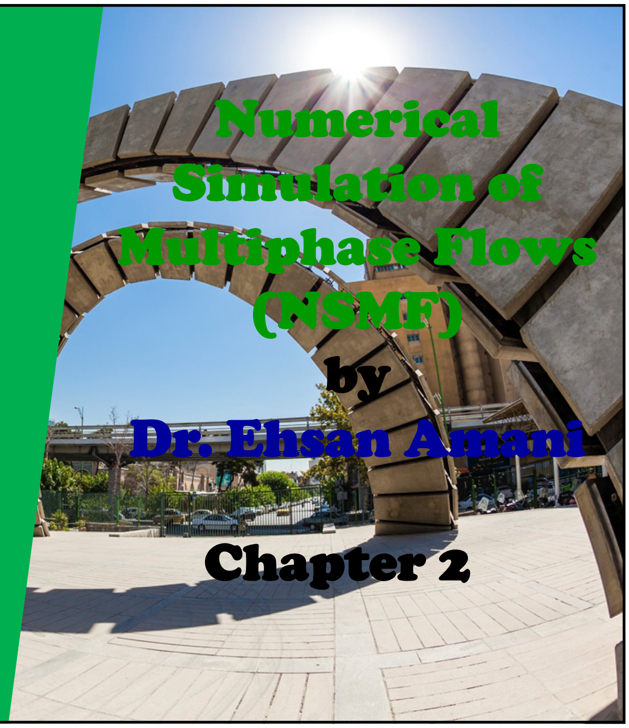


Numerical Simulation of Multiphase Flows (NSMF)

by

Dr. Ehsan Amani

Chapter 2

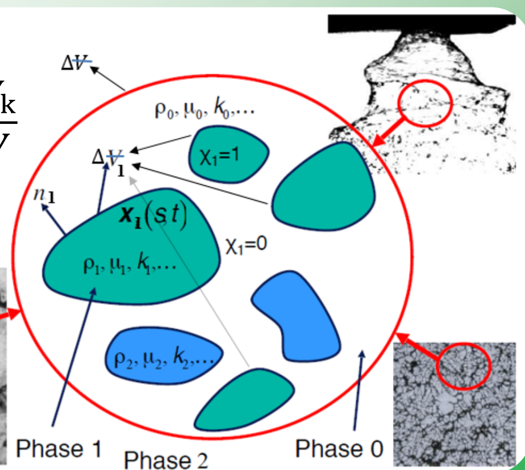
Hands-on practice

- **HW#1:**
  - ✓ **Fluent installation and preliminary practice**

Volume fraction

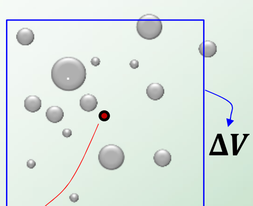
- Definition:

$$\alpha_k(\boldsymbol{x},t)=\frac{\Delta V_k}{\Delta V}$$



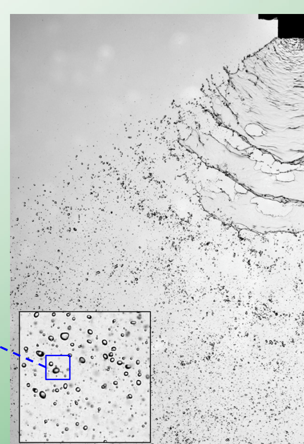
Volume fraction

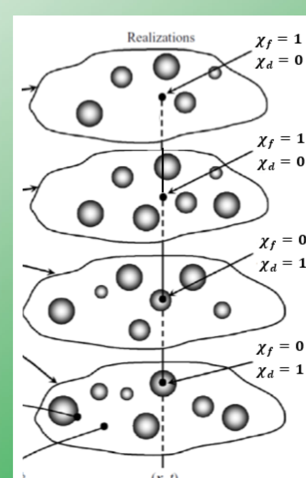
- A better alternative:



$(\vec{x},t)$

$$\alpha_k(\boldsymbol{x},t)=\frac{\Delta V_k}{\Delta V}$$



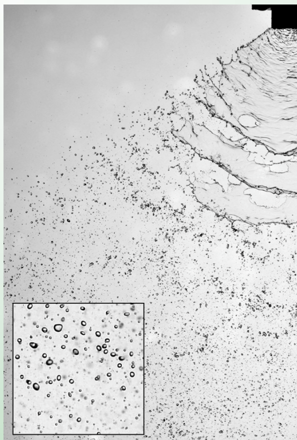


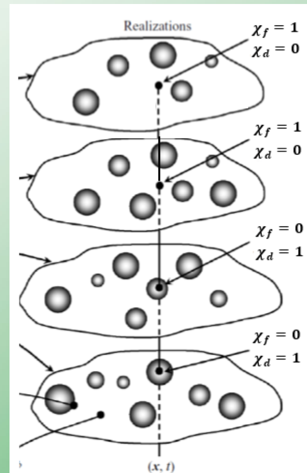
Volume fraction

- A better alternative:

Phase indicator function

$$\chi_k(\boldsymbol{x},t) = \begin{cases} 1 & ; (\boldsymbol{x},t) \text{ is in phase } k \\ 0 & ; \text{otherwise} \end{cases}$$





$$\alpha_k(\boldsymbol{x},t) = \langle \chi_k(\boldsymbol{x},t) \rangle$$

$\langle . \rangle$

Ensemble averaging operator

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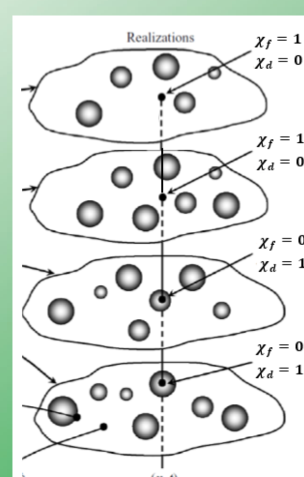
Basic concepts and key definitions

- Volume fraction (continued)

⇨ **Lecture Notes: 2.1**

- Averaging operators in multiphase flows

⇨ **Lecture Notes: 2.2**



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Different kinds of averaging

	Statistical (ensemble-based) Naud (2000)	Volume-based [2,5,6]	Kernel-based Capecelatro (2013)
Average	$\bar{Q}_{\mathrm{k}} \equiv \langle Q_{\mathrm{k}}\chi_{\mathrm{k}}\rangle$	$\bar{Q}_{\mathrm{k}} \equiv \frac{1}{\Delta V}\int_{\Delta V_k} Q_{\mathrm{k}}\, dV$	$\bar{Q}_{\mathrm{k}} \equiv \int_D \chi_{\mathrm{k}}(\vec{y}) Q_{\mathrm{k}}(\vec{y}) \times k(\lvert\vec{x}-\vec{y}\rvert)\, d\vec{y}$
Phasic average	$\langle Q\rangle_{\mathrm{\lvert k}} \equiv \frac{\langle Q_{\mathrm{k}}\chi_{\mathrm{k}}\rangle}{\langle\chi_{\mathrm{k}}\rangle}$	$\langle Q\rangle_{\mathrm{\lvert k}} \equiv \frac{1}{\Delta V_k}\int_{\Delta V_k} Q_{\mathrm{k}}\, dV$	$\langle Q\rangle_{\mathrm{\lvert k}} \equiv \frac{\bar{Q}_{\mathrm{k}}}{\int_D \chi_{\mathrm{k}}(\vec{y}) k(\lvert\vec{x}-\vec{y}\rvert)\, d\vec{y}}$
Mass-weighted average	$\tilde{Q}_{\mathrm{k}} \equiv \frac{\overline{\rho_{\mathrm{k}} Q_{\mathrm{k}}}}{\overline{\rho_{\mathrm{k}}}}$	$\tilde{Q}_{\mathrm{k}} \equiv \frac{\overline{\rho_{\mathrm{k}} Q_{\mathrm{k}}}}{\overline{\rho_{\mathrm{k}}}}$	$\tilde{Q}_{\mathrm{k}} \equiv \frac{\overline{\rho_{\mathrm{k}} Q_{\mathrm{k}}}}{\overline{\rho_{\mathrm{k}}}}$
Mixture average	$\bar{Q} \equiv \sum_{k=1}^{N} \bar{Q}_{\mathrm{k}}$	$\bar{Q} \equiv \sum_{k=1}^{N} \bar{Q}_{\mathrm{k}}$	$\bar{Q} \equiv \sum_{k=1}^{N} \bar{Q}_{\mathrm{k}}$

Time average [5] $\bar{Q}^t \equiv \frac{1}{\Delta t}\int_{\Delta t_k} Q_{\mathrm{k}}\, dt$

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Basic concepts and key definitions

- For incompressible flows:

$$\tilde{Q}_{\mathrm{k}} \equiv \frac{\overline{\rho_{\mathrm{k}} Q_{\mathrm{k}}}}{\overline{\rho_{\mathrm{k}}}} = \frac{\langle\chi_{\mathrm{k}}\rho_{\mathrm{k}}Q_{\mathrm{k}}\rangle}{\langle\chi_{\mathrm{k}}\rho_{\mathrm{k}}\rangle} = \frac{\langle\chi_{\mathrm{k}}Q_{\mathrm{k}}\rangle}{\langle\chi_{\mathrm{k}}\rangle} = \langle Q\rangle_{\mathrm{\lvert k}} \qquad (15.2)$$

- Other key parameters
- Area-weighted averaging for channel flows

⇨ **Lecture Notes: 2.3**

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Non-dimensional parameters

- Several important parameters of multi-phase flows [9]:
  - Geometric scales
  - Phasic physical properties ratios:

$$\frac{\rho_1}{\rho_2}, \quad \frac{\mu_1}{\mu_2}, \ldots$$

  - Force ratios:

Reynolds number ← $Re = \frac{LU}{\upsilon_1} \sim \frac{\text{inertia force}}{\text{viscous force}}$

1 is usually taken as the liquid phase

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Non-dimensional parameters

- Several important parameters of multi-phase flows [9]:
  - Force ratios:

Reynolds number ← $Re = \frac{LU}{\upsilon_1} \sim \frac{\text{inertia force}}{\text{viscous force}}$

Weber number ← $We = \frac{\rho_1 L U^2}{\sigma} \sim \frac{\text{inertia force}}{\text{capillary force}}$

Froude number ← $Fr = \frac{U^2}{gL} \sim \frac{\text{inertia force}}{\text{gravity force}}$

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Non-dimensional parameters

- Several important parameters of multi-phase flows [9]:
  - Force ratios (dependent parameters):

Capillary number ← $Ca = \dfrac{\mu_1 U}{\sigma} = ReWe$

Eotvos number ← $Eo = \dfrac{\Delta\rho g L^2}{\sigma} = \dfrac{We}{Fr}$

Archimedes number ← $Ar = \dfrac{g\rho_1 \Delta\rho L^3}{\mu_1^2} = \dfrac{\Delta\rho}{\rho_1}\dfrac{Re^2}{Fr}$

▲ **For buoyancy-driven flows with no explicit reference velocity if**

$$U = \sqrt{(\Delta\rho/\rho_1)gL} \longrightarrow Ar = Re^2$$

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Non-dimensional parameters

- Several important parameters of multi-phase flows [9]:
  - Force ratios (dependent parameters):

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Archimedes number ← $Ar = \dfrac{g\rho_1 \Delta\rho L^3}{\mu_1^2} = \dfrac{\Delta\rho}{\rho_1}\dfrac{Re^2}{Fr}$

Ohnesorge number ← $Oh = \dfrac{\mu_1}{\sqrt{\rho_1 \sigma L}} = \dfrac{\sqrt{We}}{Re} = \dfrac{1}{\sqrt{La}} = \dfrac{1}{Z}$

Morton number ← $M = \dfrac{\Delta\rho g \mu_1^4}{\rho_1^2 \sigma^3} = \dfrac{Eo^3}{Ar^4} = Eo\dfrac{Re^4}{We^2}$

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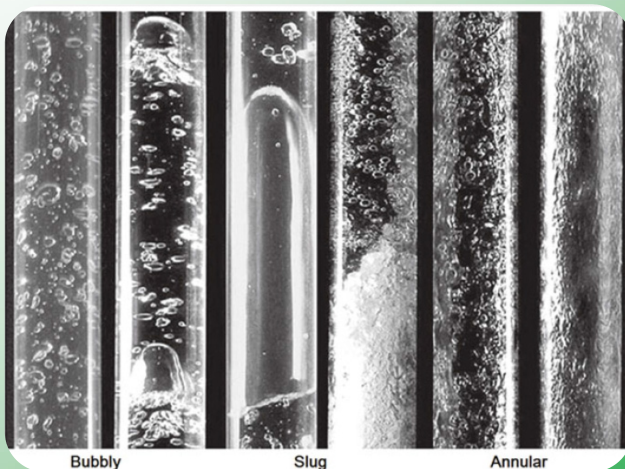
Regime diagrams

- Gas-liquid flow in vertical pipes



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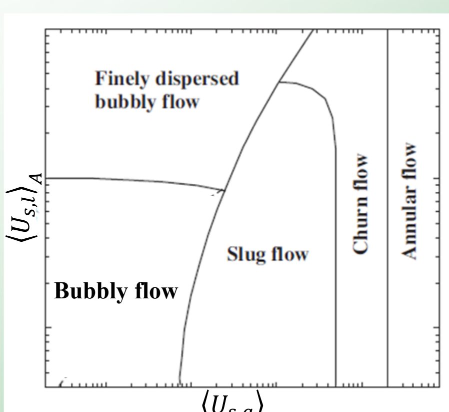
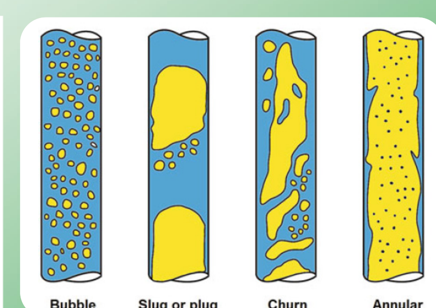
Regime diagrams

- Gas-liquid flow in vertical pipes





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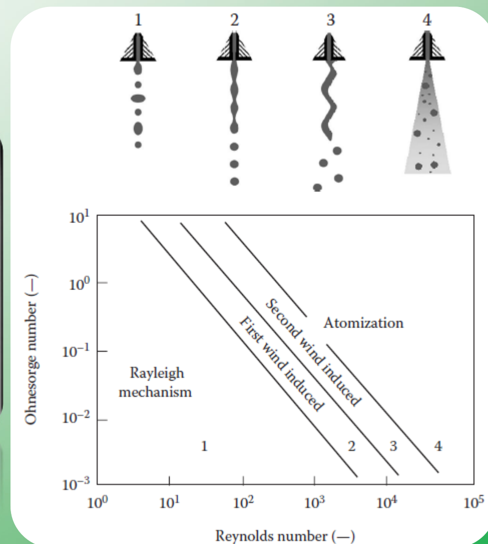
Regime diagrams

- Droplet generation



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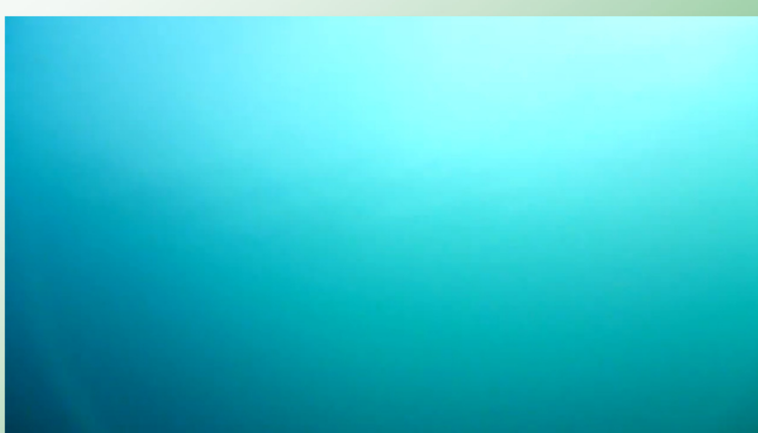
Regime diagrams

- Rising bubbles, falling drops



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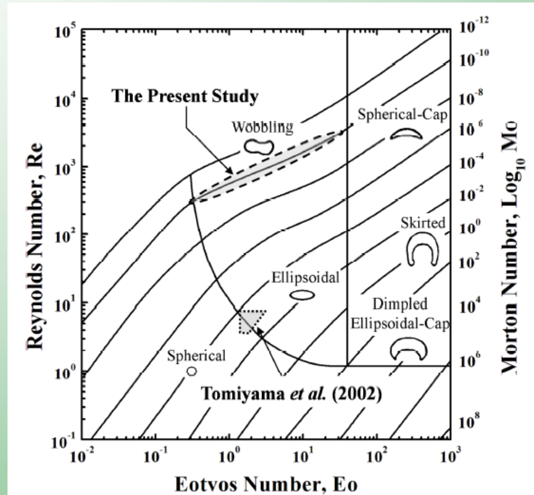
Regime diagrams

- Rising bubbles, falling drops



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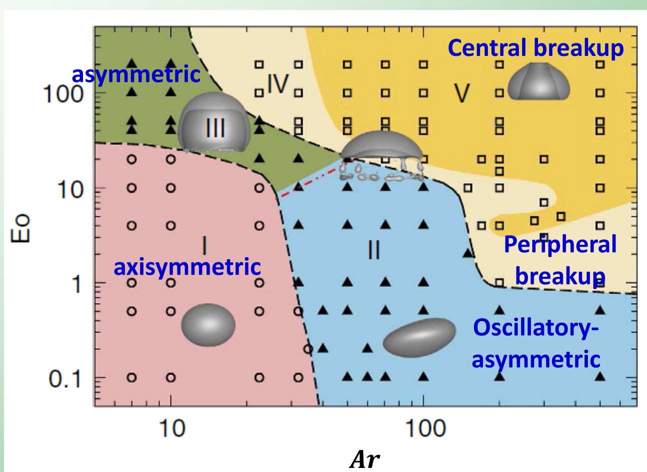
Regime diagrams

- Rising bubbles, falling drops



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Regime diagrams

- Gas-solid flow in horizontal ducts

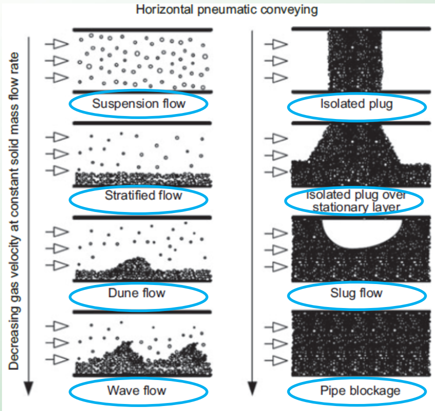

Figure 1 Schematics of flow regimes for horizontal gas-solids conveying systems.

Table 1 Flow regimes for horizontal gas-solids conveying systems.

Flow regime	Characteristics
Dilute (lean) phase	Discrete particle conveying, suspension flow, uniform distribution of solids.
Stratified flow	The pipe bottom occupied by stationary or moving particle layer.
Dune flow	Subregime of the stratified flow when the upper part of the layer creates dune.
Wavy flow	Subregime of the stratified flow when the upper part of the layer creates waves.
Isolated plugs	Particles transported as isolated plugs which are separated by air gaps.
Isolated plugs over stationary layer	Particles transported as isolated plugs over stationary layer.
Slug flow	Particles are transported with the help of bubbles on the upper part of the pipe with stationary layer at the pipe bottom.
Blockage	No ability for particle flow.

⇨ Regime diagram? (HW)

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Hands-on practice

- **HW#2:**
  - **Python installation**
  - **CFD with python (preliminary experience)**
  - **Getting familiar with the python NS solver "NSMF1.py"**
  - **Finding resources on the Net**

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