Two-Phase Flow

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Outline

- Introduction
- Terminologies
- Model assumptions
- Flow patterns
- Boiling flow
- Void fraction
- Summary

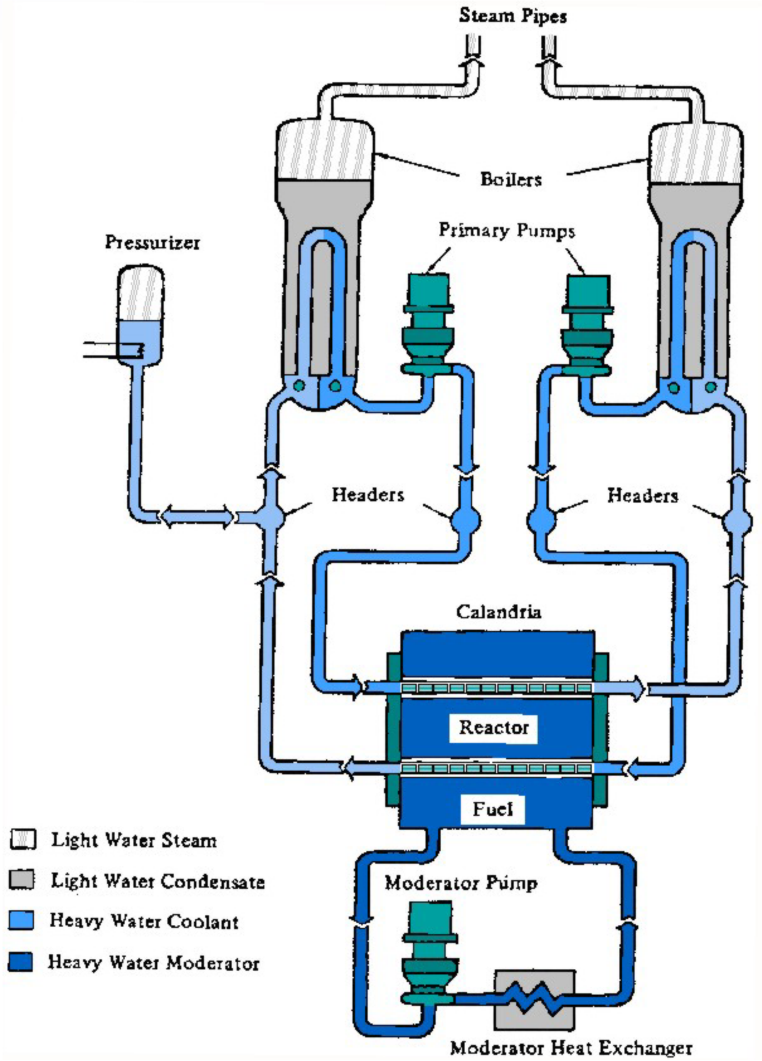
Background

- Two-phase flow is encountered in many engineering systems of chemical, process, power generation, and petroleum industries
- Typical examples are oil-gas pipelines, boilers, heat exchangers, refrigeration equipment, evaporators, nuclear reactors, etc.
- In a simple way, two-phase flow is an extension of single-phase flow
- In reality, two-phase flow is much more complex due to the uncertainty in various interfacial parameters
- Correlations are often applied in design calculations

Terminologies

- Two-phase flow
  - Simultaneous flow of liquid and vapour of a single substance
  - Examples: reactor fuel channels, steam generators, kettle on a hot stove
  - Also referred to as “Single-component two-phase flow”
- Two-component flow
  - Simultaneous flow of liquid and gas of two substances
  - Examples: oil-gas pipelines, beer, soft drink
  - Also referred to as “Two-component two-phase flow”

Two-Phase Flow in Primary HTS



Analytical Parameters

- Primary parameters
  - Thermal: power
  - Hydraulics: pressure, mass flow rate, fluid temperature, pressure drop
  - Geometry: flow and heated areas, hydraulic and heated equivalent diameters
- Calculated parameters commonly used in analyses
  - Mass flux, heat flux
  - Quality: mass, equilibrium, thermodynamic
  - Void fraction
- Fluid properties
  - Density, viscosity, enthalpy, thermal conductivity, heat capacity

Key Definitions

- **Void fraction is ratio of area occupied by vapour/gaseous phase to total flow area**

$$\alpha = \frac{A_g}{A}; \qquad (1-\alpha) = \frac{A_f}{A}$$

- **Mass quality is ratio of vapour mass flow to total mass flow**

$$x = \frac{W_g}{W} = \frac{W_g}{W_f + W_g}; \qquad (1-x) = \frac{W_f}{W} = \frac{W_f}{W_f + W_g}$$

- **Mass flux is mass flow rate per unit flow area**

$$G = \frac{W}{A} = \rho u = \frac{u}{\upsilon}; \quad G_g = G\,x; \quad G_f = G\,(1-x)$$

- **Volumetric flux (or superficial velocity) is volumetric flow rate over the total flow area**

$$j = \frac{Q}{A}; \qquad j_g = \frac{Q_g}{A}; \qquad j_f = \frac{Q_f}{A}$$

Phasic Velocity Definitions

- **Vapour phase velocity**

$$u_g = \frac{W_g}{\rho_g A_g} = \frac{Q_g}{A_g} = \frac{G\,x}{\rho_g\,\alpha}$$

- **Liquid phase velocity**

$$u_f = \frac{W_f}{\rho_f A_f} = \frac{Q_f}{A_f} = \frac{G\,(1-x)}{\rho_f\,(1-\alpha)}$$

- **Slip ratio = (vapour velocity)/(liquid velocity)**

$$\frac{u_g}{u_f} = \frac{W_g\,\rho_f\,A_f}{W_f\,\rho_g\,A_g} = \left(\frac{x}{1-x}\right)\left(\frac{\rho_f}{\rho_g}\right)\left(\frac{1-\alpha}{\alpha}\right)$$

Quality Definitions

- **Mass quality**
  - Direct measurements of vapour and liquid flow
  - Varies from 0 to 100%

$$x = \frac{W_g}{W} = \frac{W_g}{W_f + W_g}$$

- **Thermodynamic quality**
  - Based on enthalpy balance
  - Varies from negative to positive values greater than 100%

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

- **Equilibrium quality**
  - Thermodynamic quality at equilibrium conditions
  - Same as mass quality (varies from 0 to 100%)

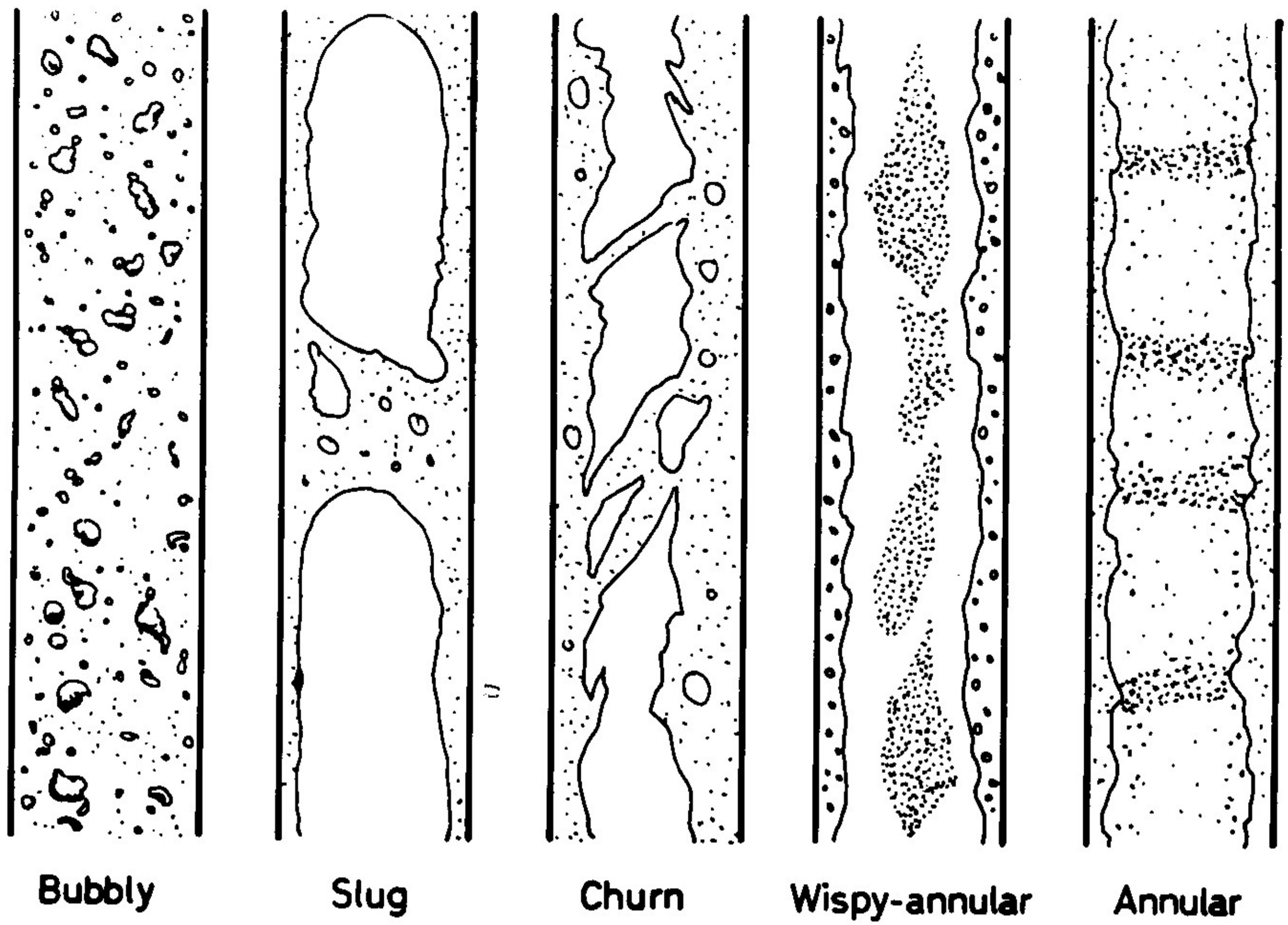
Model Assumptions

- Homogeneous flow model
  - The two-phase flow is assumed to behave as a single-phase flow with mean fluid properties
    - Equal vapour and liquid velocities
    - Thermodynamic equilibrium between these phases
- Separated flow model
  - The two phases are considered separate with different fluid properties
    - Constant but not necessarily equal velocities for the two phases
    - Thermodynamic equilibrium between these phases
- Flow-regime dependent model
  - Between homogeneous flow and separated flow assumptions
  - Complex
  - Requires good flow-pattern transition criterion

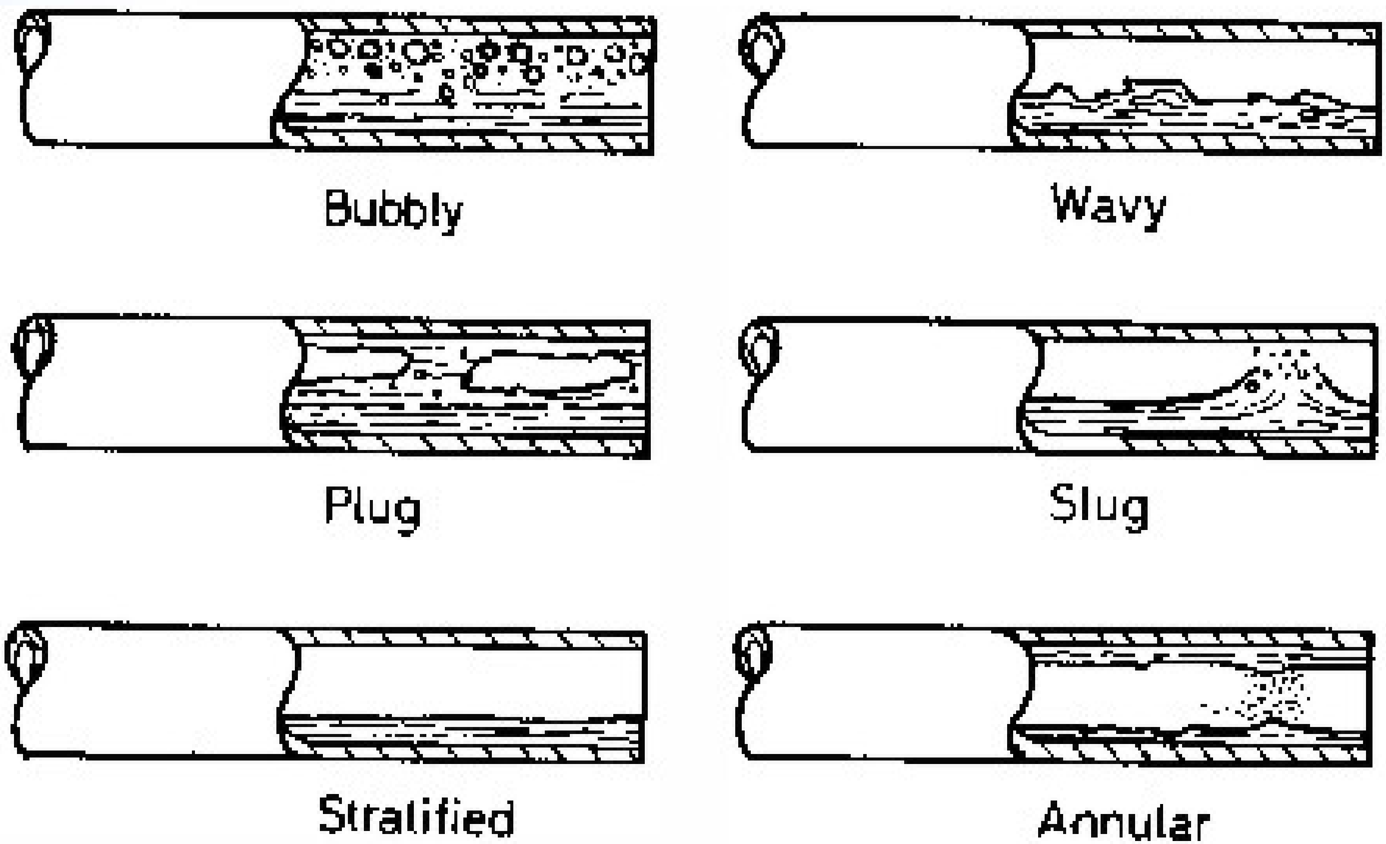
Flow Patterns

- Distribution of phases inside a confined area
- Depend strongly on liquid and vapour velocities
- Channel geometry
  - Minor effect for simple channel with no interconnected subchannel
  - Complex for channel with interconnected subchannel (such as bundle) due to flow and quality distributions
- Surface heating
  - Influence near-wall flow patterns resulted in an internal void gradient
  - Wrap-around dry-wall flow patterns not encountered in adiabatic conditions
- Appendages
  - Homogenize the flow pattern at downstream locations
  - Transit back to basic pattern at locations far away

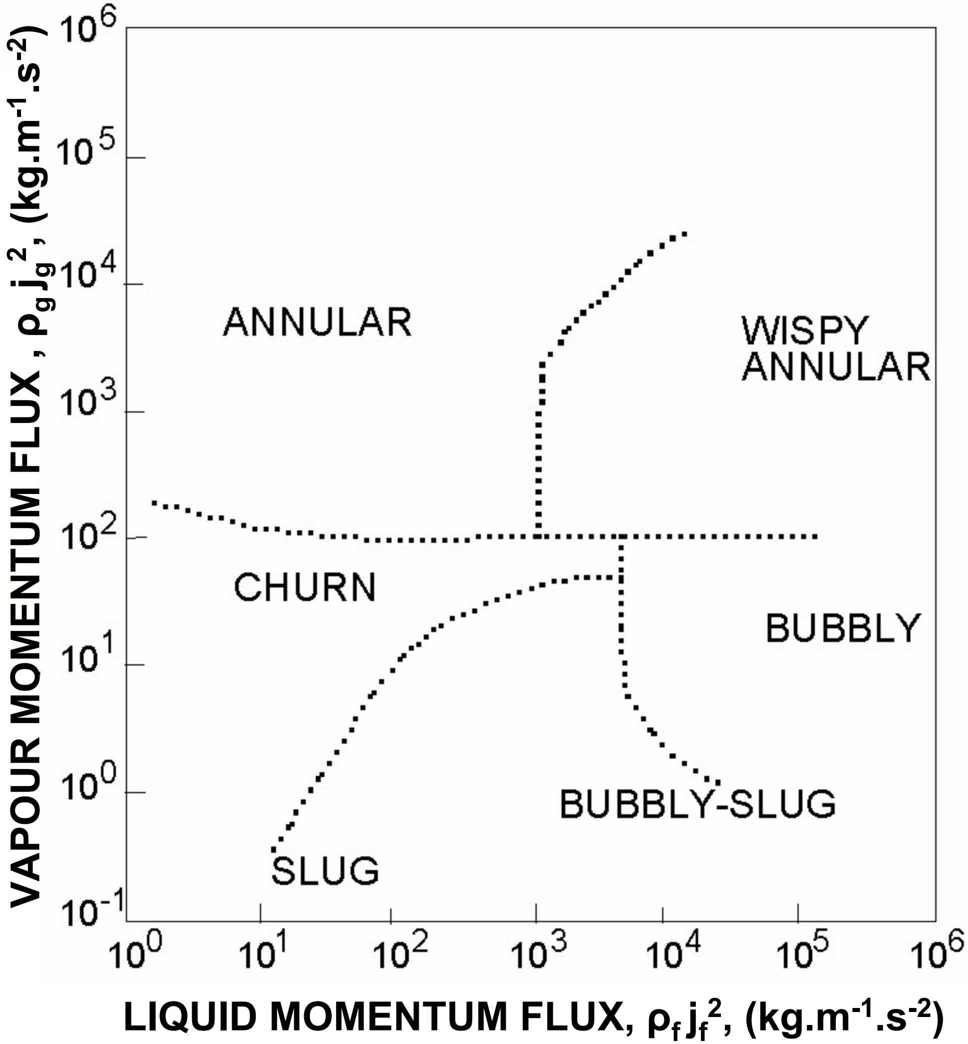
Flow Patterns in Vertical Flow



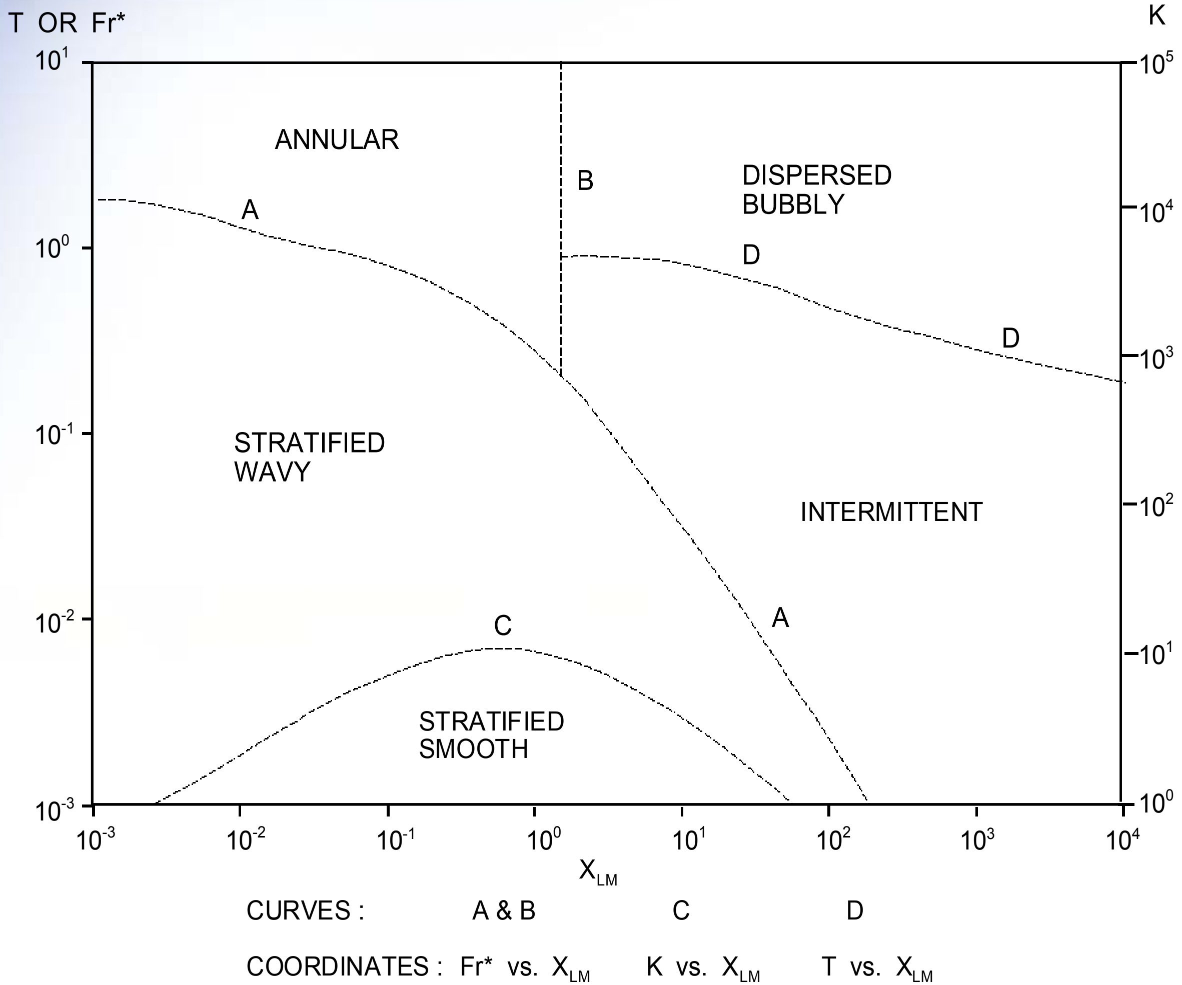
Flow Patterns in Horizontal Flow



Flow Pattern Map for Vertical Flow



Flow Pattern Map for Horizontal Flow



$$X_{LM} = \left(\frac{(dP/dZ)_{f,\,fric.}}{(dP/dZ)_{g,\,fric.}} \right)^2$$

$$Fr^* = \left(\frac{\rho_g}{\rho_f - \rho_g} \right)^{0.5} \frac{j_g}{(D\, g \cos\theta)^{0.5}}$$

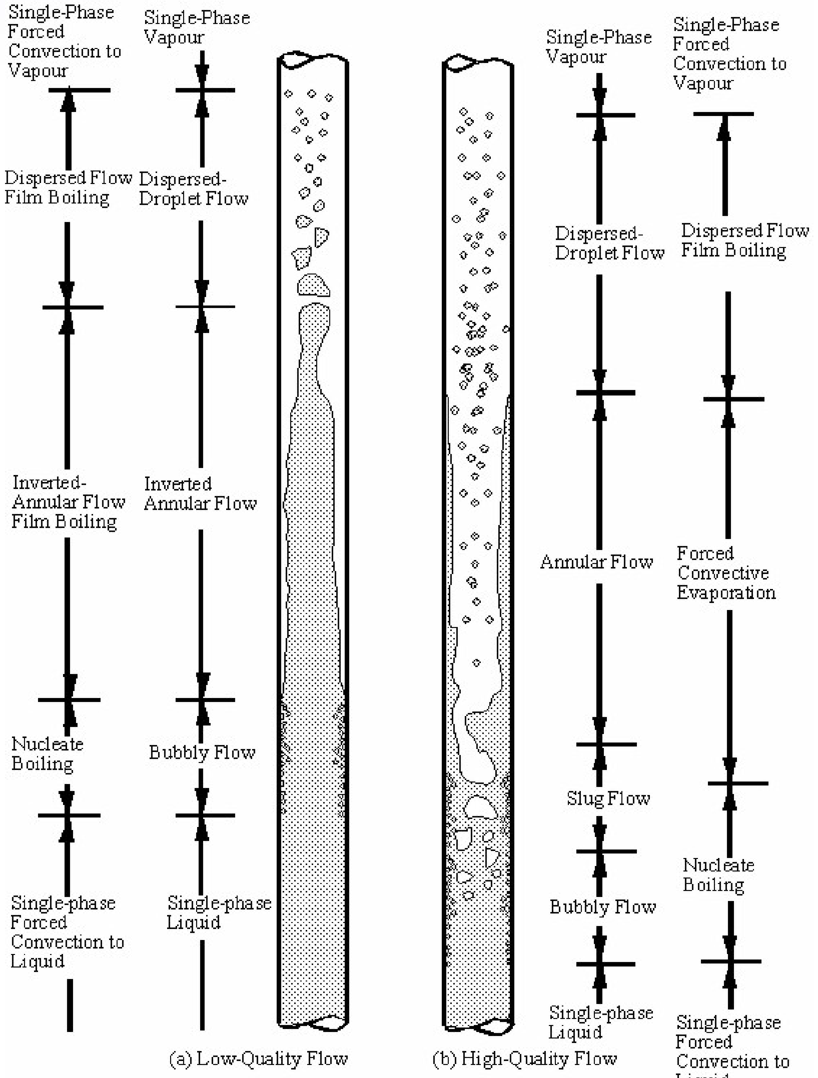
$$K = \left(\frac{\rho_g\, j_g^{\,2}\, j_f}{(\rho_f - \rho_g)\, g\, \nu_f \cos\theta} \right)^{0.5}$$

$$T = \left(\frac{(dP/dz)_{f,\,fric.}}{(\rho_f - \rho_g)\, g \cos\theta} \right)^{0.5}$$

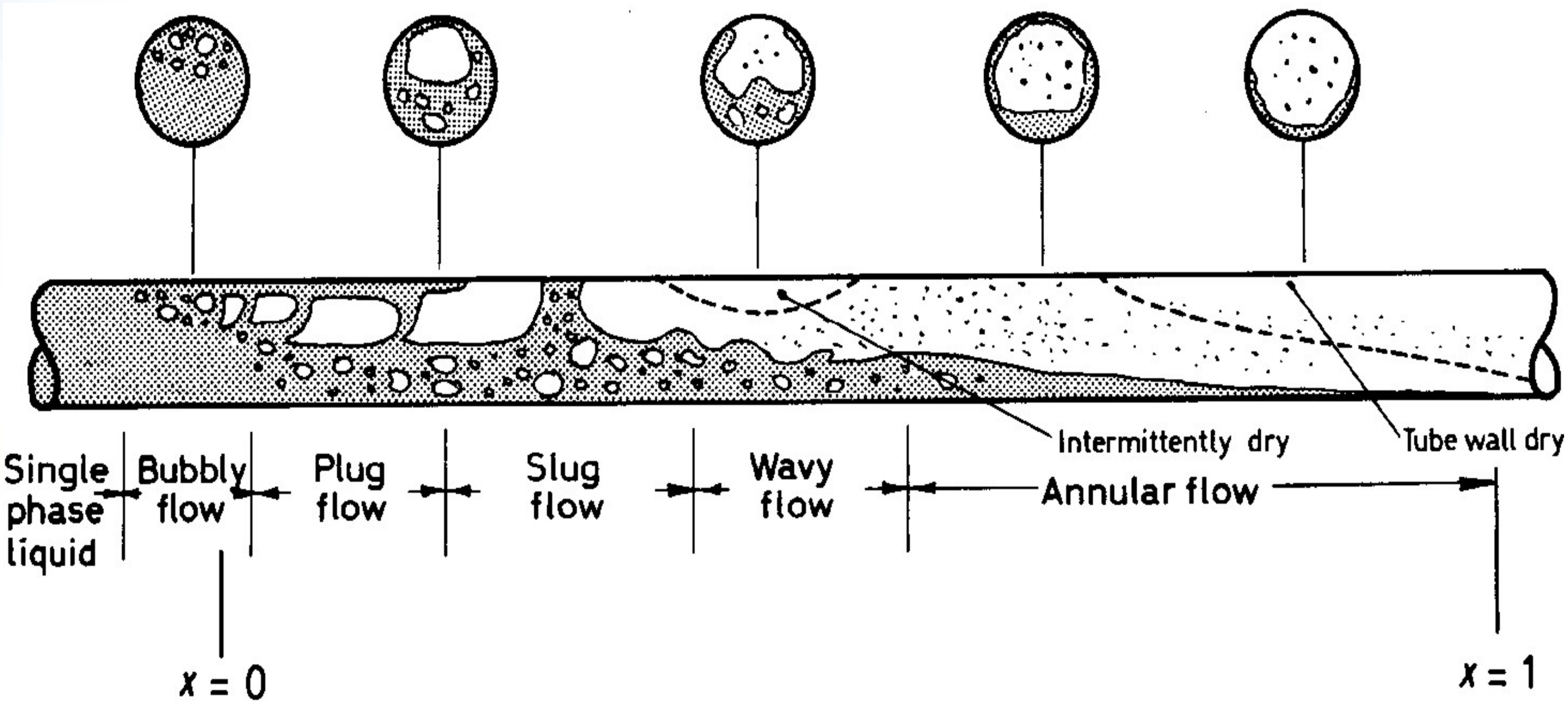
Boiling

- Vapour formation (nucleation)
  - Liquid superheating (at the surface)
  - Homogeneous (molecular dynamic within the fluid)
  - Heterogeneous (requires nucleation sites in the fluid or at the surface)
- Bubble detachment
  - Balance of dynamic, buoyancy and surface tension forces
- Types
  - Pool boiling
  - Convective boiling

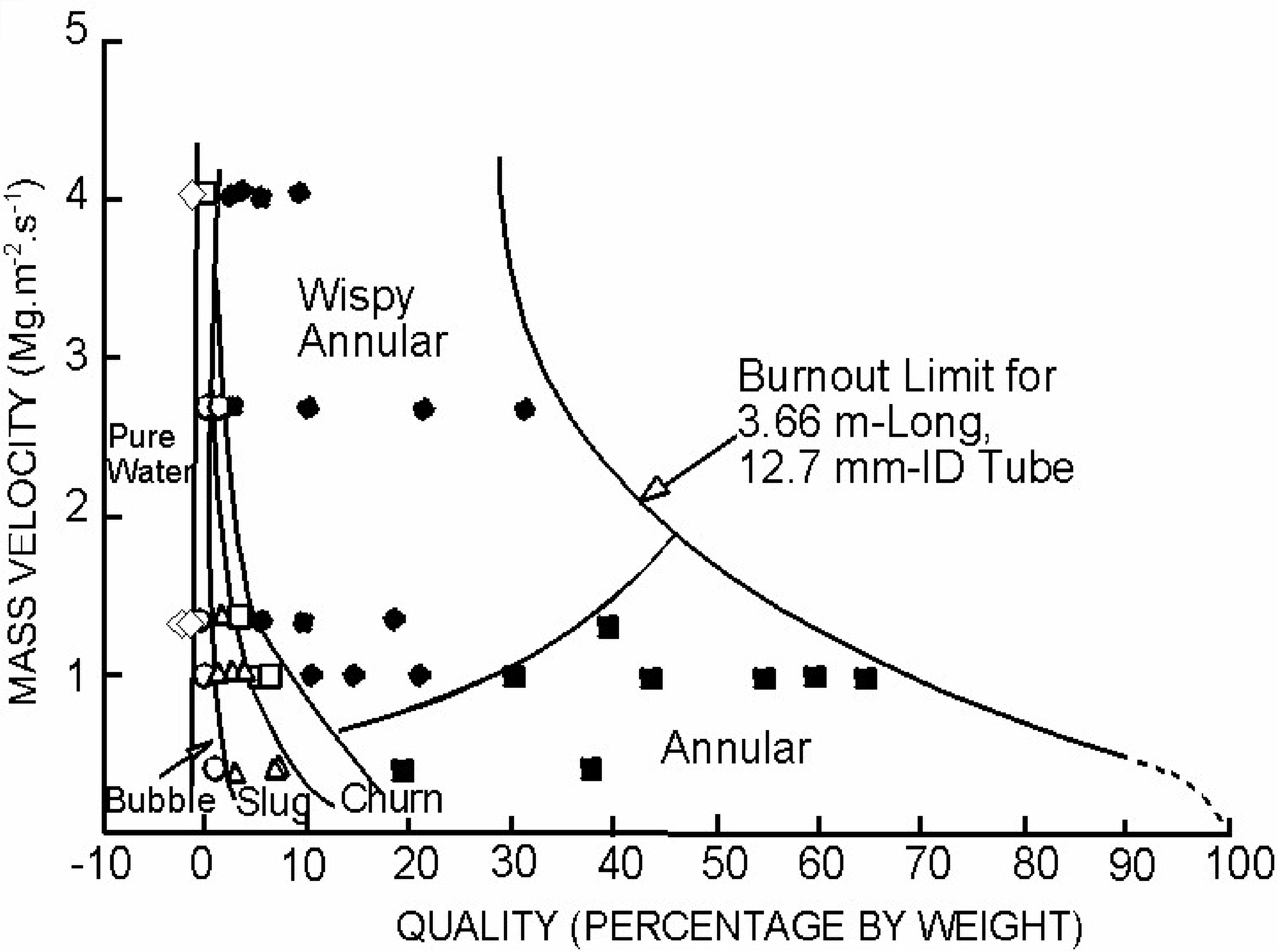
Flow Patterns in Vertical Heated Channels



Flow Patterns in Horizontal Heated Channel



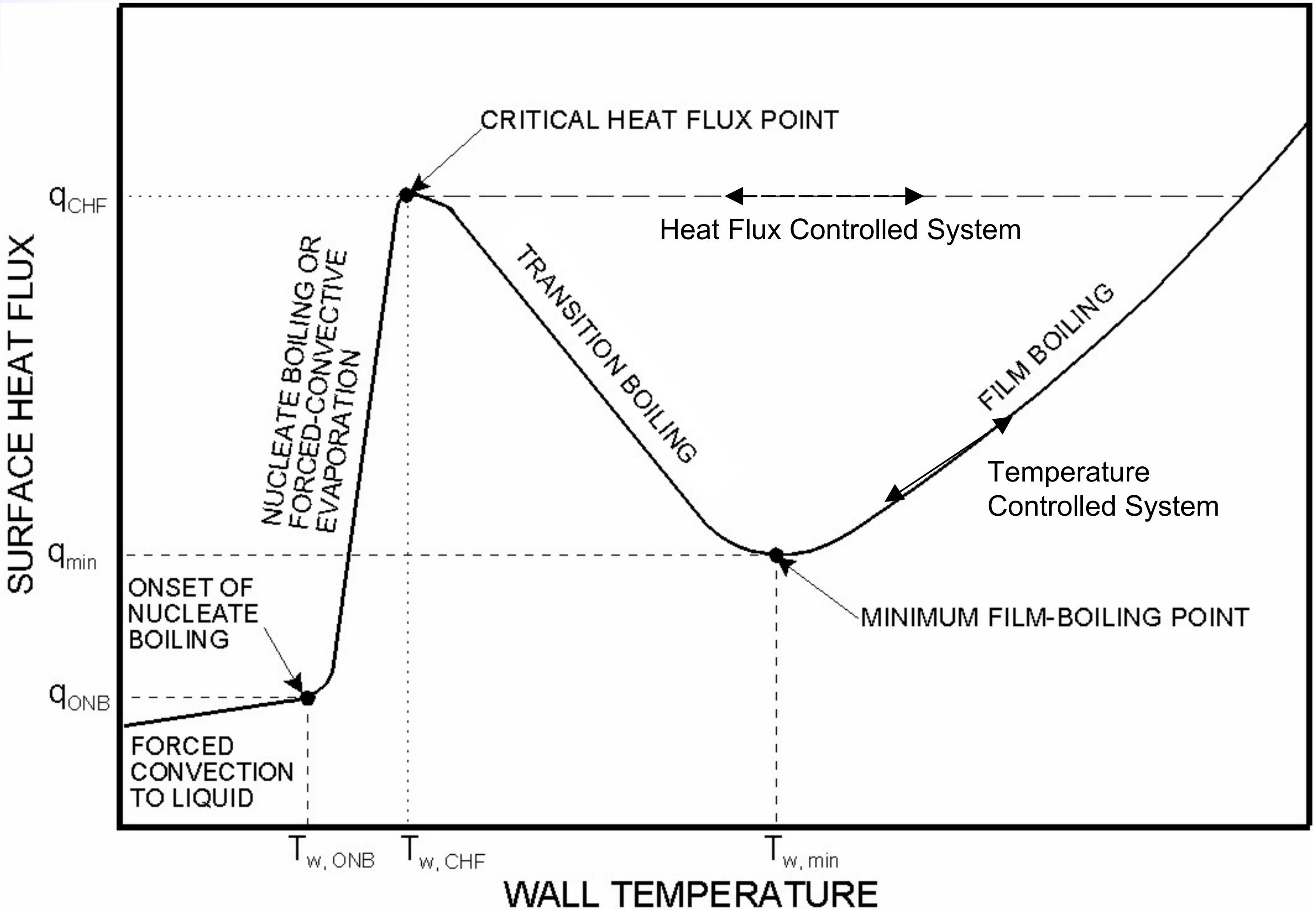
Flow Pattern Map in a Heated Channel



Definitions for Transition Points

- Onset of nucleate boiling
  - Transition point between single-phase and boiling heat transfer
- Onset of net vapour generation (or significant void)
  - Transition point between single-phase and two-phase flow (mainly for pressure-drop calculations)
- Saturation point
  - Boiling initiation point in an equilibrium system
- Critical heat flux point
  - Transition point between nucleate boiling and transition/film boiling
- Minimum film-boiling point
  - Transition point between transition boiling and film boiling

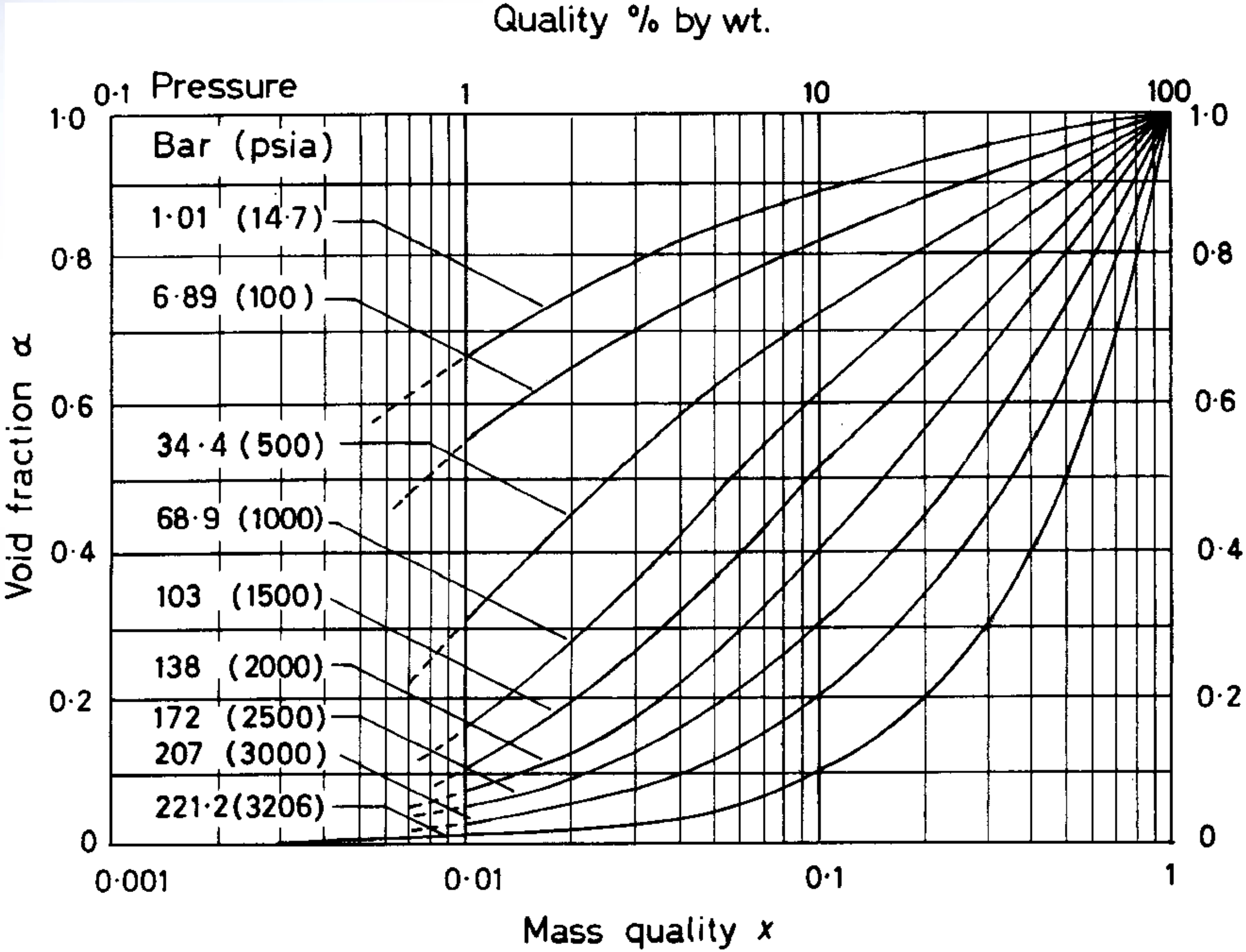
Boiling Curve



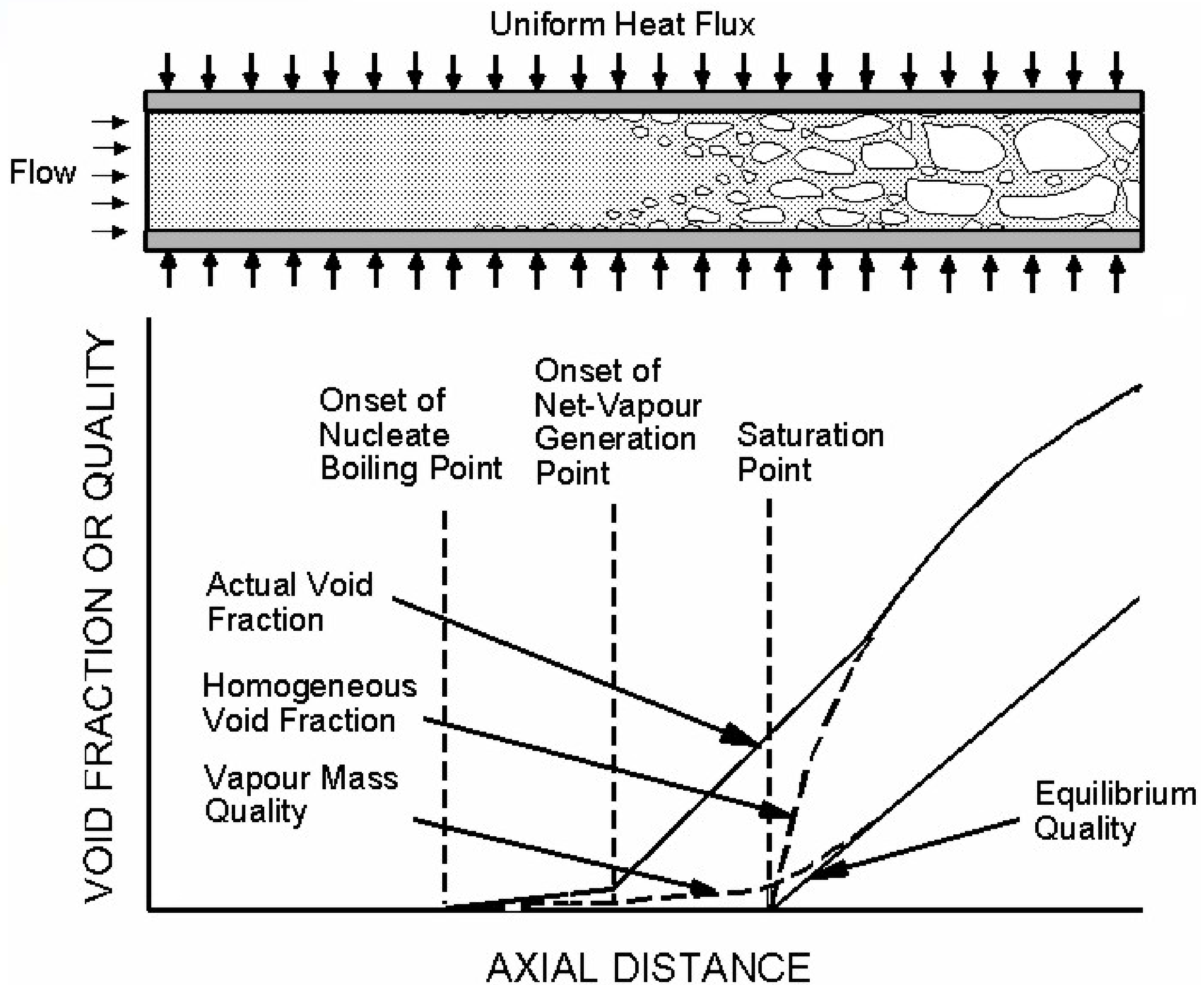
Void Fraction

- Ratio of vapour flow area to total flow area
- Depends strongly on pressure, mass flux, and quality
- Applied to calculate the acceleration pressure drop in steady-state homogeneous code
- Large number of correlations proposed
  - Homogeneous equation is the simplest
  - Chexal correlation is the most complex
  - Armand-Massina correlation is applied in the NUCIRC code
- Solved from the conservation equations in two-fluid reactor safety codes

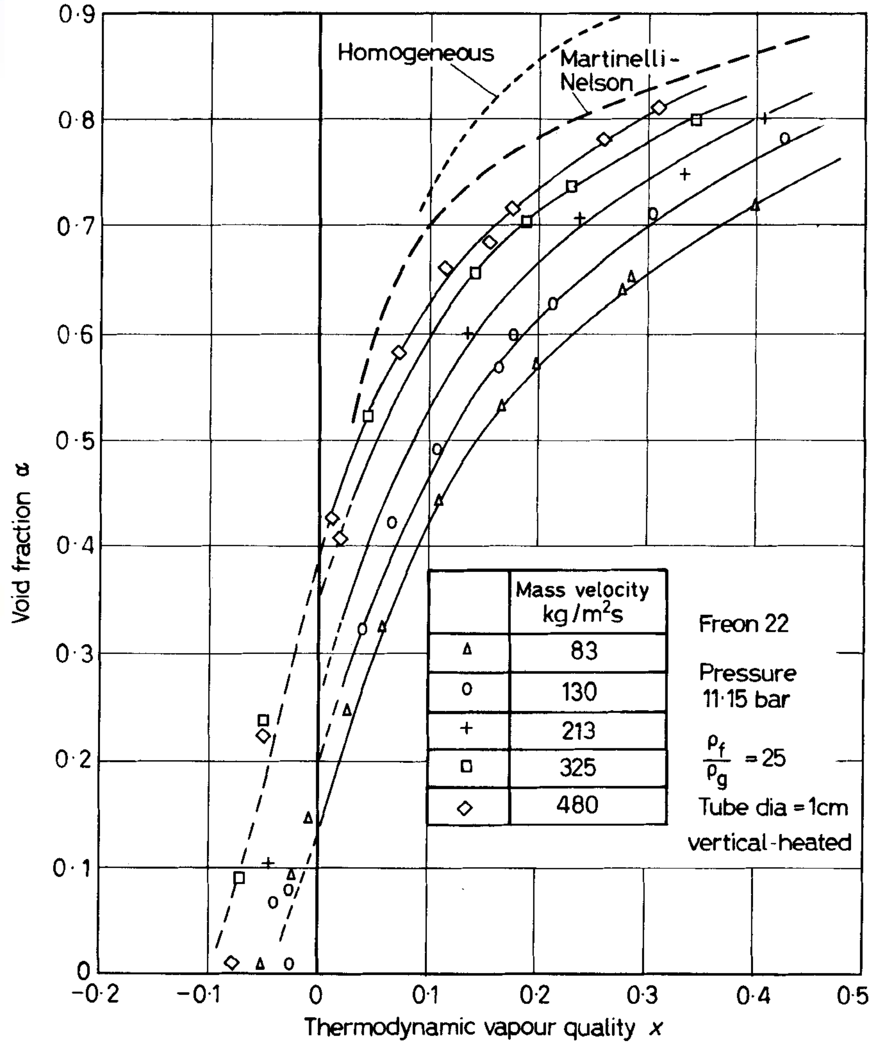
Effects of Pressure and Quality



Subcooled Boiling



Subcooled Void Measurements



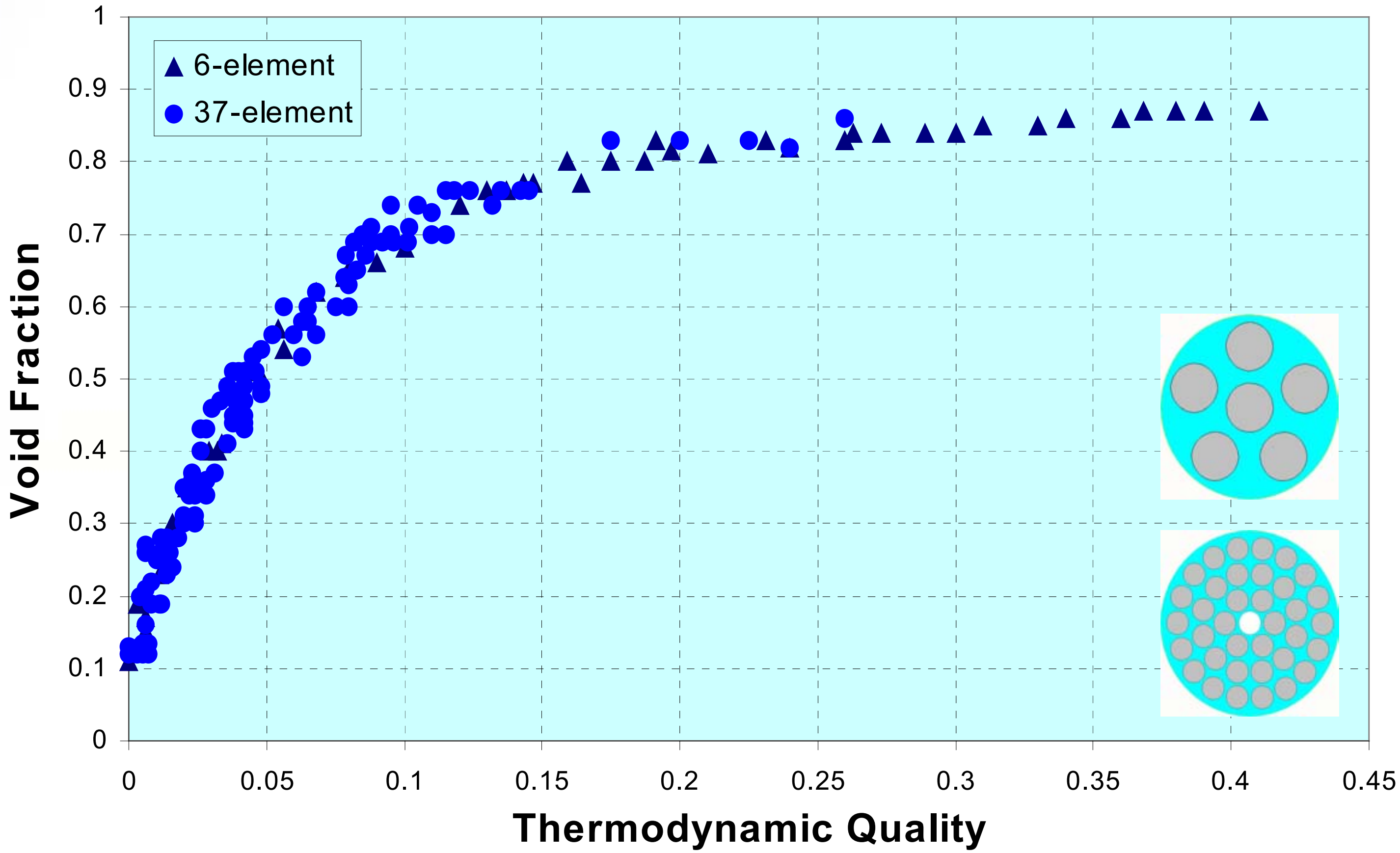
Void Fraction in Bundles

- Void-fraction database
  - Tube, annuli, and bundles (from 3 to 37 elements).
  - Covered a wide range of flow conditions.
  - Uniformly heated (axial and radial)
  - A bundle in various sizes of flow tube.
- Effect of bundle geometry on void fraction is small.
- Effect of mass flux is strong.
- Changes in flow-tube size and heat flux affect mainly the low-quality region (change in onset of significant void).

Bundle Geometry Effect

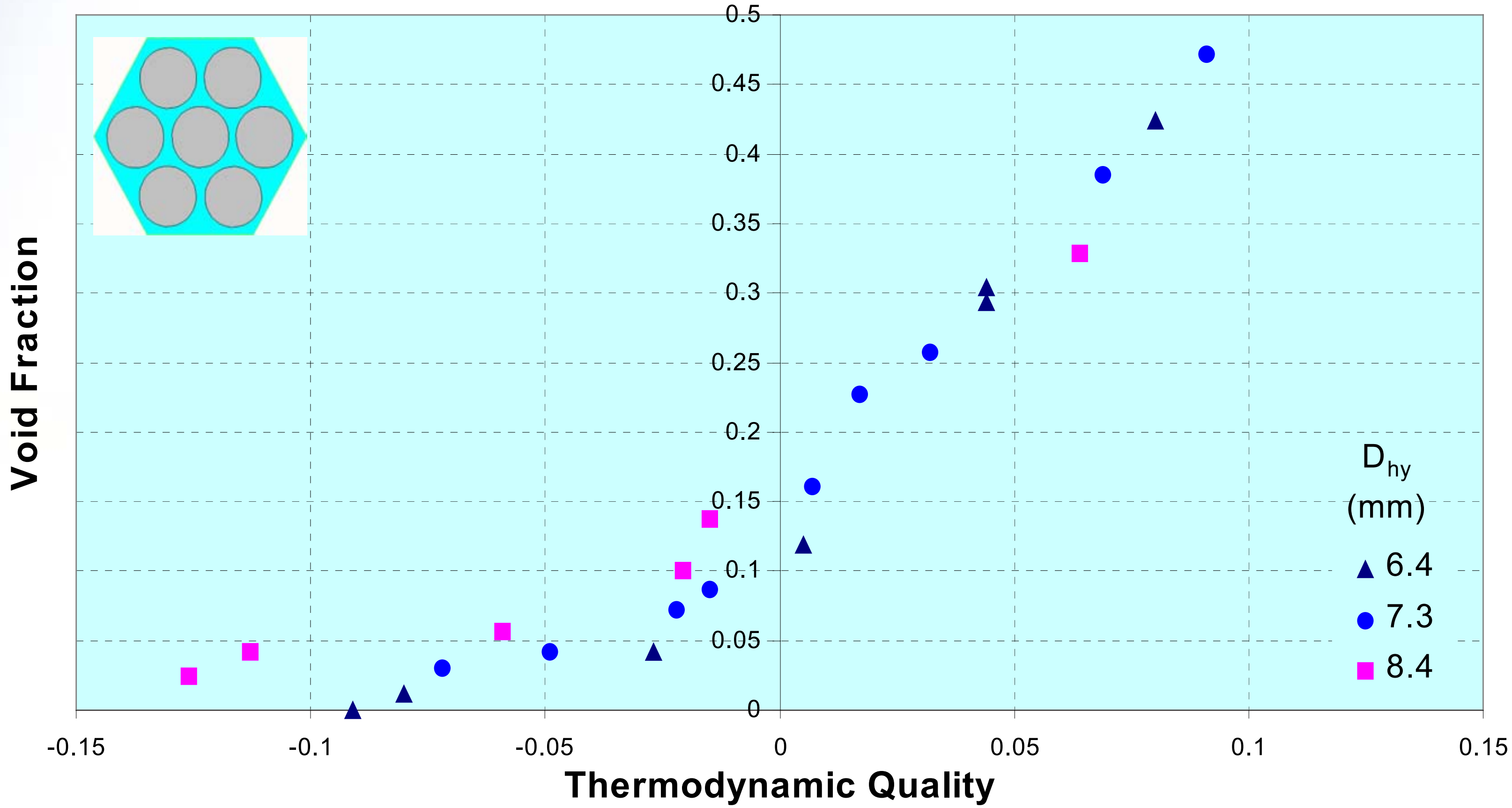
Pressure: 5 MPa, Mass Flux: 0.5 to 1.6 $Mg.m^{-2}.s^{-1}$,

Heat Flux: 0.1 to 0.98 $MW.m^{-2}$



Effect of Flow Tube Size

Pressure: 9.8 MPa, Mass Flux: 2 $Mg.m^{-2}.s^{-1}$, Heat Flux: 0.8 $MW.m^{-2}$



Void Fraction Correlations

- **Homogeneous equation**

$$\alpha = \frac{x_a \upsilon_g}{(1 - x_a)\upsilon_f + x_a \upsilon_g}$$

- **Armand-Massina correlation**

$$\alpha = \frac{(0.833 + 0.167\, x_a)\, x_a \upsilon_g}{(1 - x_a)\upsilon_f + x_a \upsilon_g}$$

Specific Applications

- Critical Flow
- Pump operation
- Natural Circulation (thermosyphoning)

Summary

- Two-phase flow terminologies and definitions presented
- Homogeneous and separated-flow models assumptions described
- Flow patterns and transition boundaries presented for vertical and horizontal flows in unheated and heated tubes
- Convective boiling and heat-transfer modes described
- Void fraction data and correlations illustrated

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