# UNENE Graduate Course Reactor Thermal-Hydraulics Design and Analysis

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# Two-Phase Flow Fundamentals

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# Outline

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

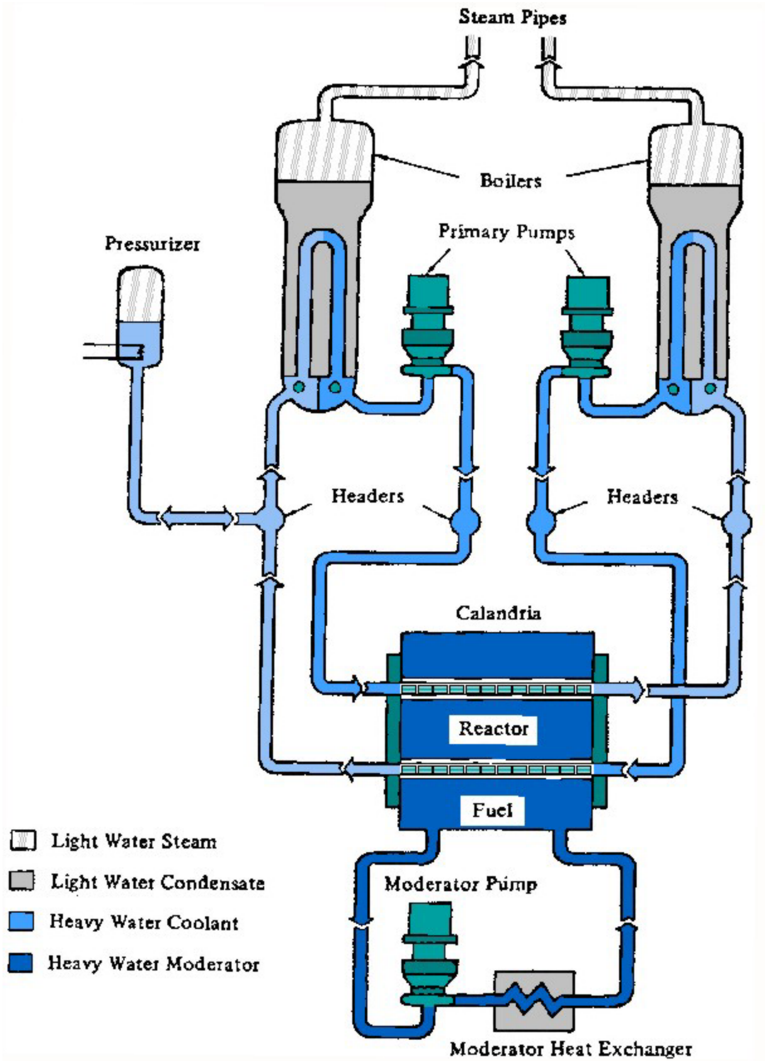
# Background

- 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 any two phases (liquid-gas/vapour, solid-gas, liquid-solid) 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%)

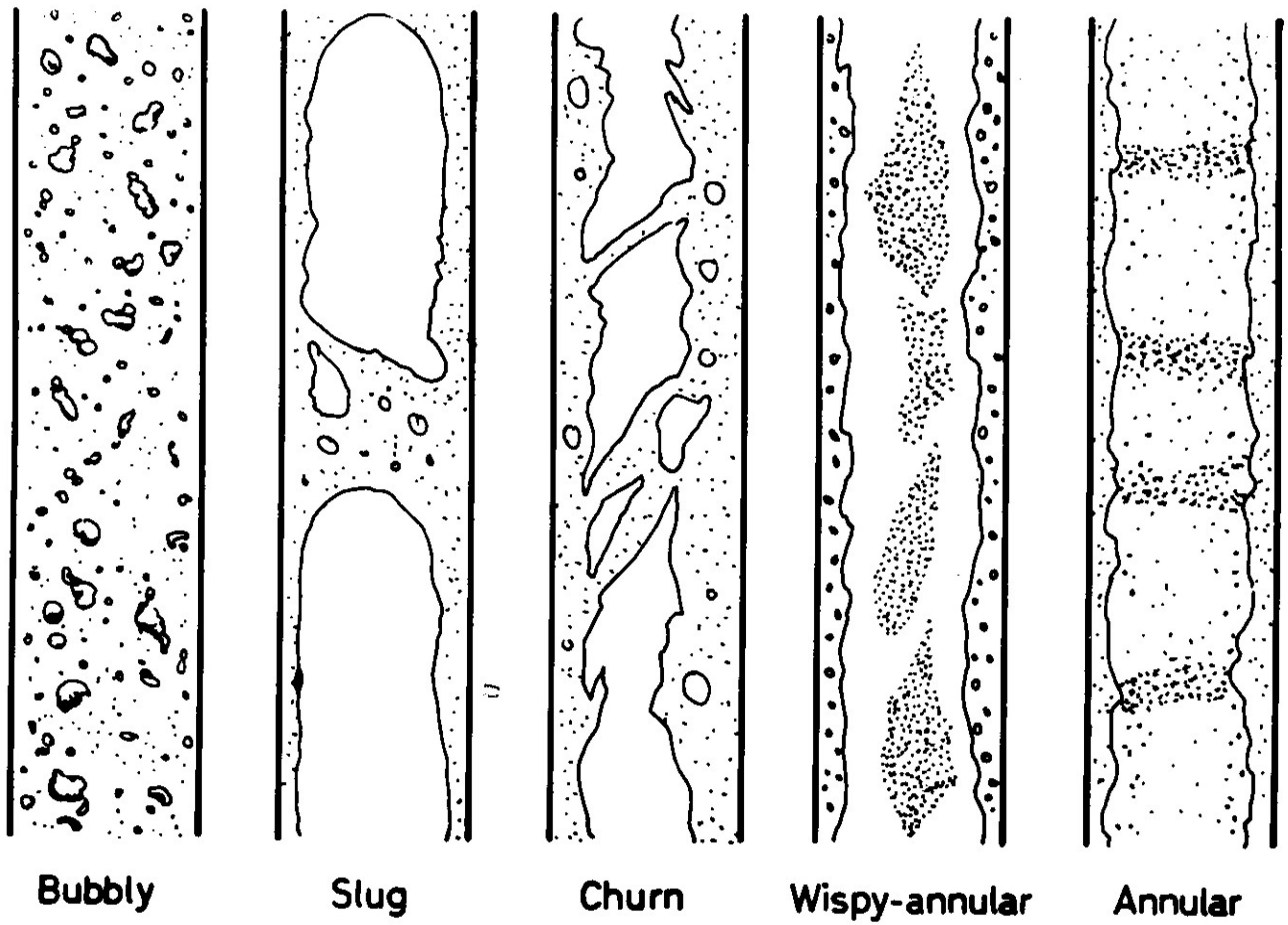
# Model Assumptions

- 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

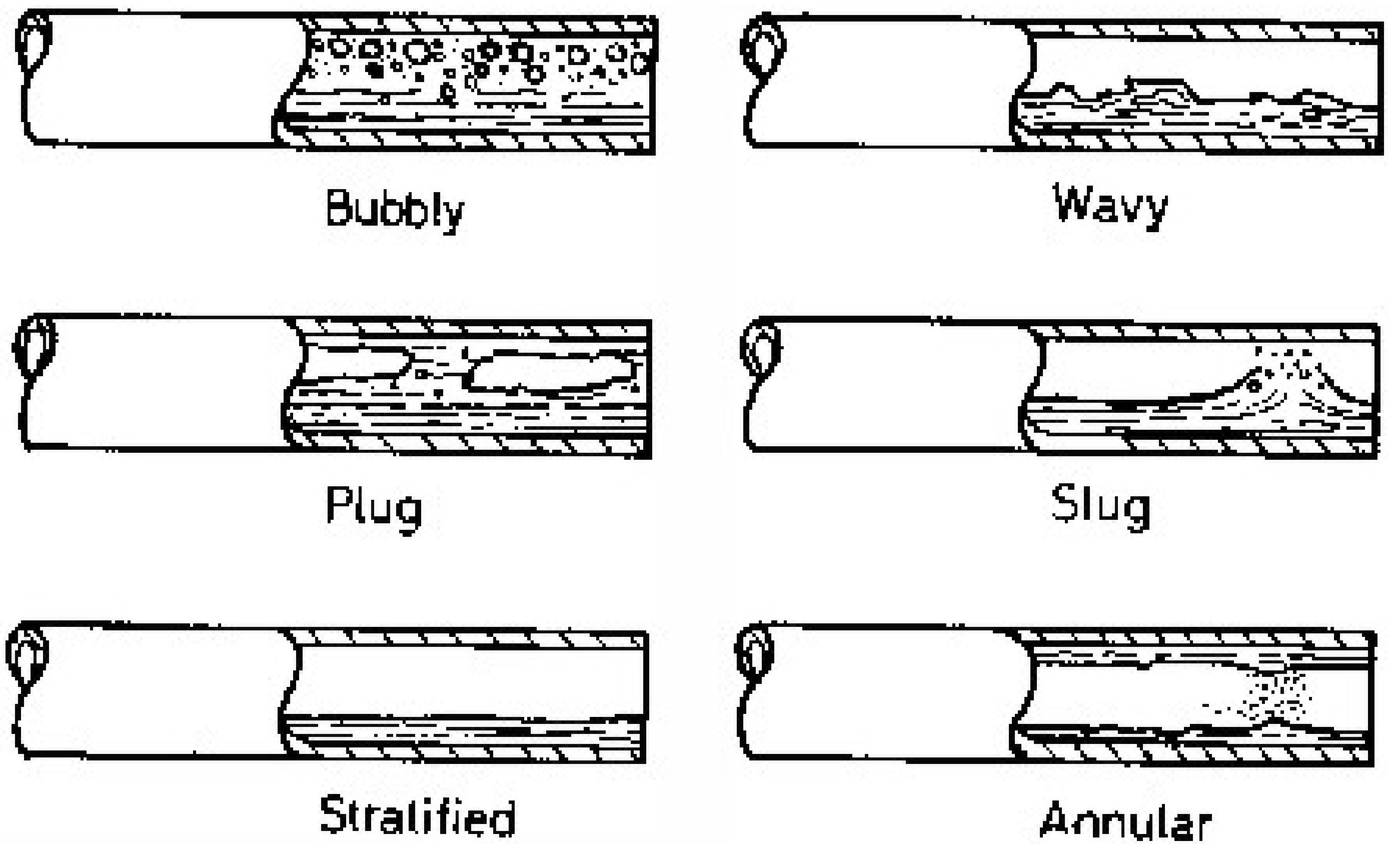
# Flow Patterns

- 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

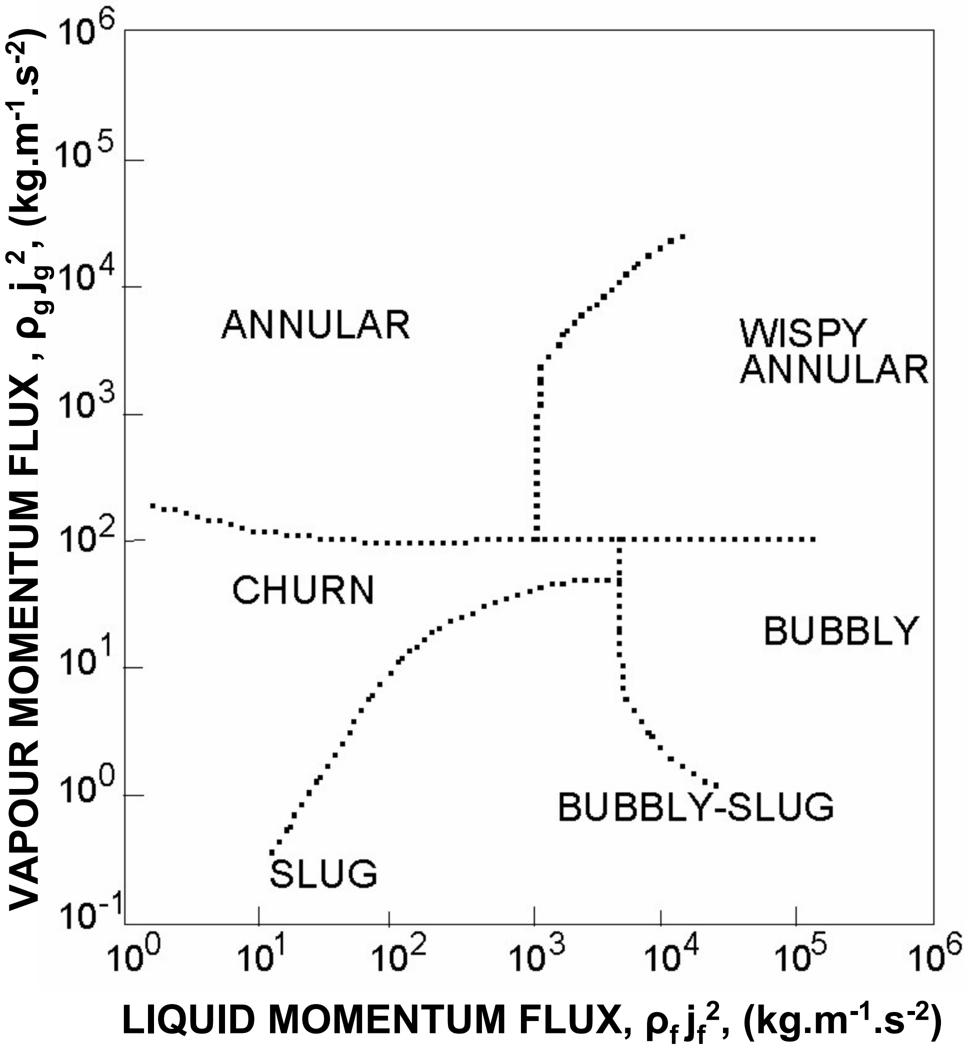
# Flow Patterns in Vertical Flow



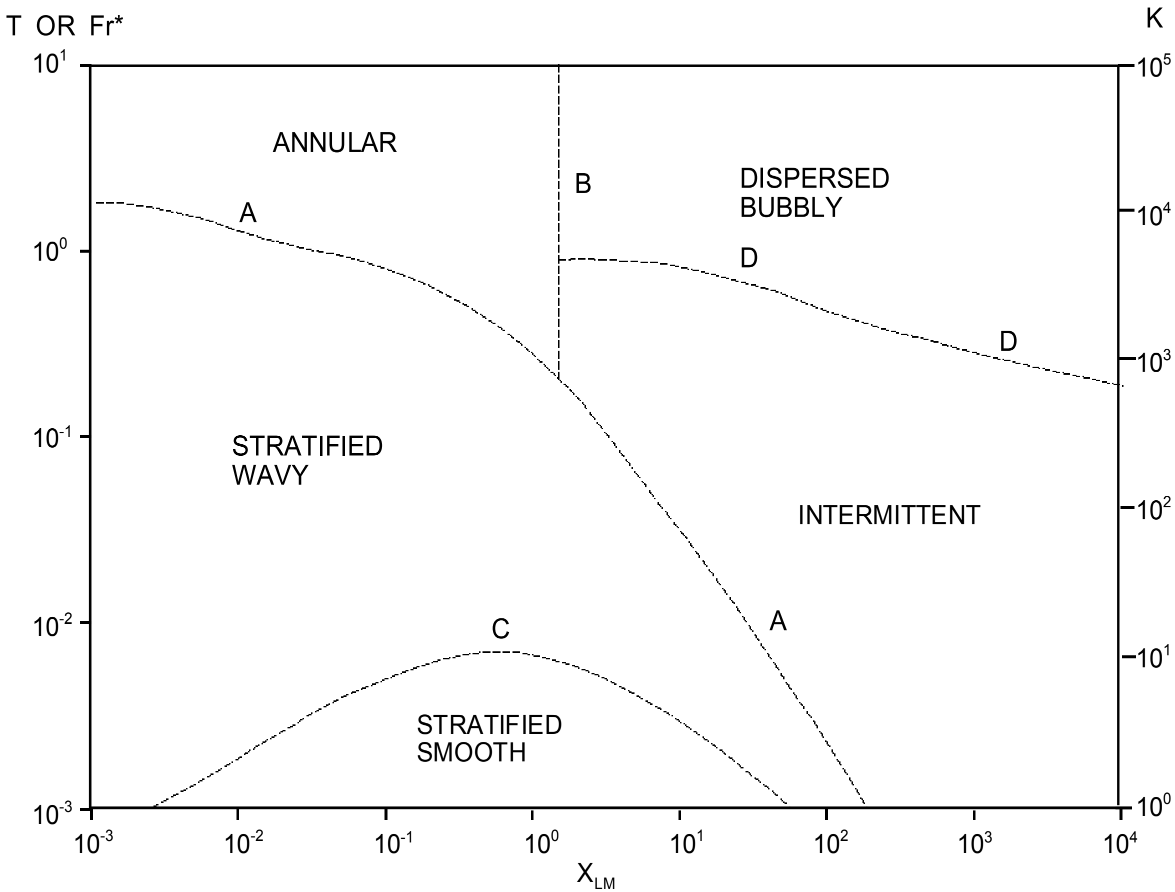
# Flow Patterns in Horizontal Flow



# Flow Pattern Map for Vertical Flow



# Flow Pattern Map for Horizontal Flow




CURVES : A & B C D

COORDINATES : $Fr^*$ vs. $X_{LM}$ $K$ vs. $X_{LM}$ $T$ vs. $X_{LM}$

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

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

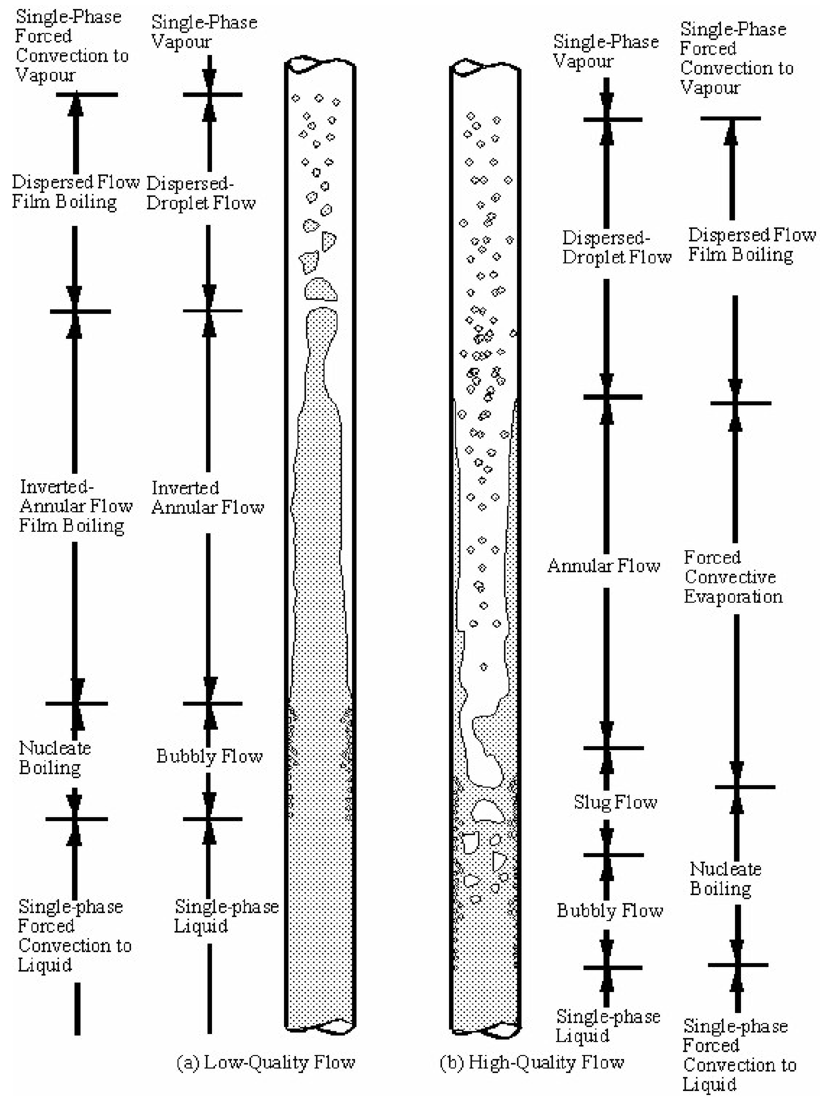
$$K = \left( \frac{\rho_g\, j_g^2\, j_f}{(\rho_f - \rho_g)\, g\, \nu_f \cos\theta} \right)^{0.5}$$

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

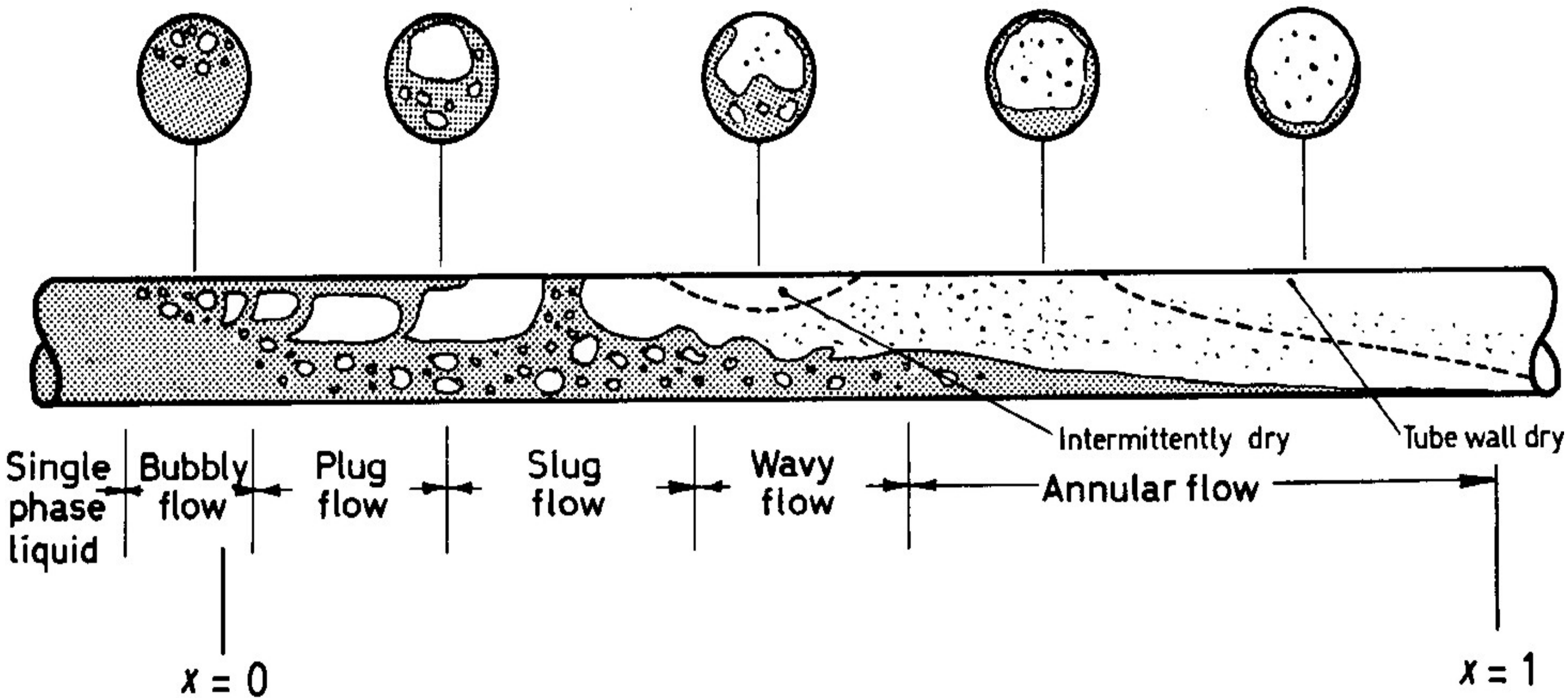
# Boiling

- 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

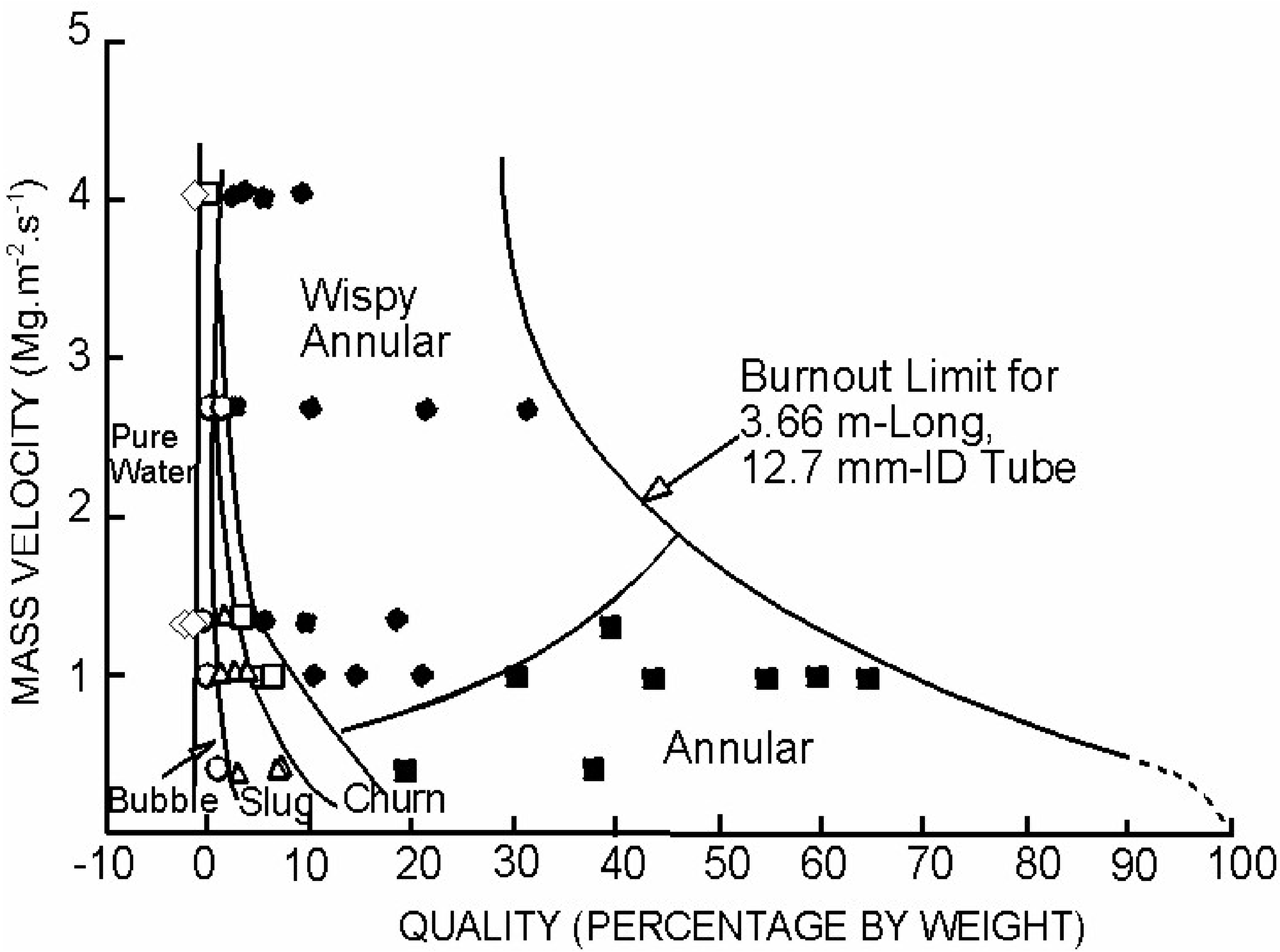
# Flow Patterns in Vertical Heated Channels



# Flow Patterns in Horizontal Heated Channel



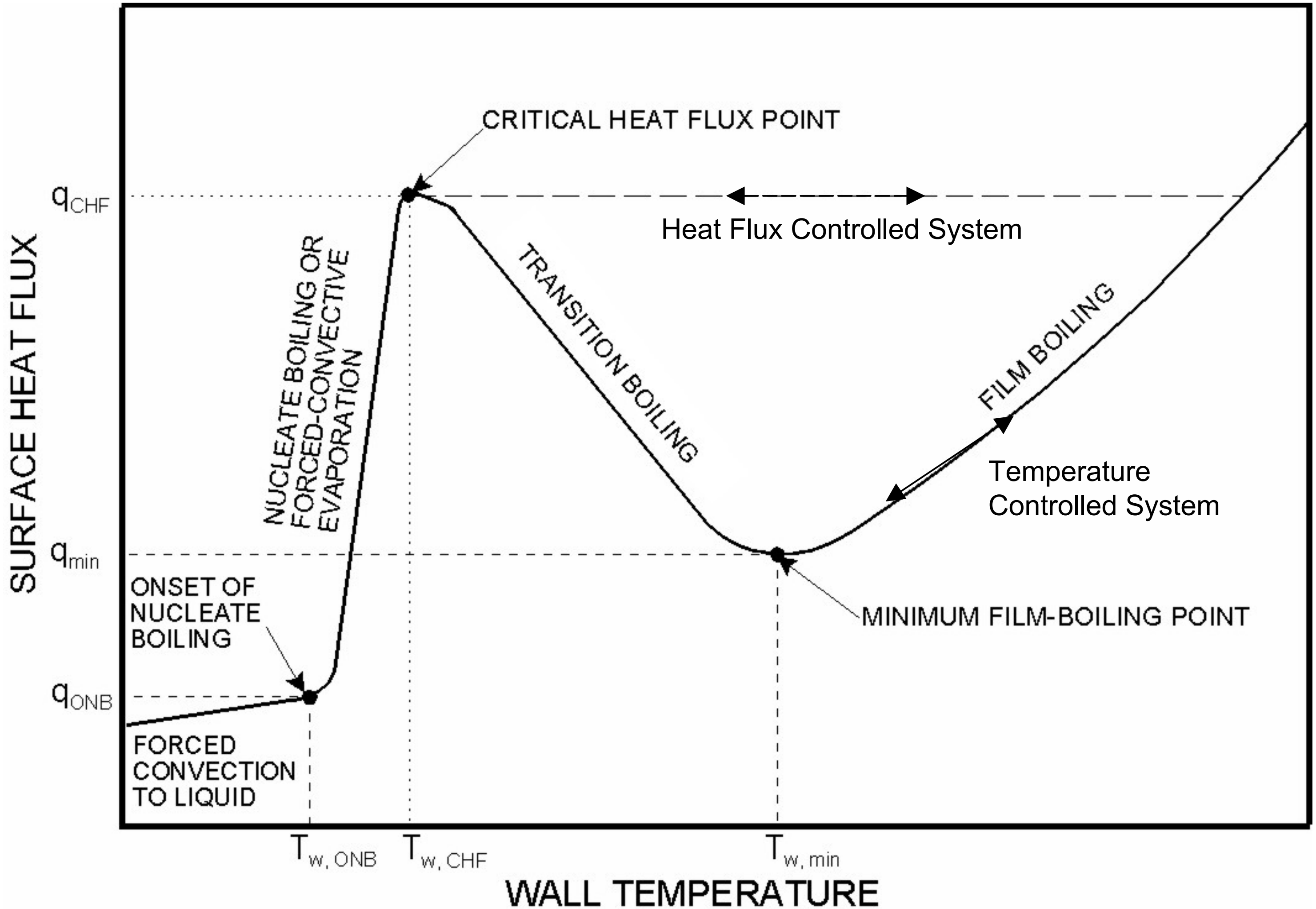
# Flow Pattern Map in a Heated Channel



# 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

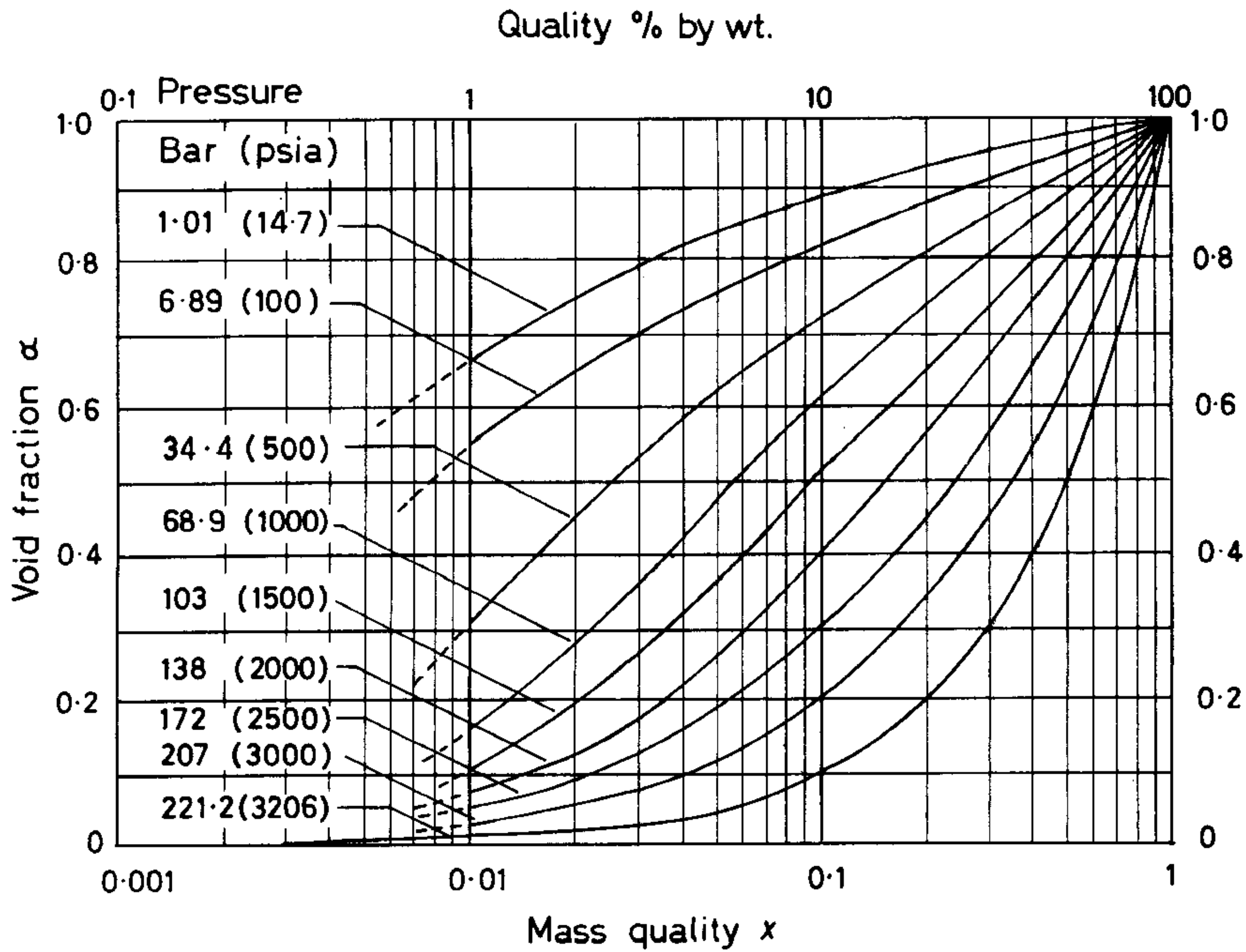
# Boiling Curve



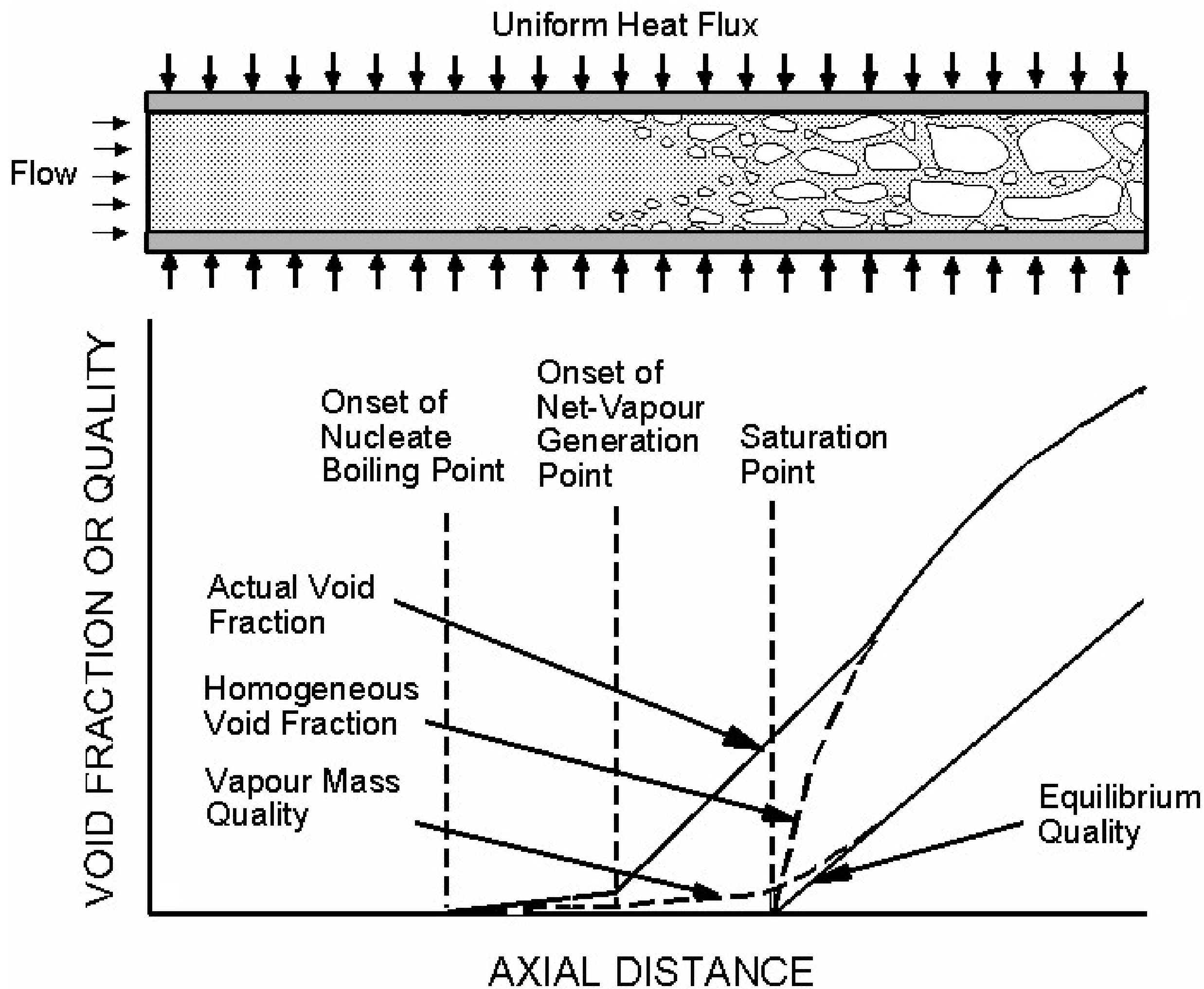
# Void Fraction

- 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

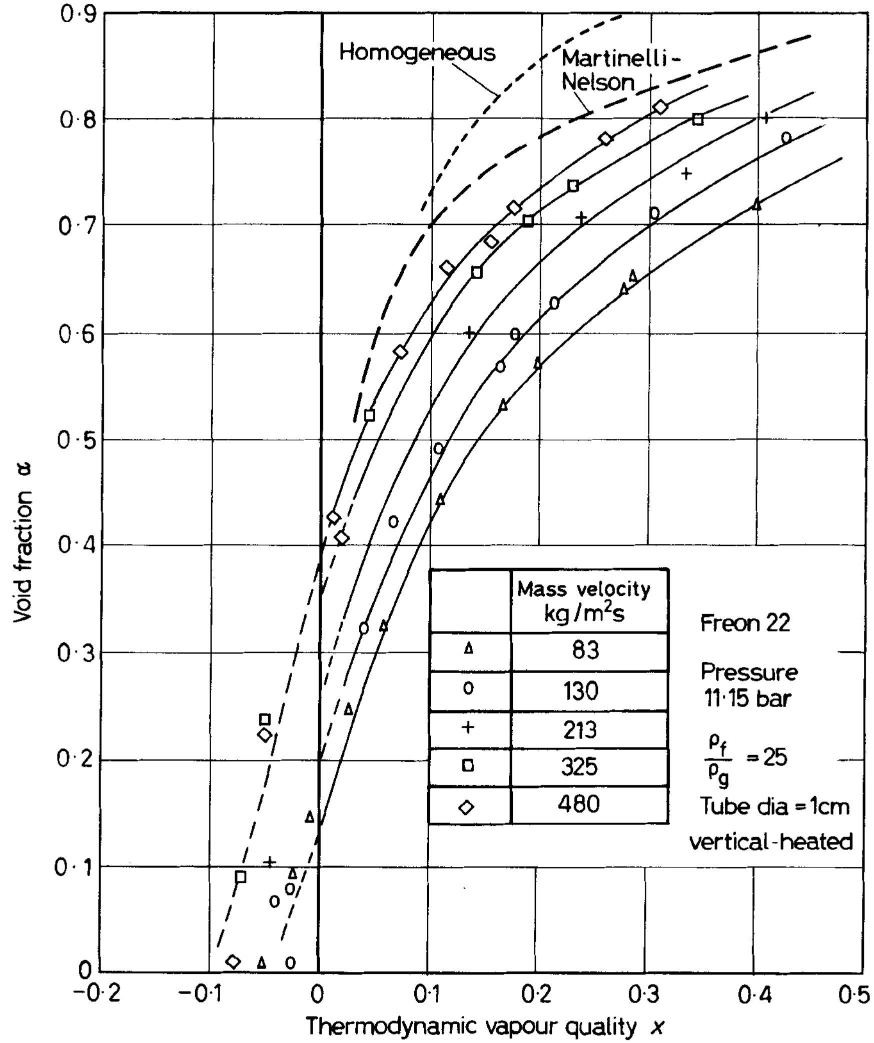
# Effects of Pressure and Quality



# Subcooled Boiling



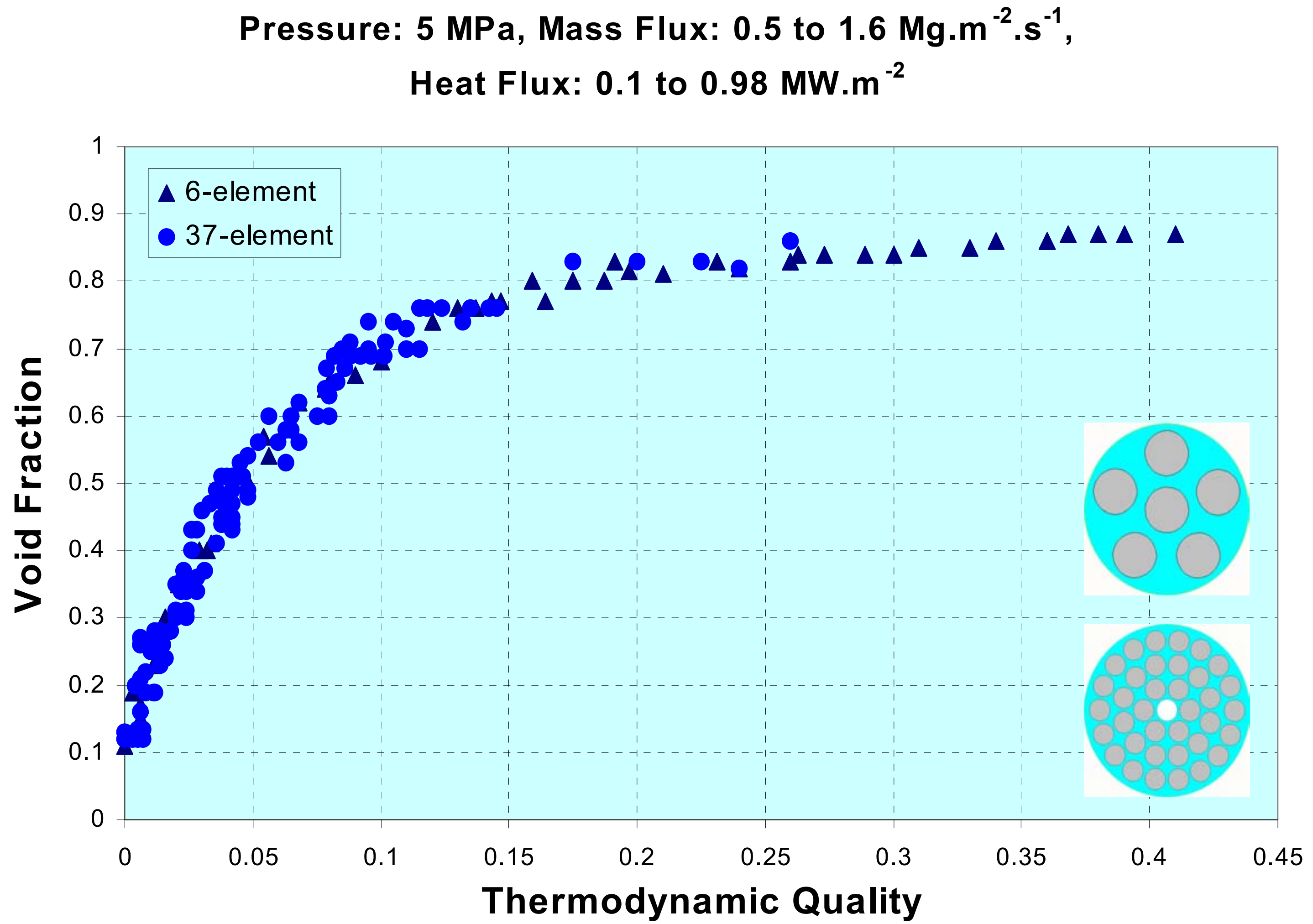
# Subcooled Void Measurements



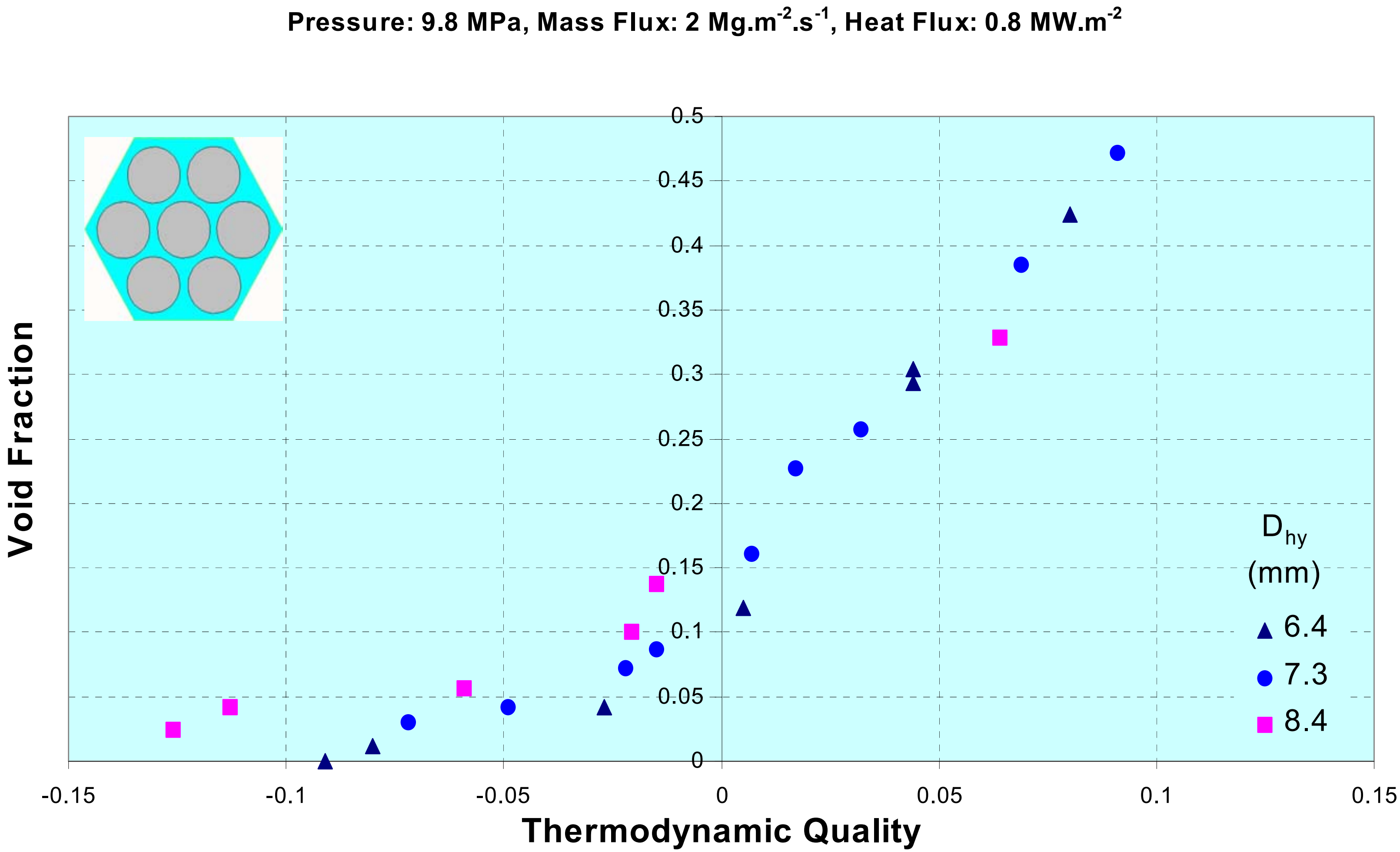
# Void Fraction in Bundles

- 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



# Effect of Flow Tube Size



# 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

# Questions?