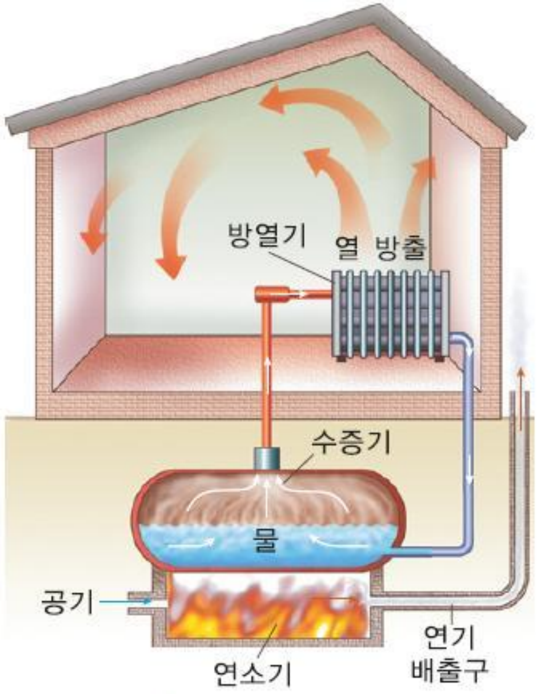
2상유동 열전달 공학
Two-phase flow and heat transfer Engineering

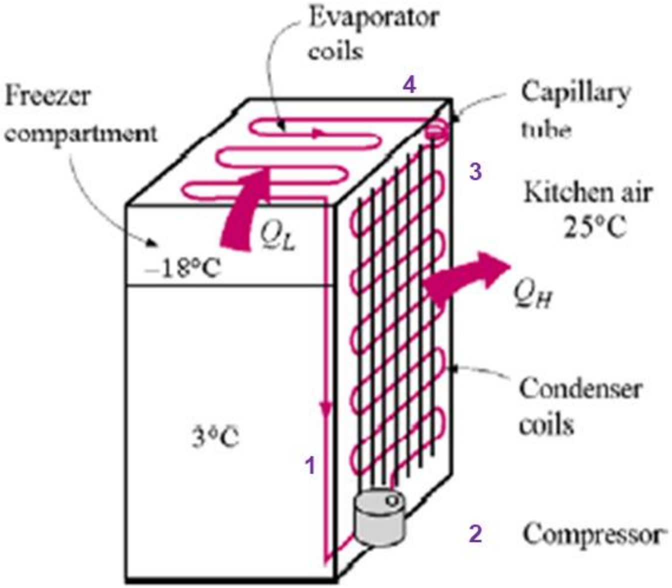
2022년 1학기

서울대학교 원자핵공학과
조형규

Two-phase flows in our daily life

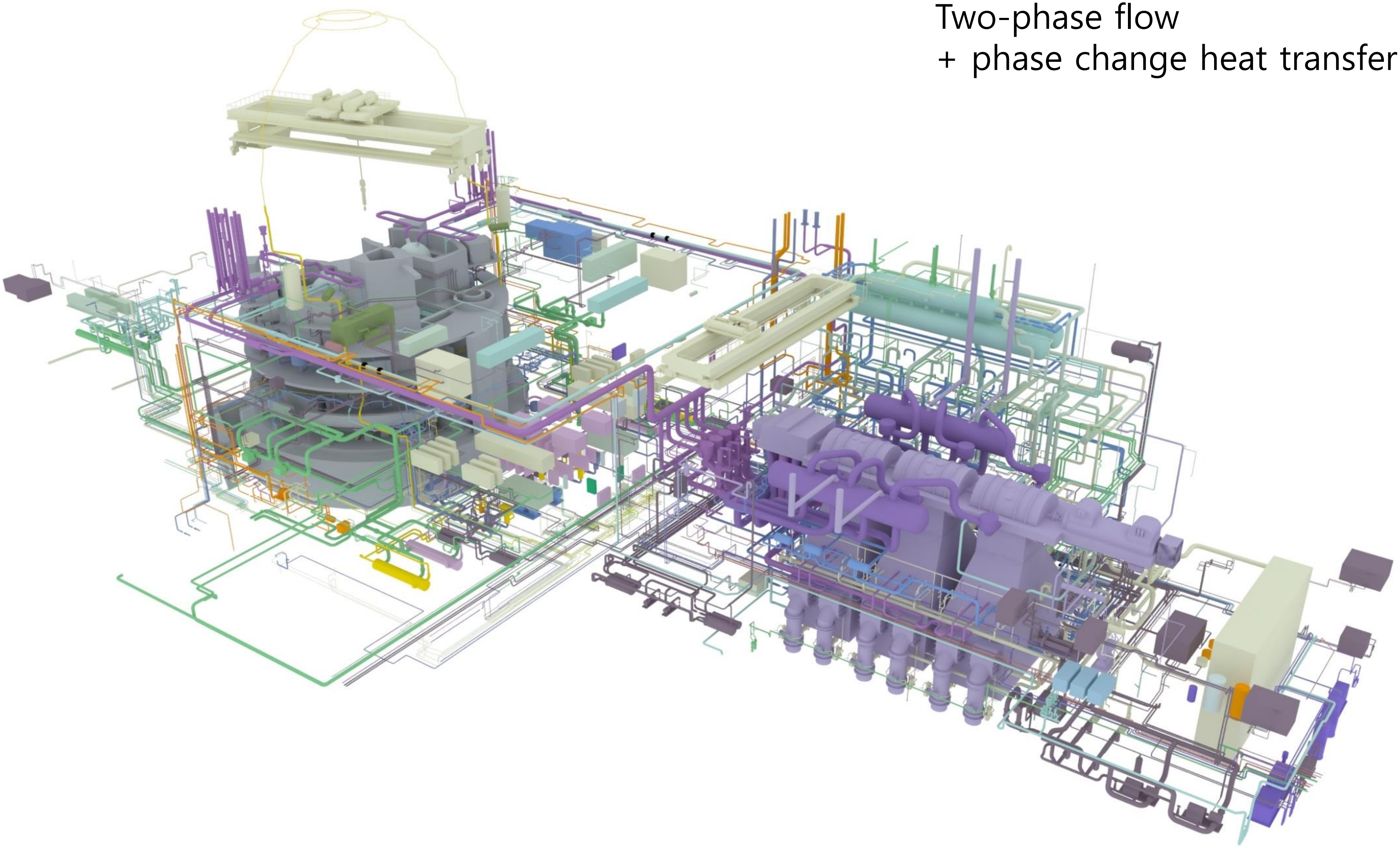


스팀 난방의 원리

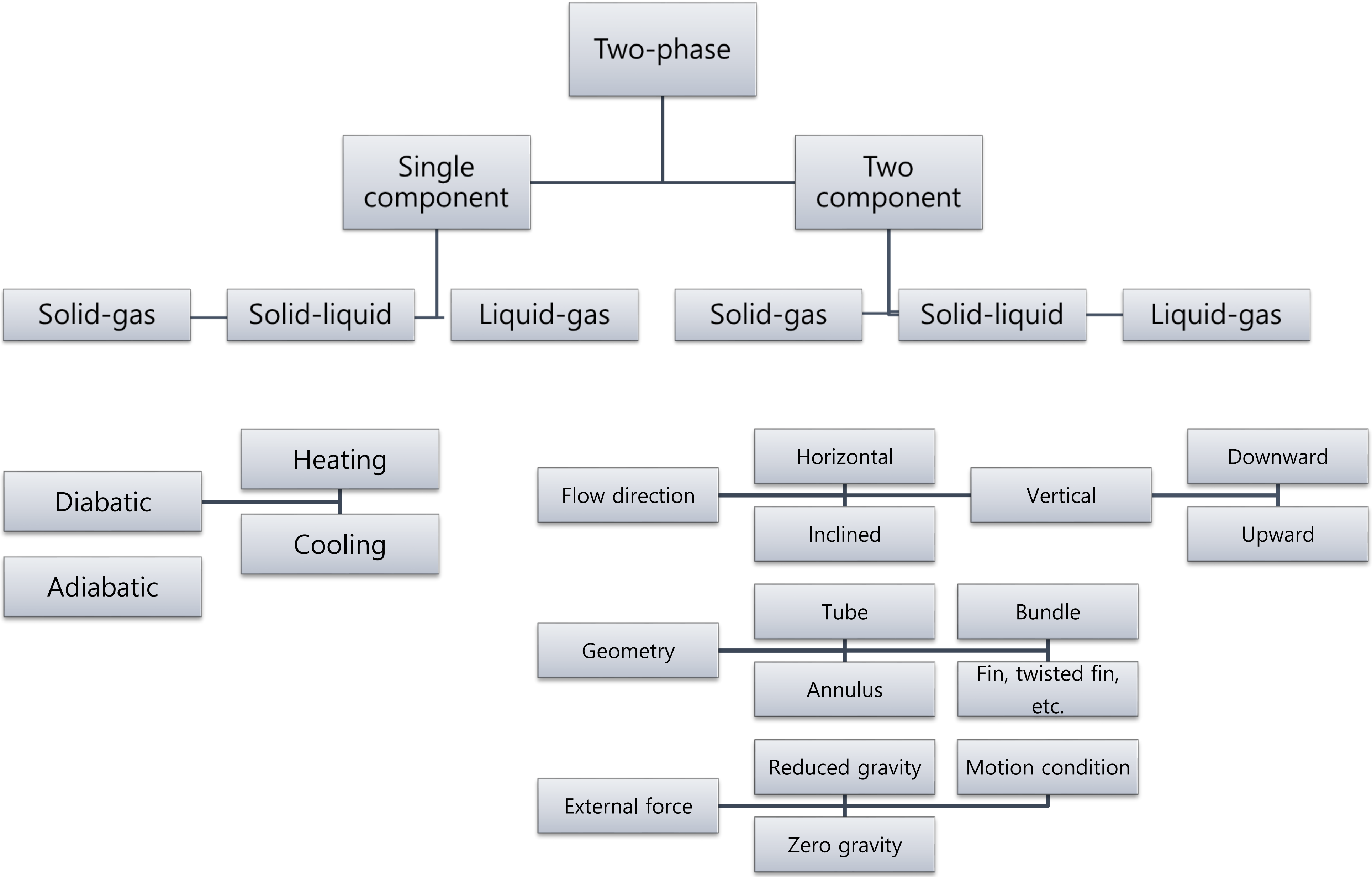


Two-phase flow in nuclear system

Two-phase flow
+ phase change heat transfer



Classification of Two-Phase Flow

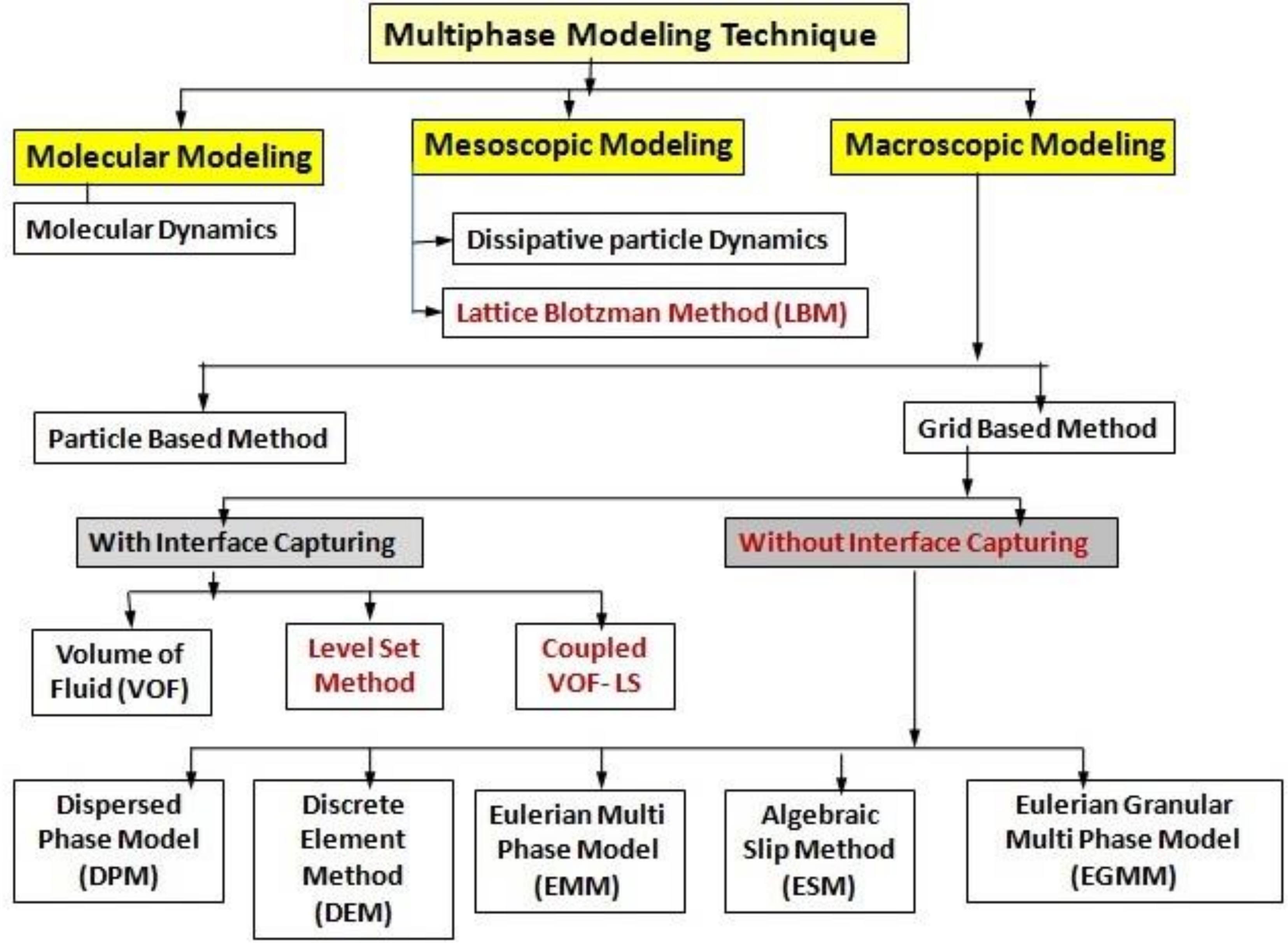


- Two-phase
  - Single component
    - Solid-gas
    - Solid-liquid
    - Liquid-gas
  - Two component
    - Solid-gas
    - Solid-liquid
    - Liquid-gas

- Diabatic
  - Heating
  - Cooling
- Adiabatic

- Flow direction
  - Horizontal
  - Inclined
  - Vertical
    - Downward
    - Upward
- Geometry
  - Tube
  - Annulus
  - Bundle
  - Fin, twisted fin, etc.
- External force
  - Reduced gravity
  - Zero gravity
  - Motion condition

Classification of Two-Phase Flow Modelling



Multiphase Modeling Technique

Molecular Modeling

Molecular Dynamics

Mesoscopic Modeling

Dissipative particle Dynamics

Lattice Blotzman Method (LBM)

Macroscopic Modeling

Particle Based Method

Grid Based Method

With Interface Capturing

Volume of Fluid (VOF)

Level Set Method

Coupled VOF- LS

Without Interface Capturing

Dispersed Phase Model (DPM)

Discrete Element Method (DEM)

Eulerian Multi Phase Model (EMM)

Algebraic Slip Method (ESM)

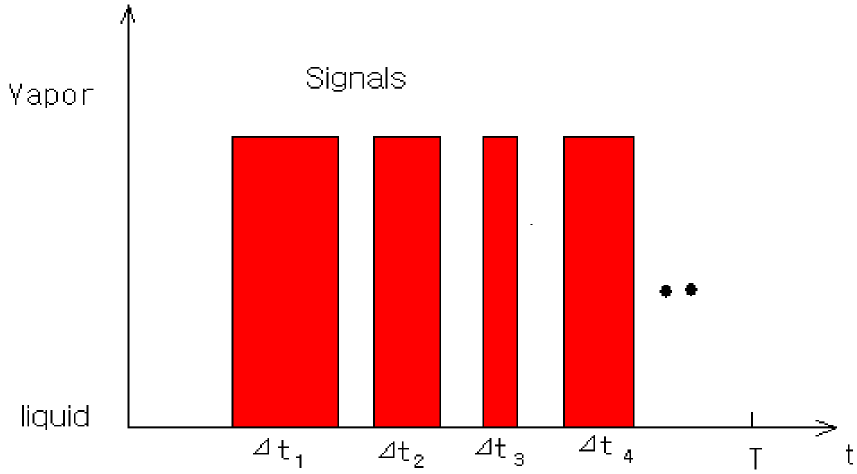
Eulerian Granular Multi Phase Model (EGMM)

https://cfdflowengineering.com/basics-of-multi-phase-flow-and-its-cfd-modeling/

Basic Parameters

❖ Void fraction

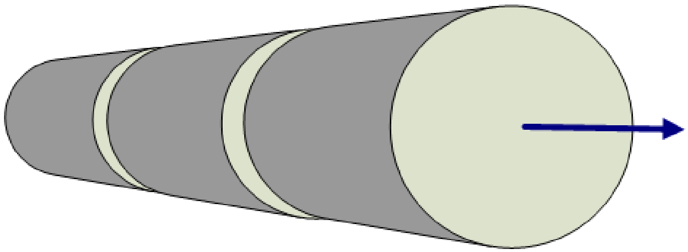
- ✓ Volume fraction of gas
- ✓ In a local instantaneous analysis
  - ▪ Delta function
- ✓ Averaged void fraction
  - ▪ Time averaged
  - ▪ Volume averaged
  - ▪ Area averaged



$$\alpha(\mathbf{x}) = \frac{1}{T}\sum_{i=1}^{N}\Delta t_i$$

$$\alpha(\mathbf{x}) = \frac{1}{T}\int_{t-T}^{t} X_v(\mathbf{x},t')\,dt'$$

$$X_v(\mathbf{x},t) = \begin{cases} 1 & \text{when vapor is at point } \mathbf{x} \text{ at time } t \\ 0 & \text{otherwise} \end{cases}$$



- ✓ In one-dimensional approaches,
  - ▪ Area averaging is necessary!

Basic Parameters

❖ Void fraction

- ✓ Volume average

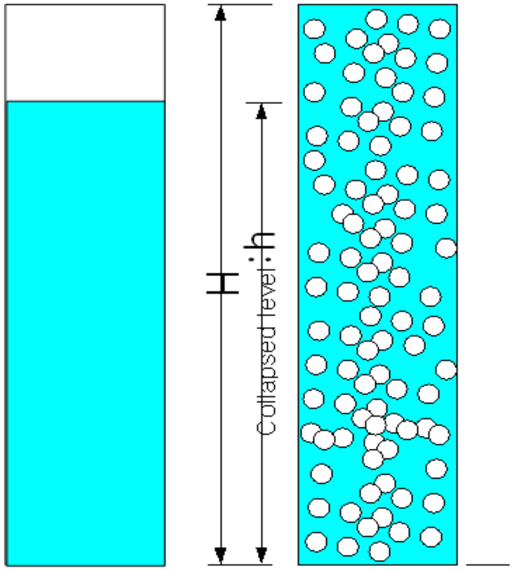
$$<< \alpha(t) >> = \frac{1}{V}\iint_V \alpha(X,t)\,dv = \frac{V_g}{V_l + V_g}$$

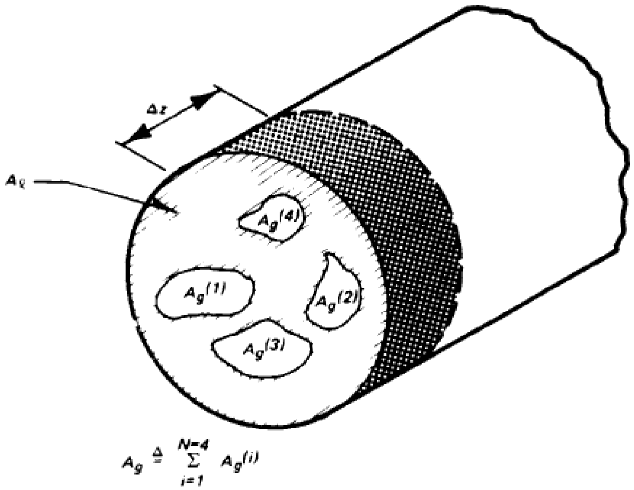
- ✓ Area-averaged void fraction

$$< \alpha(t) > = \frac{\Delta z \iint_{A_g} dA}{\Delta z \iint_A dA} = \frac{A_g}{A_l + A_g}$$

- ✓ Void fraction range

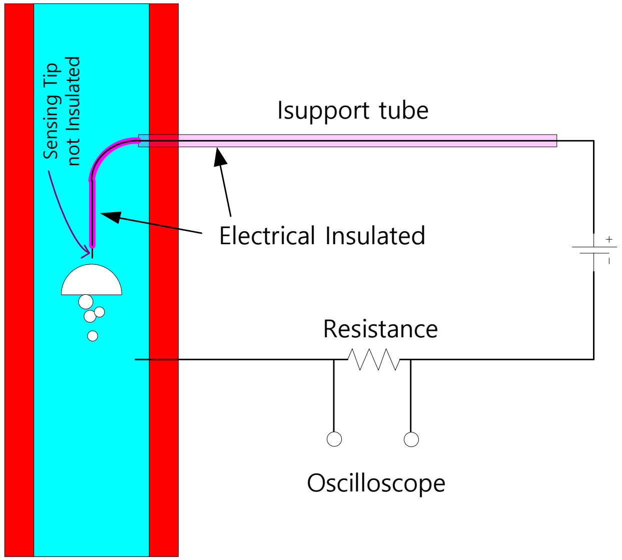
$$0 \le \alpha \le 1$$

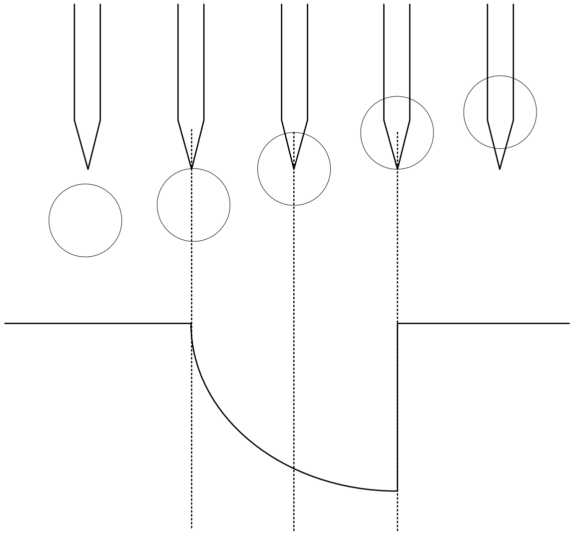


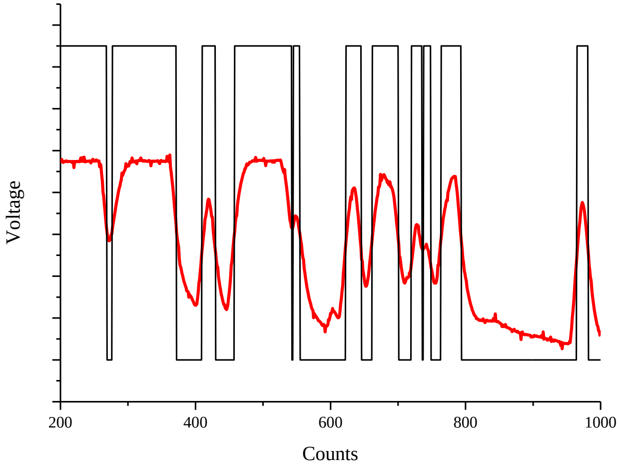


Basic Parameters

- Void fraction measurement





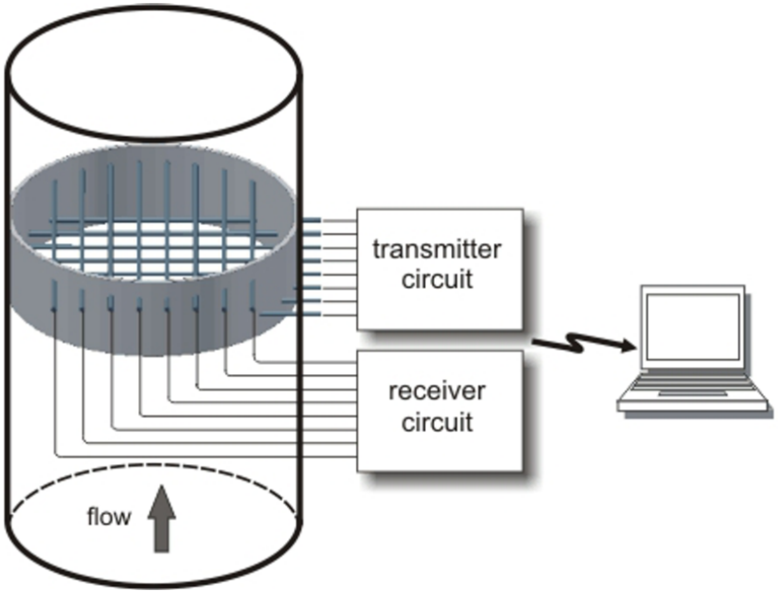


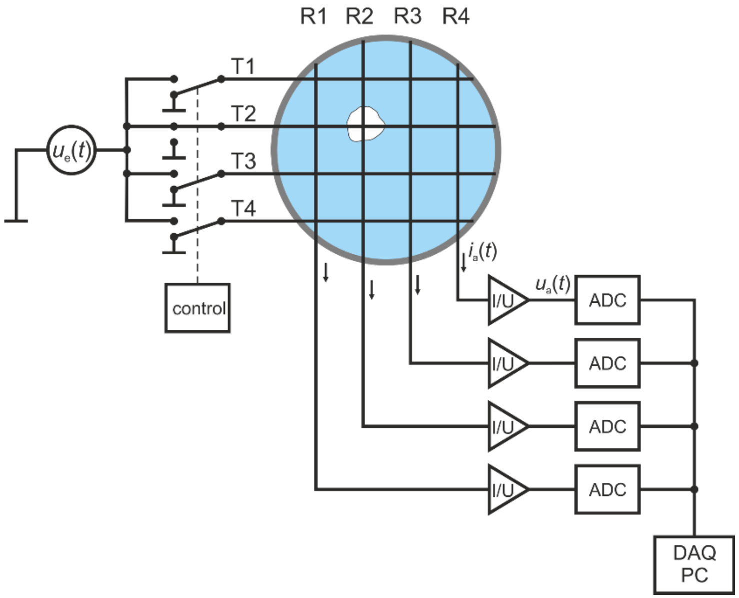
Basic Parameters

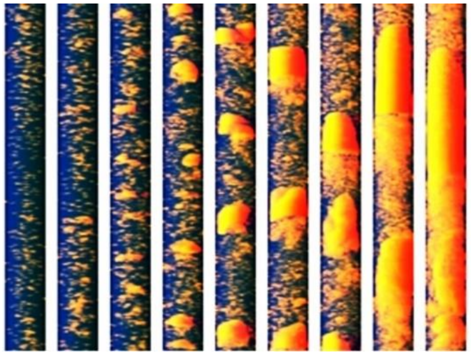
❖ Void fraction measurement

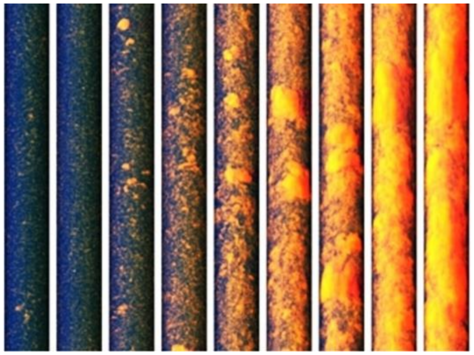
https://www.hzdr.de/db/Cms?pOid=55368&pNid=393

- ✓ Wire mesh sensor



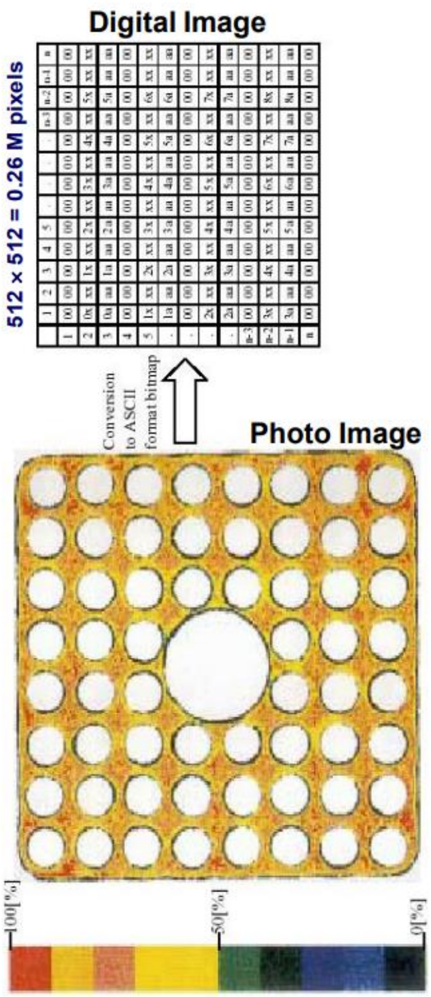


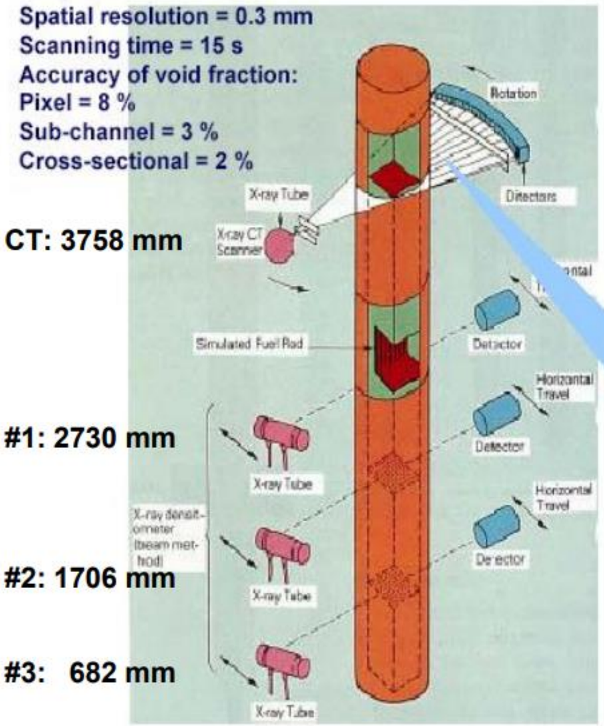


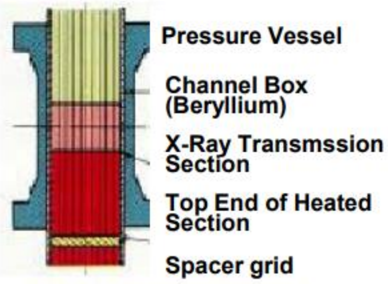


Basic Parameters

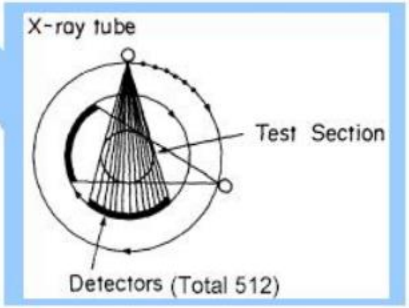
- Void fraction measurement
  - ✓ Gamma ray or x-ray densitometer




Spatial resolution = 0.3 mm
Scanning time = 15 s
Accuracy of void fraction:
Pixel = 8 %
Sub-channel = 3 %
Cross-sectional = 2 %



X-ray CT scanning section



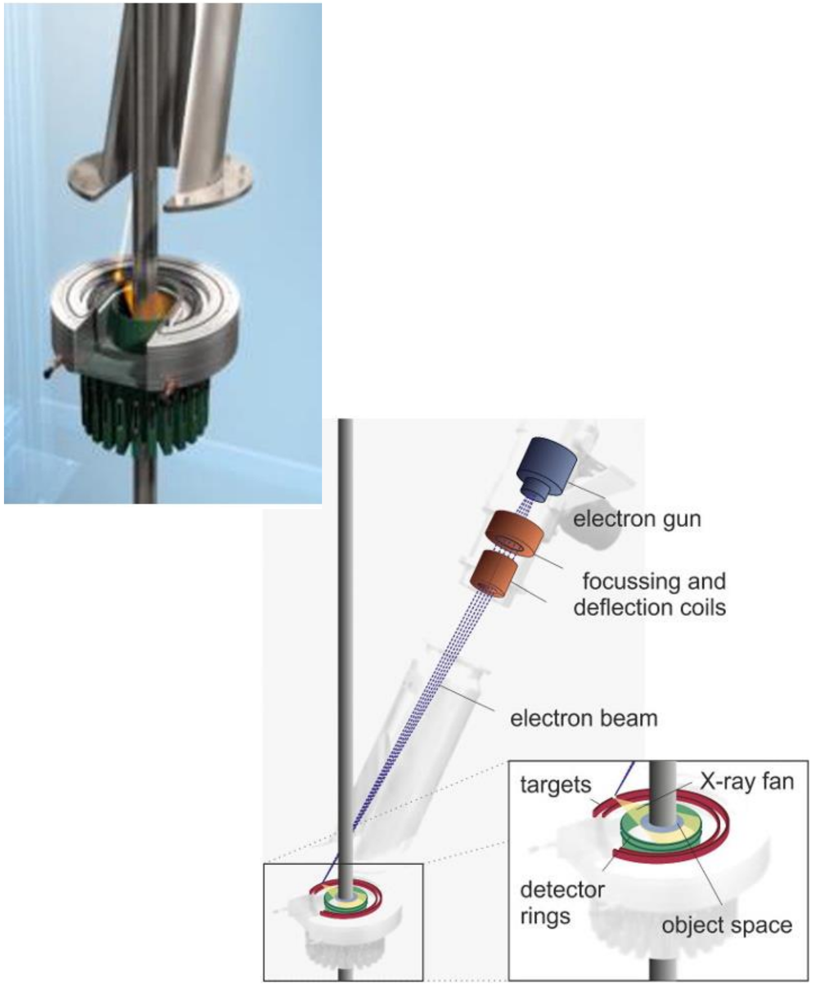
X-ray CT scanning method

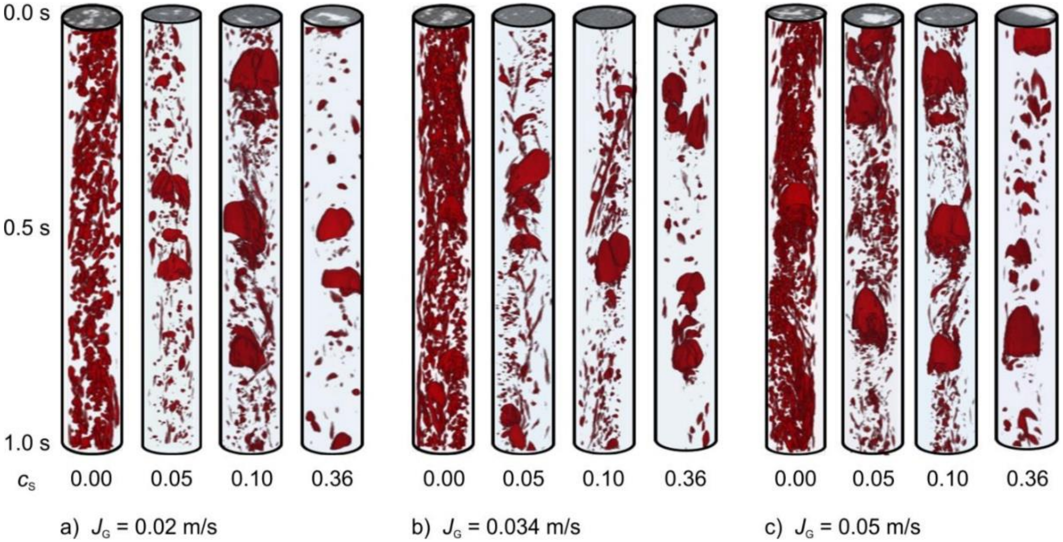
Scan method	360° rotation with pulse X-rays
Type of X-ray beam	Fan-shaped X-ray beam of 34° radiation angle
Voltage of X-ray tube	Max. 120 kV
Current	Max 400mA
Scanning time	15s
Scanning region	D=300 mm
Dimensions of reconstruction element	0.3mm X 0.3mm

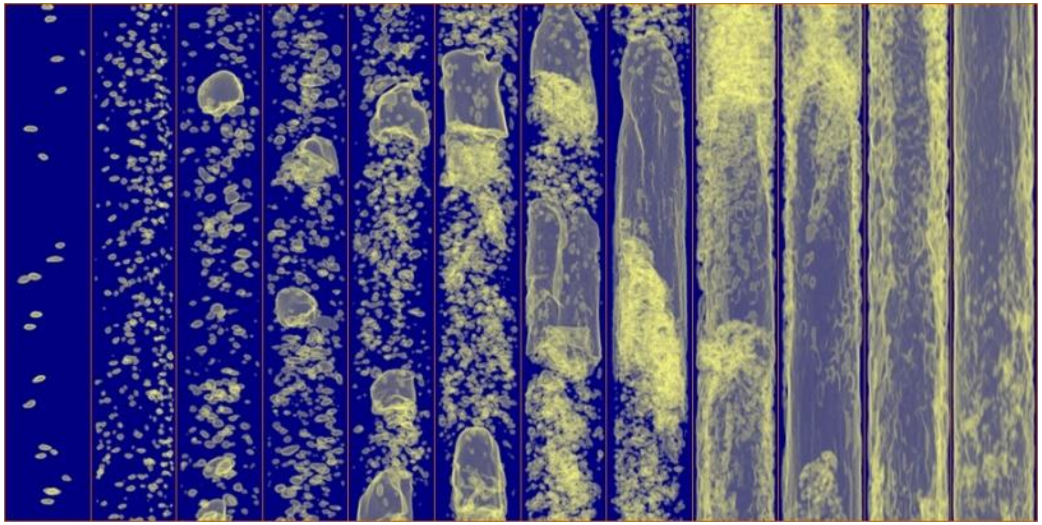
Basic Parameters

Void fraction measurement

- ✓ Ultra fast x-ray CT

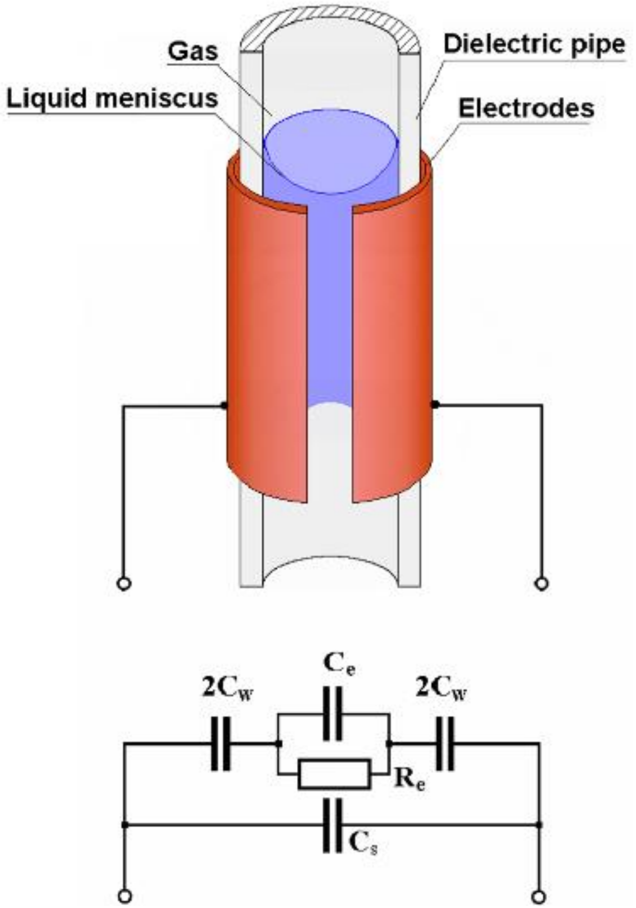




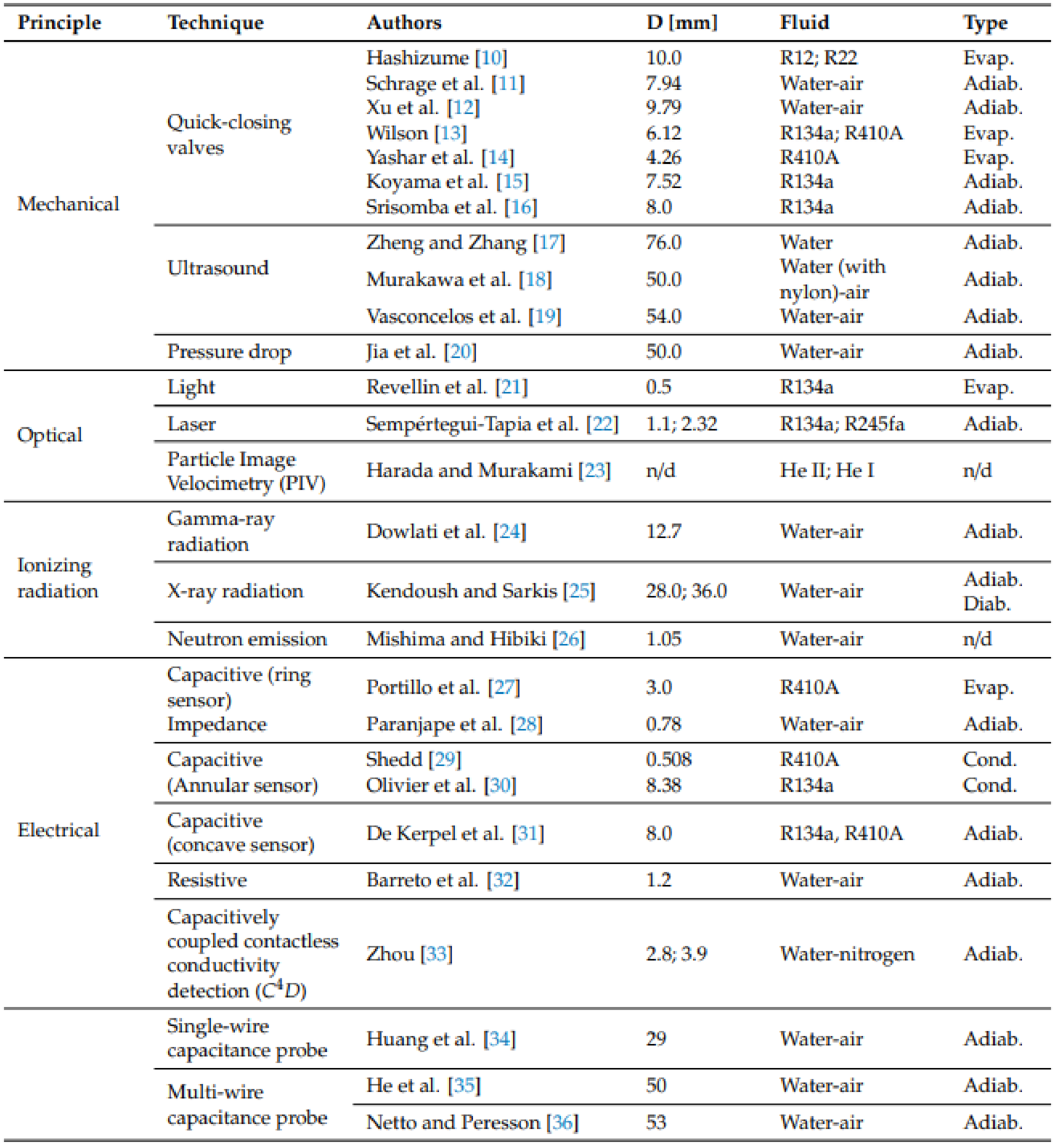


Basic Parameters

- Void fraction measurement
  - ✓ Etc.



https://www.mdpi.com/2311-5521/5/4/216/htm

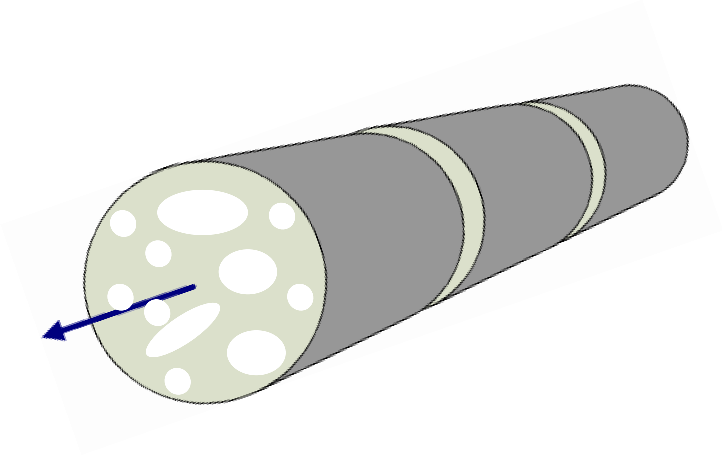


Principle	Technique	Authors	D [mm]	Fluid	Type
Mechanical	Quick-closing valves	Hashizume [10]	10.0	R12; R22	Evap.
		Schrage et al. [11]	7.94	Water-air	Adiab.
		Xu et al. [12]	9.79	Water-air	Adiab.
		Wilson [13]	6.12	R134a; R410A	Evap.
		Yashar et al. [14]	4.26	R410A	Evap.
		Koyama et al. [15]	7.52	R134a	Adiab.
		Srisomba et al. [16]	8.0	R134a	Adiab.
	Ultrasound	Zheng and Zhang [17]	76.0	Water	Adiab.
		Murakawa et al. [18]	50.0	Water (with nylon)-air	Adiab.
		Vasconcelos et al. [19]	54.0	Water-air	Adiab.
	Pressure drop	Jia et al. [20]	50.0	Water-air	Adiab.
Optical	Light	Revellin et al. [21]	0.5	R134a	Evap.
	Laser	Sempértegui-Tapia et al. [22]	1.1; 2.32	R134a; R245fa	Adiab.
	Particle Image Velocimetry (PIV)	Harada and Murakami [23]	n/d	He II; He I	n/d
Ionizing radiation	Gamma-ray radiation	Dowlati et al. [24]	12.7	Water-air	Adiab.
	X-ray radiation	Kendoush and Sarkis [25]	28.0; 36.0	Water-air	Adiab. Diab.
	Neutron emission	Mishima and Hibiki [26]	1.05	Water-air	n/d
Electrical	Capacitive (ring sensor)	Portillo et al. [27]	3.0	R410A	Evap.
	Impedance	Paranjape et al. [28]	0.78	Water-air	Adiab.
	Capacitive (Annular sensor)	Shedd [29]	0.508	R410A	Cond.
		Olivier et al. [30]	8.38	R134a	Cond.
	Capacitive (concave sensor)	De Kerpel et al. [31]	8.0	R134a, R410A	Adiab.
	Resistive	Barreto et al. [32]	1.2	Water-air	Adiab.
	Capacitively coupled contactless conductivity detection (C^4D)	Zhou [33]	2.8; 3.9	Water-nitrogen	Adiab.
	Single-wire capacitance probe	Huang et al. [34]	29	Water-air	Adiab.
	Multi-wire capacitance probe	He et al. [35]	50	Water-air	Adiab.
		Netto and Peresson [36]	53	Water-air	Adiab.

Basic Parameters

- Velocities
  - ✓ Actual velocity (phase velocity)

$$u_l = \frac{Q_l}{A_l} \qquad u_g = \frac{Q_g}{A_g}$$



  - ✓ Superficial velocity

$$j_G = \frac{Q_G}{A} = \frac{Q_G/A_g}{(A_l + A_g)/A_g} = \alpha_g u_G \qquad j_l = \frac{Q_l}{A} = \alpha_l u_l = (1 - \alpha_g)u_l$$

$$j = \frac{Q}{A} = \frac{Q_g + Q_l}{A} = j_g + j_l$$

For two-phase flows, the phase velocities are larger than the corresponding volumetric fluxes of each phase.

Basic Parameters

❖ Velocities

- ✓ Relative velocity or slip velocity

$$u_R = u_g - u_l$$

- ✓ Homogeneous flow (?)
  - No slip between two phases $u_R = 0$

$$u_R = u_g - u_l = \frac{j_g}{\alpha_g} - \frac{j_l}{(1-\alpha_g)} = 0$$

$$\alpha_g = \frac{1}{j_g + j_l}$$

Basic Parameters

- Velocities
  - ✓ Slip ratio

$$S = \frac{u_g}{u_l}$$

    - For homogeneous flow, ?
    - If not,

$$S = \frac{u_g}{u_l} = \frac{\dot{m}_g/\rho_g A_g}{\dot{m}_l/\rho_l A_l} = \left(\frac{x}{1-x}\right)\left(\frac{\rho_l}{\rho_g}\right)\left(\frac{1-\alpha_g}{\alpha_g}\right)$$

Basic Parameters

❖ Quality

- ✓ Thermodynamic equilibrium quality: x_e

$$x_e = \frac{h - h_f}{h_{fg}}$$

- ✓ Flow quality: x

$$x = \frac{\dot{m}_g}{\dot{m}_g + \dot{m}_l} = \frac{\rho_g u_g A_g}{\rho_g u_g A_g + \rho_l u_l A_l}$$

- ✓ Static quality: x_s

$$x_s = \frac{m_g}{m_g + m_l} = \frac{\rho_g A_g}{\rho_g A_g + \rho_l A_l}$$

Volumetric quality

$$\beta = \frac{Q_g}{Q_g + Q_l} = \frac{j_g A}{jA} = \frac{j_g}{j}$$

Basic Parameters

- Quality
  - ✓ Flow quality vs. static quality

$$x = \frac{\dot{m}_g}{\dot{m}_g + \dot{m}_l} = \frac{\rho_g u_g A_g}{\rho_g u_g A_g + \rho_l u_l A_l} \qquad x_s = \frac{m_g}{m_g + m_l} = \frac{\rho_g A_g}{\rho_g A_g + \rho_l A_l}$$

$$\frac{x}{1-x} = \frac{\rho_g u_g A_g}{\rho_l u_l A_l} = \left(\frac{u_g}{u_l}\right)\left(\frac{x_s}{1-x_s}\right)$$

- For homogeneous flow

$$x = x_s$$

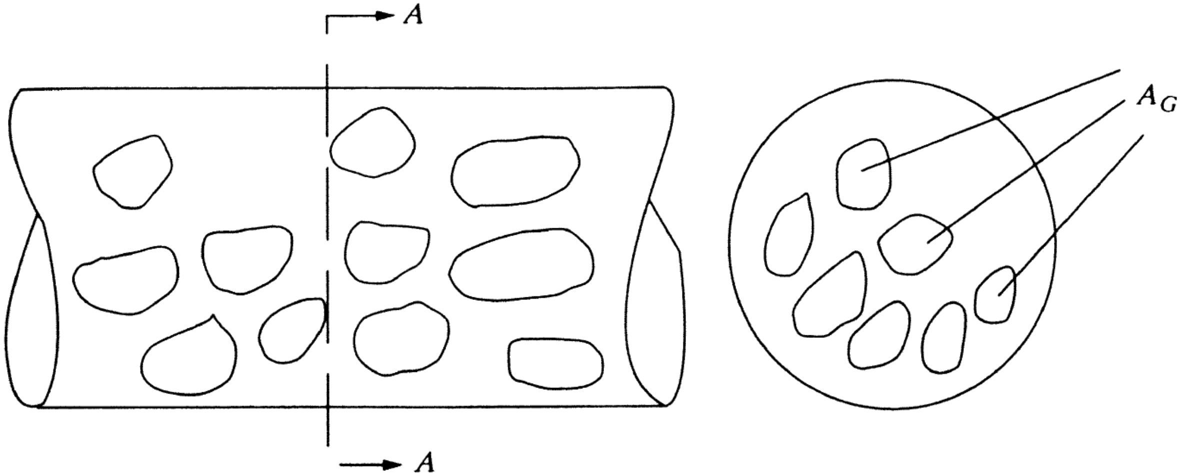
Basic Parameters

❖ Area-averaging Operator : Zuber notation

- ✓ Averaged properties

$$<\xi>=\frac{1}{A}\int_A \xi\, dA$$

$$<\alpha>=A_G/A$$



- ✓ Phasic average

$$<\xi_G>_G=\frac{1}{A_G}\int_{A_G}\xi_G dA_G=\frac{1}{<\alpha>A}\int_A \xi_G\,\alpha\, dA=\frac{<\xi_G\,\alpha>}{<\alpha>}$$

$$<\xi_L>_L=\frac{1}{A_L}\int_{A_L}\xi_L dA_L=\frac{1}{A(1-<\alpha>)}\int_A \xi_L(1-\alpha)\,dA=\frac{<\xi_L(1-\alpha)>}{<1-\alpha>}$$

Basic Parameters

❖ Who is Novak Zuber?

- ✓ “Thermodynamics is a funny subject. The first time you go through it, you don’t understand it at all. The second time you go through it, you think you understand it, except for one or two small points. The third time you go through it, you know you don’t understand it, but by that time you are so used to it, it doesn’t bother you anymore.”

- ✓ Drift flux model
- ✓ Uncertainty of the large-break loss-ofcoolant-accident (LOCA) predictions were made in the TRAC code
- ✓ Developing something called phenomena identification and ranking tables (PIRT) to guide the process
- ✓ A general scaling approach he called fractional scaling analysis (FSA)

- ✓ Check the supplement

Basic Parameters

- Averaged flow parameters
  - ✓ Mass flow rate

$$\dot{m}_g = \rho_g < u_g >_g A_g = \rho_g < u_g >_g < \alpha > A = G < x > A$$

$$\dot{m}_l = \rho_l < u_l >_l A_l = \rho_l < u_l >_l (1 - < \alpha >)A = G(1 - < x >)A$$

$$\dot{m} = \dot{m}_g + \dot{m}_l = G < x > A + G(1 - < x >)A = GA$$

$$G = \frac{\dot{m}}{A} = \frac{\dot{m}_g}{< x > A} = \frac{\rho_g < u_g >_g < \alpha >}{< x >} = \frac{\rho_l < u_l >_l (1 - < \alpha >)}{1 - < x >}$$

$$G_g = \frac{\dot{m}_g}{A} \qquad G_l = \frac{\dot{m}_l}{A} \qquad G = G_g + G_l$$

$$< u_g >_g = \frac{G < x >}{\rho_g < \alpha >} \qquad < u_l >_l = \frac{G(1 - < x >)}{\rho_l(1 - < \alpha >)}$$

Basic Parameters

- Void-quality relation

$$S = \frac{u_g}{u_l} = \frac{\dot{m}_g/\rho_g A_g}{\dot{m}_l/\rho_l A_l} = \left(\frac{x}{1-x}\right)\left(\frac{\rho_l}{\rho_g}\right)\left(\frac{1-\alpha_g}{\alpha_g}\right)$$

$$\frac{<x>}{1-<x>} = \left(\frac{\rho_l}{\rho_g}\right)\left(\frac{1-<\alpha_g>}{<\alpha_g>}\right)S \qquad <\alpha_g> = \frac{<x>}{<x>+S\left(\frac{\rho_g}{\rho_l}\right)(1-<x>)}$$

✓ For homogeneous flow or for the static quality

$$<\alpha_g> = \frac{<x>}{<x>\rho_l + \rho_g(1-<x>)}$$

Basic Parameters

- Two-phase density
  - ✓ Mixture density and specific volume

$$<\bar{\rho}>=(1-<\alpha>)\rho_l+<\alpha>\rho_g$$

$$<\bar{v}>=(1-<x>)v_l+<x>v_g$$

Basic Parameters

- Interfacial Area Concentration (IAC)

$$IAC = \frac{Interfacial\ area}{Mixture\ volume} \quad [1/m]$$

  - ✓ Importance of IAC
    - (Interfacial Transfer Terms) ~ (IAC) X (Driving Force)
      - ✓ First Order Importance to Interfacial Transfer Terms
      - ✓ Driving Force: Local Transport Mechanism
        - » Potential Related to the Momentum & Energy Transport
    - Significantly Affect the Results of Two-Phase Flow Analysis

- IAC models
  - ✓ Correlation bases on static flow regime map
  - ✓ Dynamic Flow Regime Map Based on Transport Equation