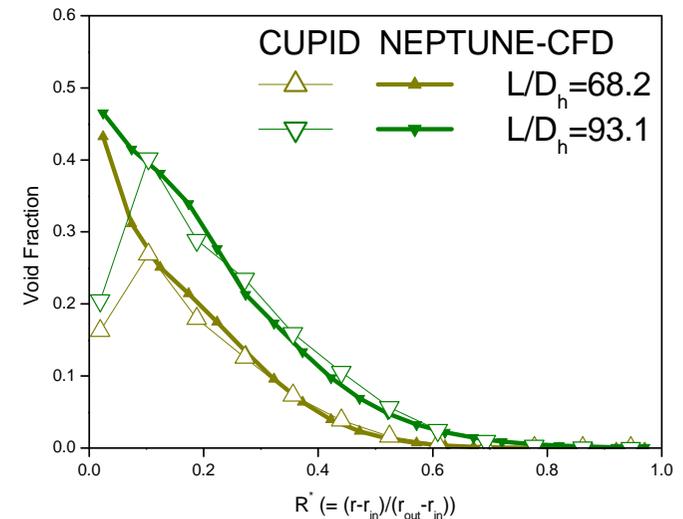
$$C_2 = 0.05$$

Distance from the wall

Effective only near the wall

Surface tension prevents bubbles from approaching solid walls

This force is analogous to a lubrication force and acts on a bubble near a wall to prevent the bubble from touching the wall

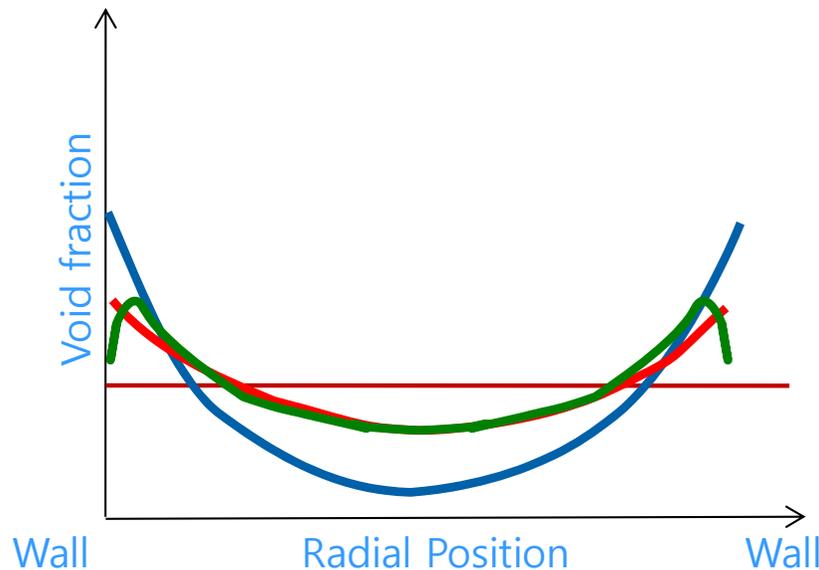


# Two-phase Flow Models

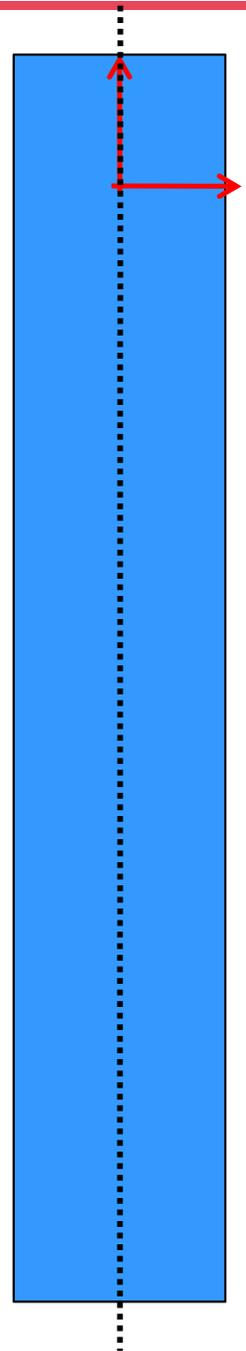
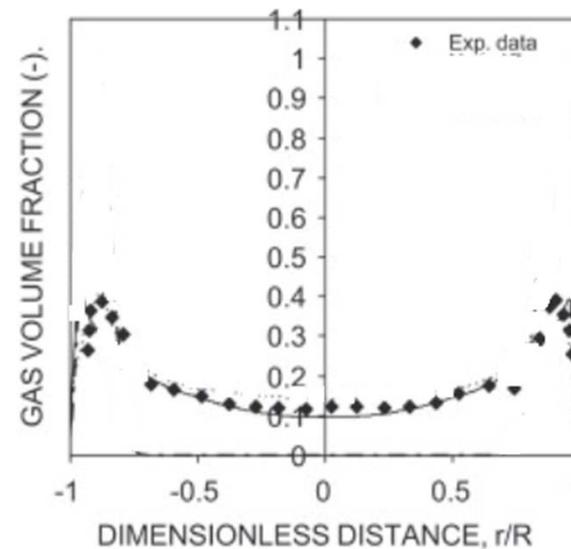
## □ 계면 견인력 (Interfacial non-drag force)

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- Radial directional profile
- Low pressure, bubble diameter 1 mm
  - 1) Only with lift force
  - 2) 1) + turbulent dispersion force
  - 3) 2) + wall lubrication force



Example of the void fraction profile in an air-water flow



### □ 2-유체 모델 생성항 모델

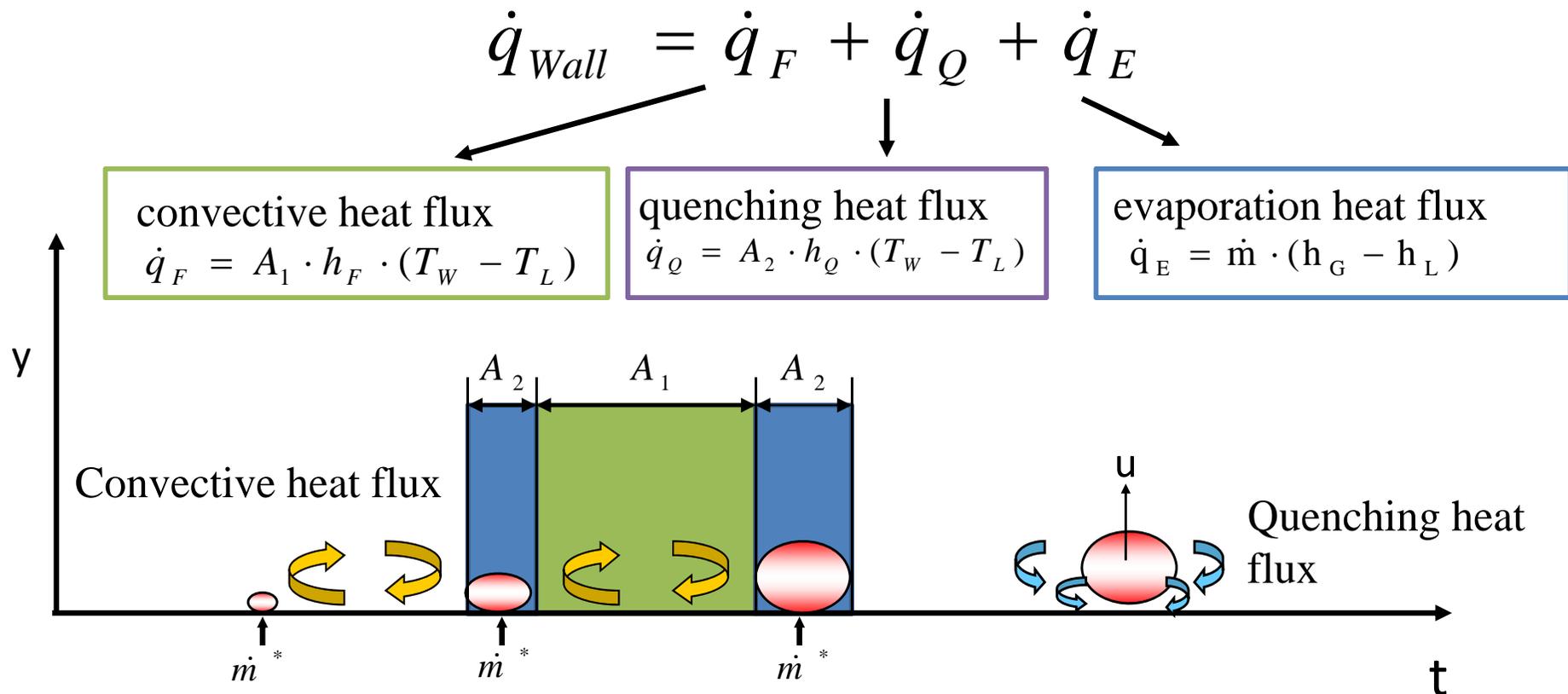
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# Two-phase Flow Models

## □ 벽면 열분배 모델 (Wall heat partitioning model)

- RPI 모델

✓ IR 카메라 및 ITO 가열 기법을 활용한 실험

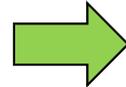
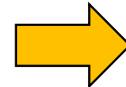


## Two-phase Flow Models

### □ 벽면 열분배 모델 (Wall heat partitioning model)

- RPI 모델

$$q_{wall} = q_Q + q_E + q_F$$



Added to the source term of the liquid energy equation

Added to the mass source term

$$\dot{q}_F = A_1 \cdot h_F \cdot (T_W - T_L)$$

$$\dot{q}_Q = A_2 \cdot h_Q \cdot (T_W - T_L)$$

$$h_Q = 2f \sqrt{\frac{t_w \rho_L C_{PL} \lambda_L}{\pi}}$$

$$q_E = N'' f \left( \frac{\pi}{6} D_{b,depart}^3 \right) \rho_g h_{fg}$$

$N''$  Active nucleate site density

$f$  Bubble departure frequency

$D_{b,depart}$  Bubble departure diameter

$t_w$  Bubble waiting time

$A_1$  Single-phase H/T area

$A_2$  Two-phase H/T area

### □ 2-유체 모델 생성항 모델

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### □ 기포 기인 난류 (Bubble induced turbulence)

- Sato's model

$$\mu_L^{eff} = \mu_L^{mol} + \mu_L^{turb} + \mu_L^{bub}$$

$$\mu_L^{bub} = C_B \rho_L \alpha_G d_B |\mathbf{u}_G - \mathbf{u}_L|$$

- Modification of the two-equation model

$$S_L^k = \mathbf{F}_L^{drag} \cdot (\mathbf{u}_G - \mathbf{u}_L)$$

$$S_L^\varepsilon = C_{\varepsilon B} \frac{S_L^k}{\tau}$$

## 기포 기인 난류 (Bubble induced turbulence)

- Two-phase wall function

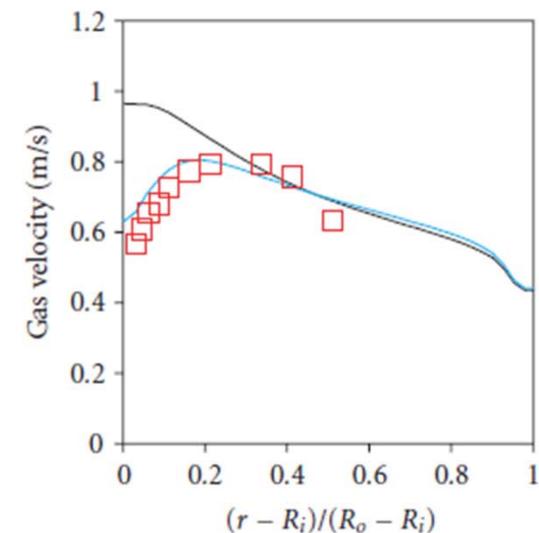
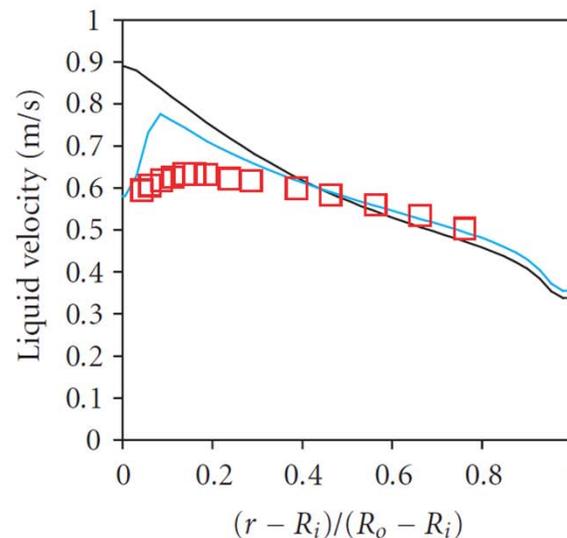
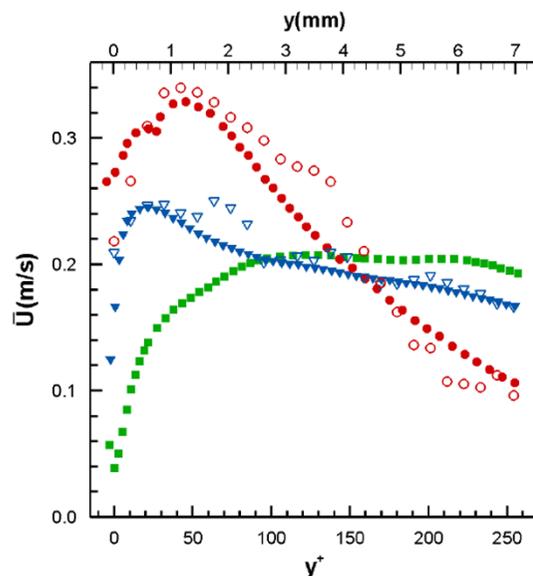
- ✓ Surface roughness analogy
- ✓ Nucleating bubbles on the wall disturb the boundary layer

$$u^+ = \frac{1}{\kappa} \ln(y^+) + B - \Delta u^+$$

$$\Delta u^+ = \begin{cases} \frac{1}{\kappa} \ln(1 + C_{kr} y_r^+); & y_r^+ > 11.3 \\ 0; & y_r^+ \leq 11.3 \end{cases}$$

$$y_r^+ = \frac{\rho_l y_r u_\tau}{\mu_l} \qquad y_r = \eta d_{bw} \left( \frac{\Phi_{nb}}{\Phi_w} \right)^5 = \eta d_{bw} \left( 1 - \frac{\Phi_C}{\Phi_w} \right)^5$$

Texas A&M experiment



- 원자력 계의 다차원 2상 유동 해석 현황 소개
  - 2상 유동 CFD의 필요성
  - 2-유체 모델의 주요 생성항