Multiphase Flow and Heat Transfer

ME546

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Two Phase Flow

Reference:

S. Mostafa Ghiaasiaan, *Two-Phase Flow, Boiling and Condensation*, Cambridge University Press.

http://dx.doi.org/10.1017/CBO9780511619410

Two Phase Flow - Introduction

- Two phase flows are commonly found in ordinary life and in industrial processes
- Gas-liquid flow also occurs in boiling and condensation operations
- Inside pipelines which carry oil or gas alone, but which actually carry a mixture of oil and gas.

Two Phase Flow – How They Differs

Single phase flow

Laminar, transition, and turbulent

When the flow regime changes from laminar to turbulent

the personality of the fluid completely changes

the phenomena governing the transport processes change

Two phase flow

Similar situation

However, there is a multitude of flow regimes

The behavior of a gas–liquid mixture depends strongly on the flow regimes.

Methods for predicting the major flow regimes are required, for the modeling and analysis of two-phase flow systems

Two Phase Flow Patterns

Morphological variations

1. $\Delta\rho$ between phases. Respond differently to gravity and centrifugal forces
2. The deformability of the gas-liquid interphase that often results in incessant coalescence and breakup processes
3. Surface tension forces, maintains one phase dispersal

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Flow regimes and their ranges of occurrence are **sensitive** to

- fluid properties, system configuration/and orientation, size scale of the system, occurrence of phase change, etc.
- Most widely used: steady-state and adiabatic air-water and steam-water in uniform-cross-section long vertical pipes, or large vertical rod bundles with uniform inlet conditions

Basic Definitions

Quality and void fractions are two parameters which characterize two-phase flows.

Equilibrium Quality

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

Quality

Flow quality

$$x = \frac{\dot{m}_g}{\dot{m}_g + \dot{m}_f}$$

Represents the true flow fraction of vapor in a flow stream, irrespective of whether equilibrium exists or not

Static quality

$$x_s = \frac{m_g}{m_g + m_f}$$

Represents mass fraction of vapor phase at a particular cross section. The static quality is important for a closed system thermodynamic analysis and in nuclear applications for such things are reactivity calculations.

Void Fraction

Void Fraction: Time averaged volume fraction of the vapor in a two phase control volume.

$$\alpha = \frac{\iiint_{V_g} dV}{\iiint_V dV} = \frac{V_g}{V_g + V_f} = \frac{\Delta z \iint_{A_g} dA}{\Delta z \iint_A dA} = \frac{A_g}{A}$$

In choosing a control volume of thickness Δz, the randomness and transient is left in the area term. Void fraction, like the flow is a random, fluctuating quantity. However, it is assumed that the VF is a stationary random process such that the simple time average and ensemble average are the same such that the void fraction as defined above is a time-averaged deterministic quantity.

Velocity

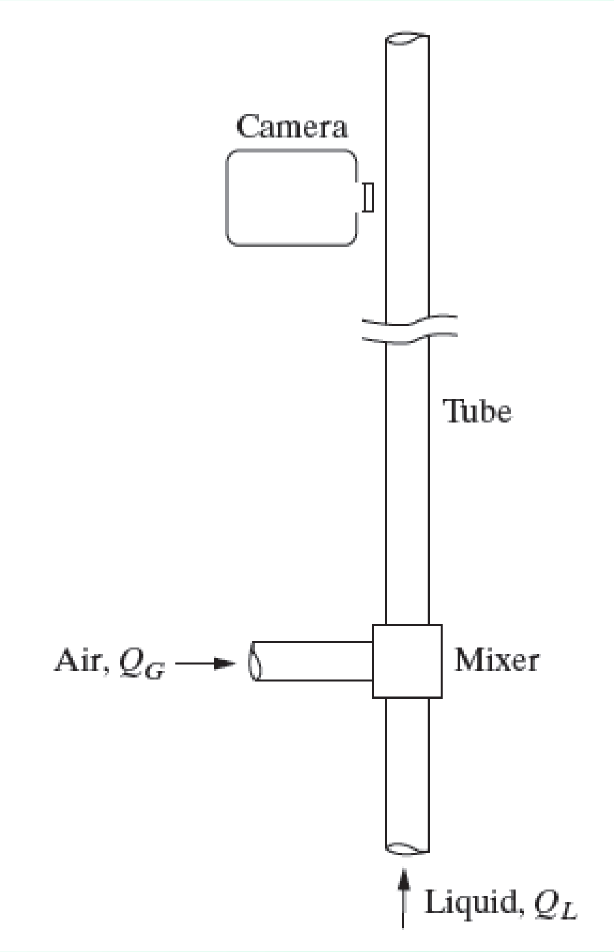
Phase Velocity: The one-dimensional velocity of each phase is defined as the volumetric flow of the given phase through its individual phase cross sectional area.

$$u_f = \frac{Q_f}{A_f}, u_g = \frac{Q_g}{A_g}$$

Volumetric flux or Superficial velocity: Volumetric flow of a particular phase divided by the total flow area of the field.

$$j_f = \frac{Q_f}{A}, j_g = \frac{Q_g}{A}$$

Vertical, Co-current, Upward Flow



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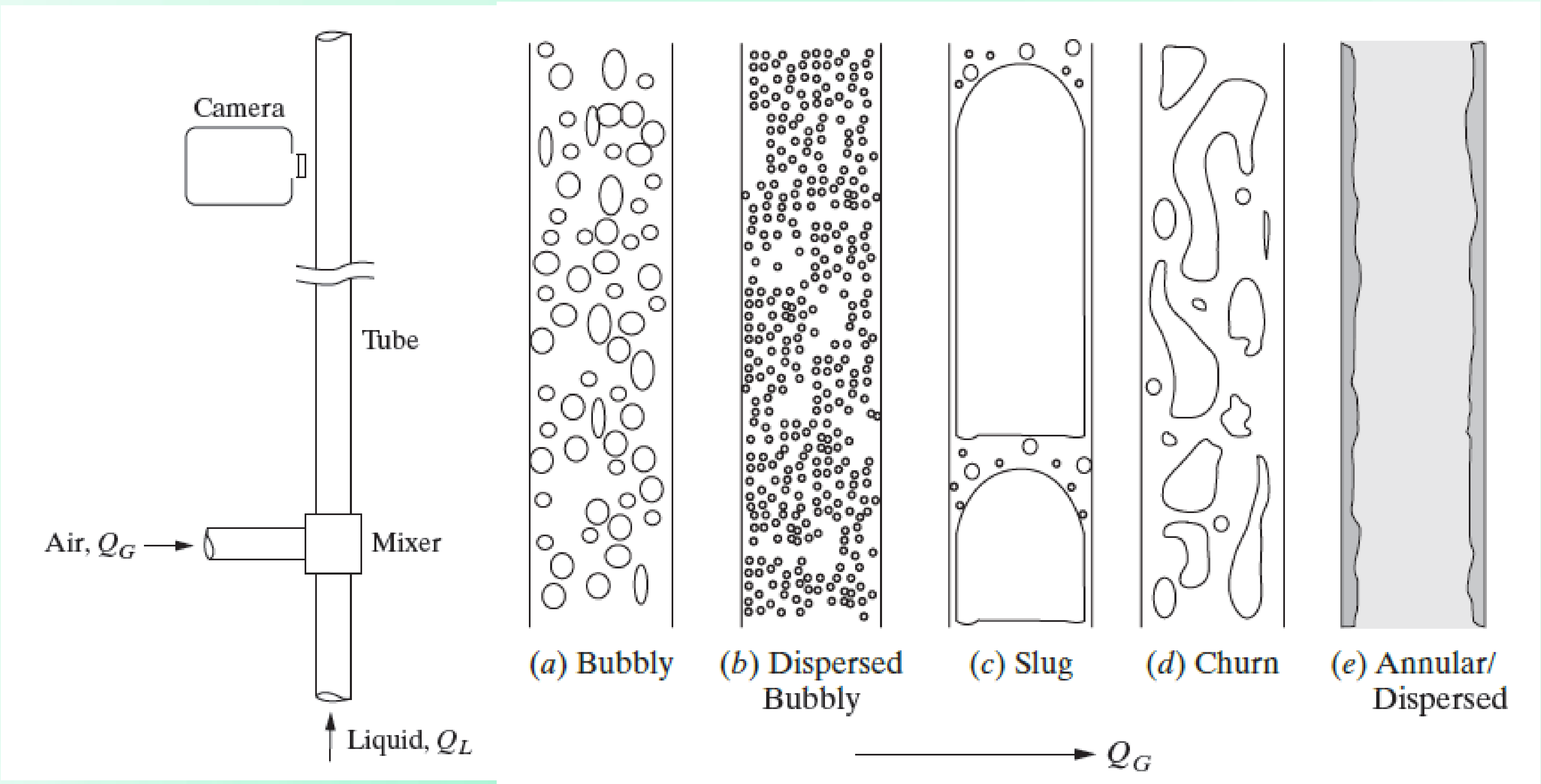
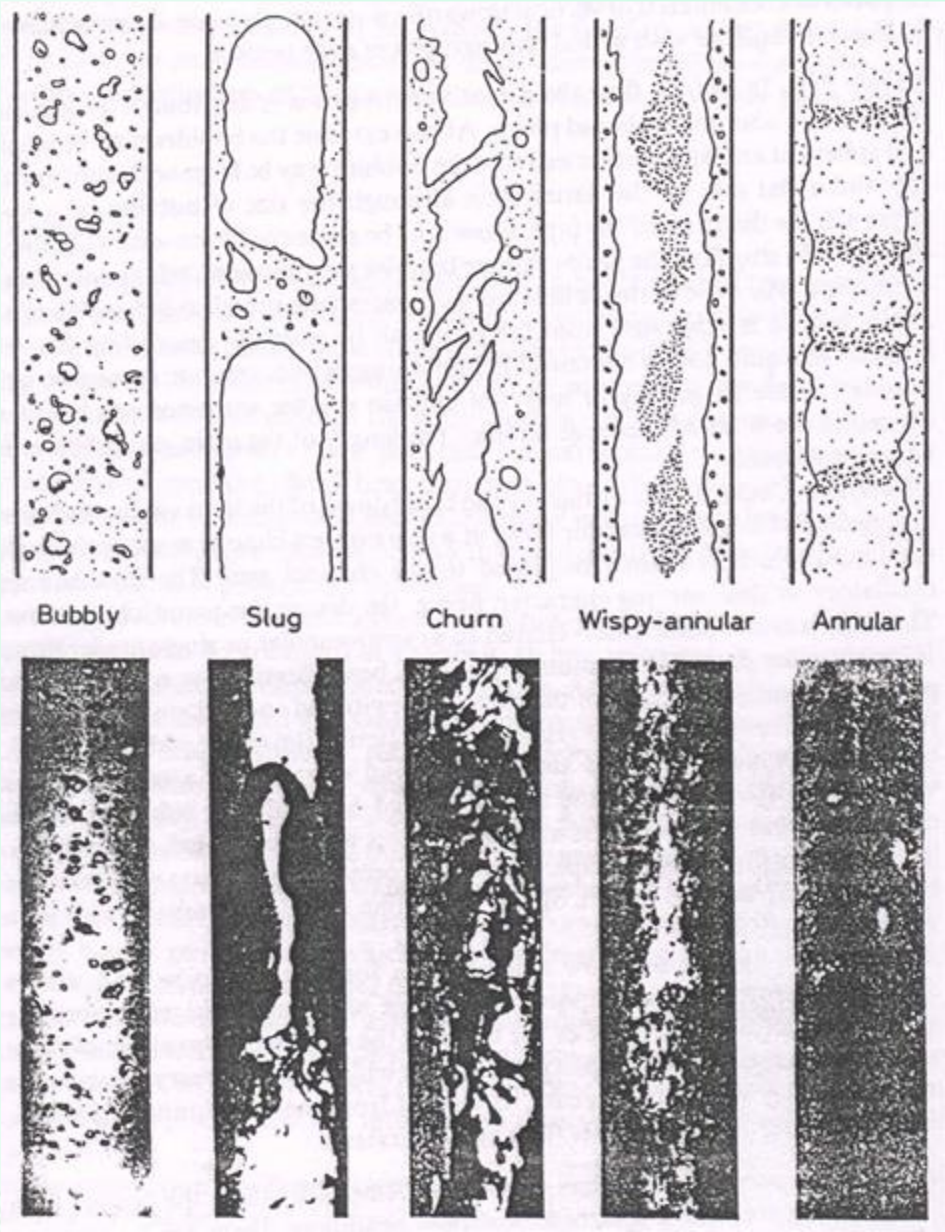


Vertical Co-current Flow (Adiabatic)



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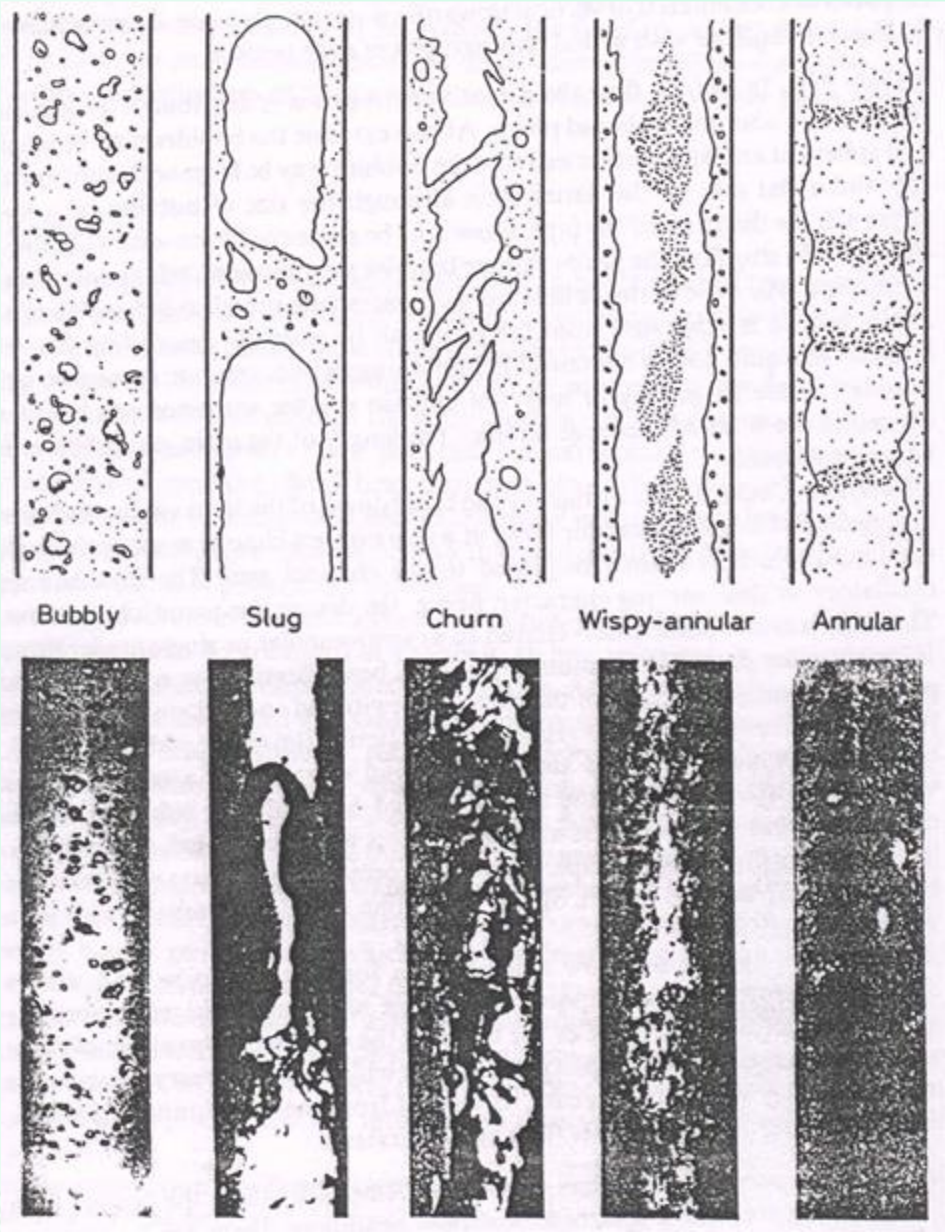

Bubbly – bubbles are of uniform size. Least interaction at very low Q_G, but increase in number density with Q_G. At higher Q_G, bubbles interact, leading to their coalescence and breakup.

Plug/Slug – Forms very large bubbles. Bullet-shaped (Taylor bubbles) with hemispherical caps and are separated by *liquid slugs* (contains small bubbles). The maximum $L_s/D \sim 16$,

Churn – highly unstable/chaotic motion flow of an oscillatory nature: the liquid near the tube wall continually pulses up and down.

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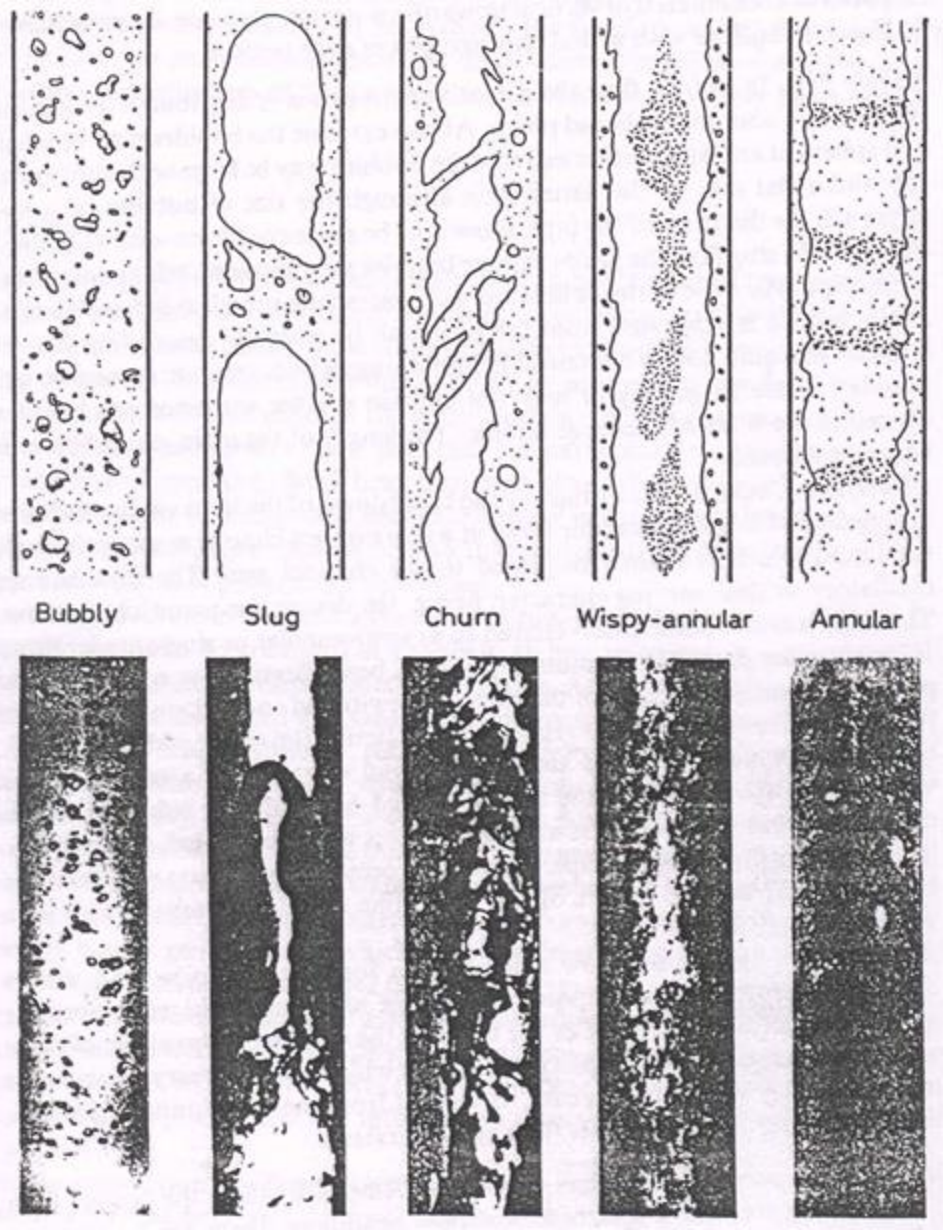


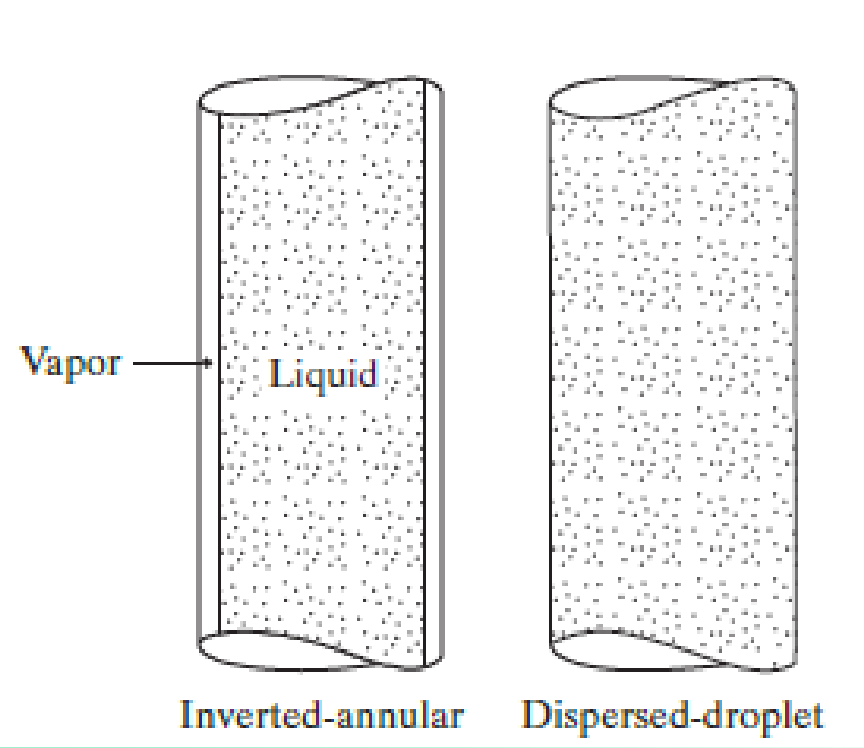
Wispy annular - The liquid in the film is aerated by small gas bubbles and the entrained liquid phase appears as large droplets which have agglomerated into long irregular filaments or wisps.

Annular – liquid travels partly as an annular film on the walls of the tube and partly as small drops distributed in the gas which flows in the center of the tube

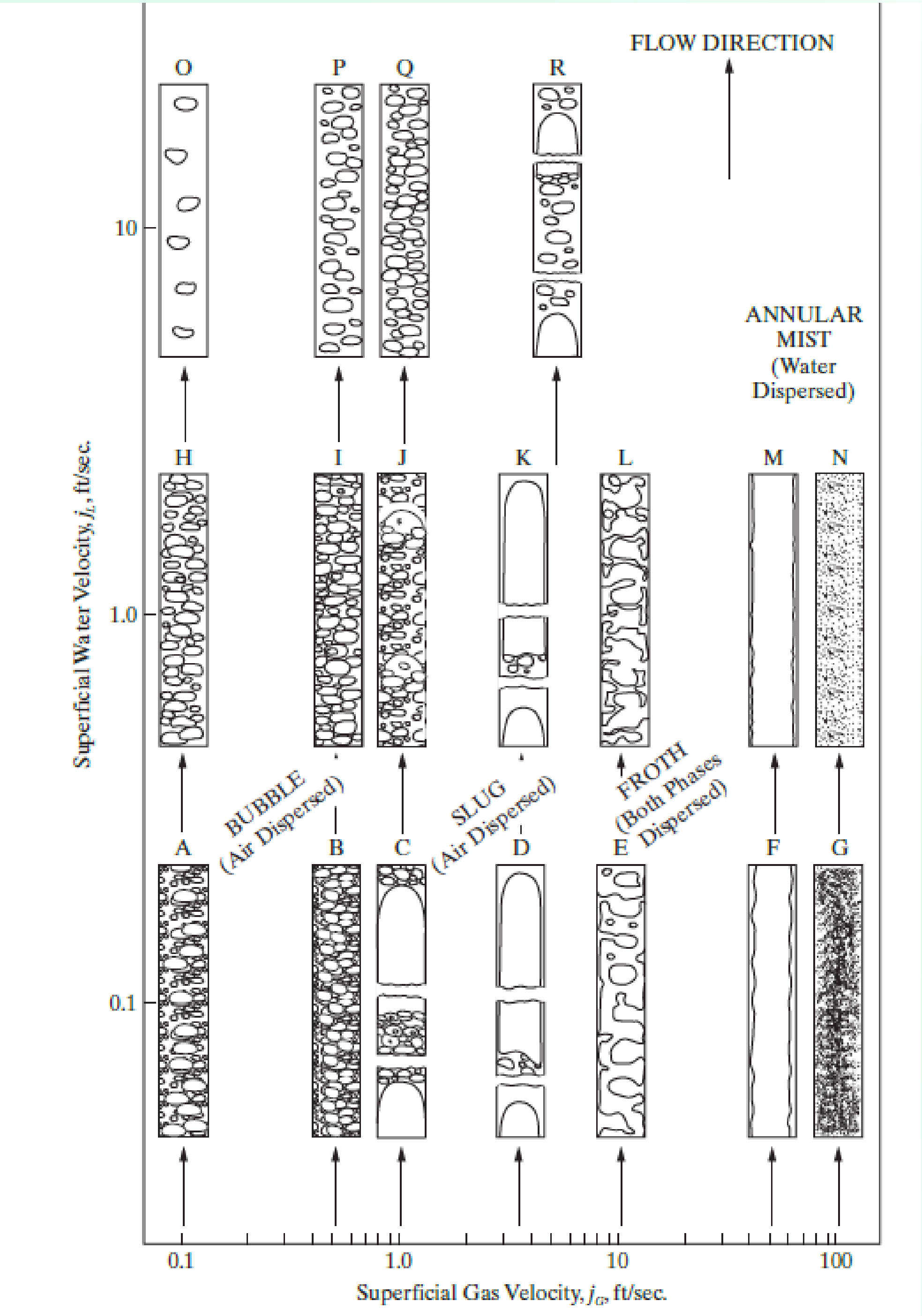
Vertical Co-current Flow (Boiling Channels)

Inverted-annular – This flow regime takes place in channels subject to high wall heat fluxes and leads to an undesirable departure from nucleate boiling.

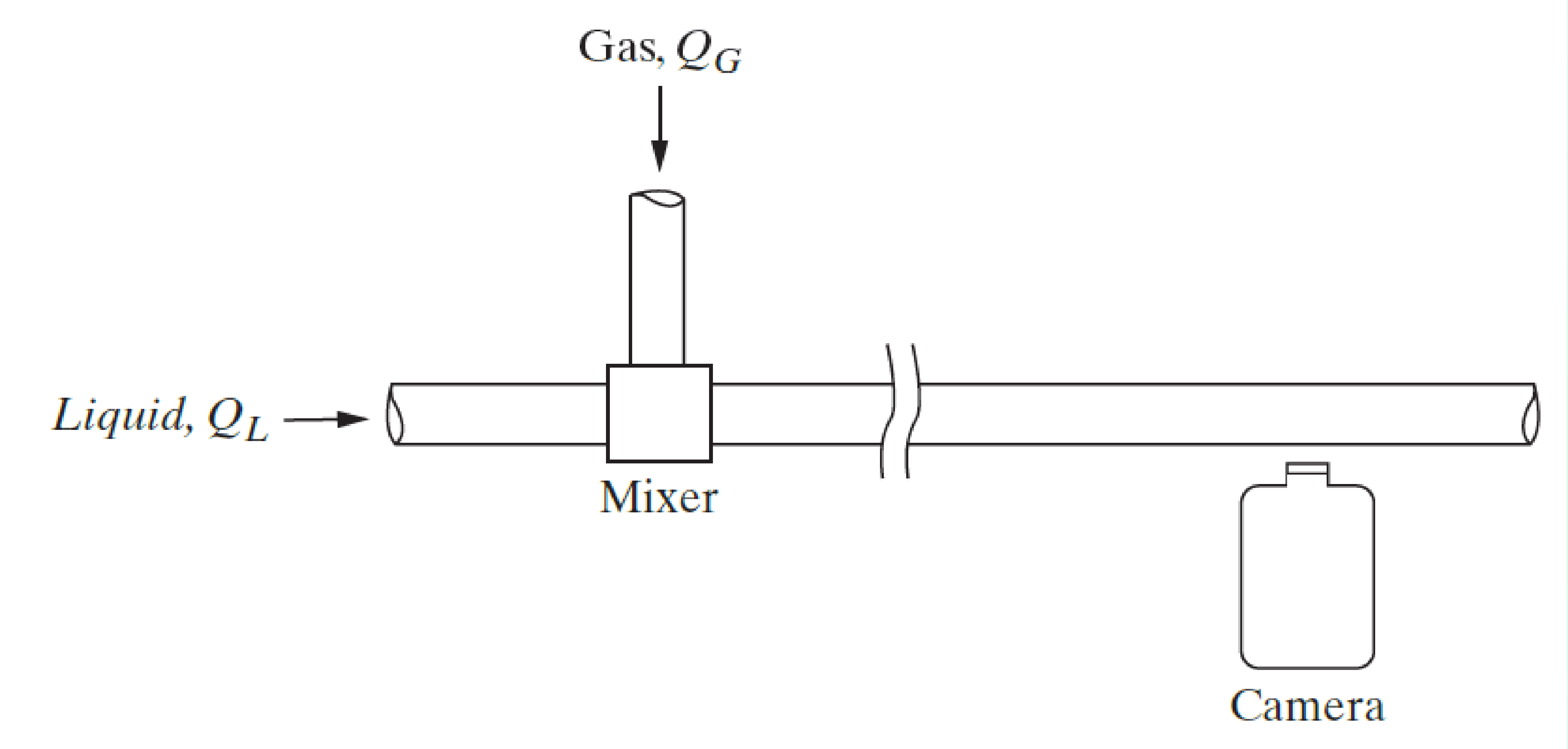
Dispersed-droplet – superheated vapor containing entrained droplets flows in a dry channel. Occurs when massive evaporation has already caused the depletion of most of the liquid.



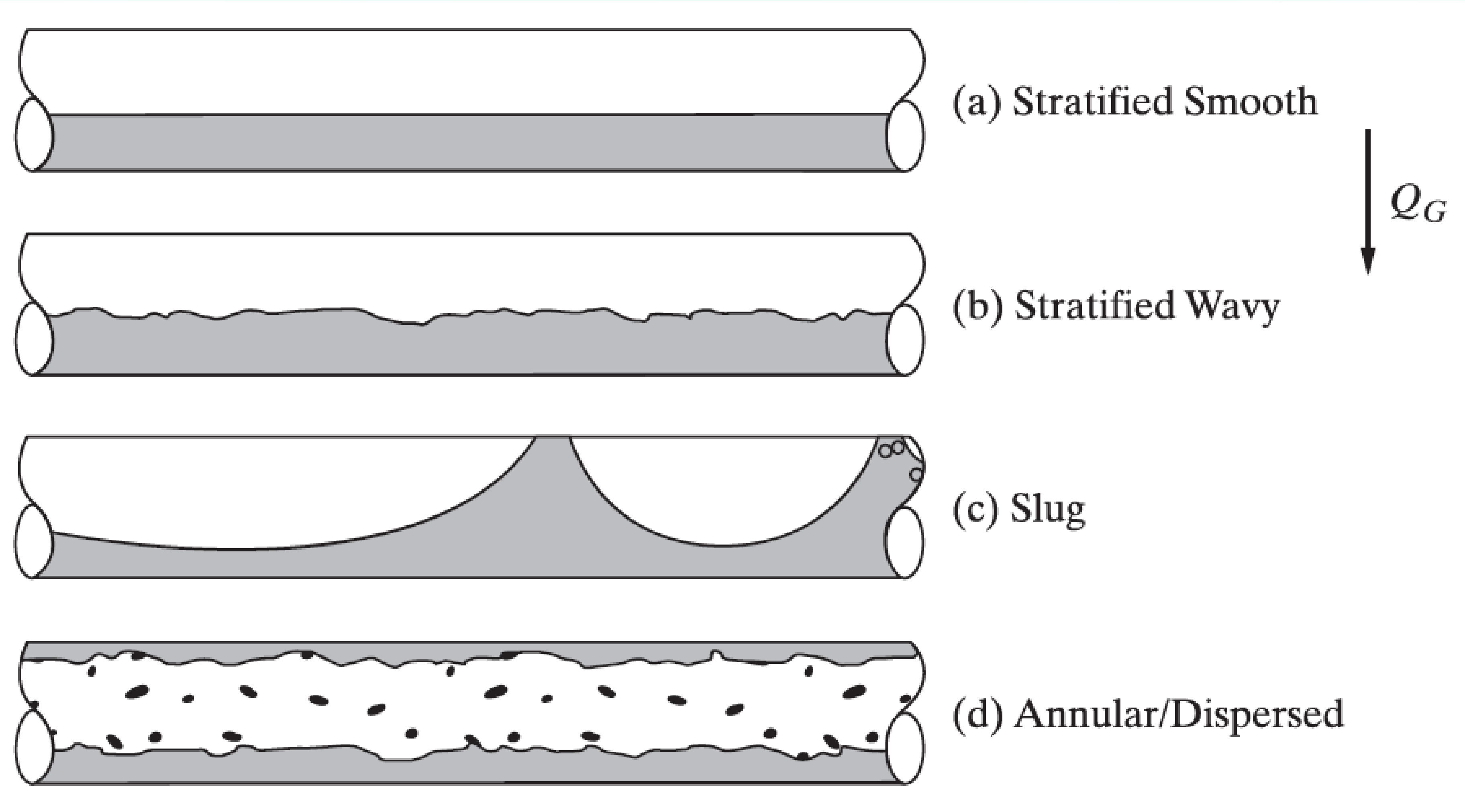
Flow regimes of air-water flow in a 2.6 cm diameter vertical tube



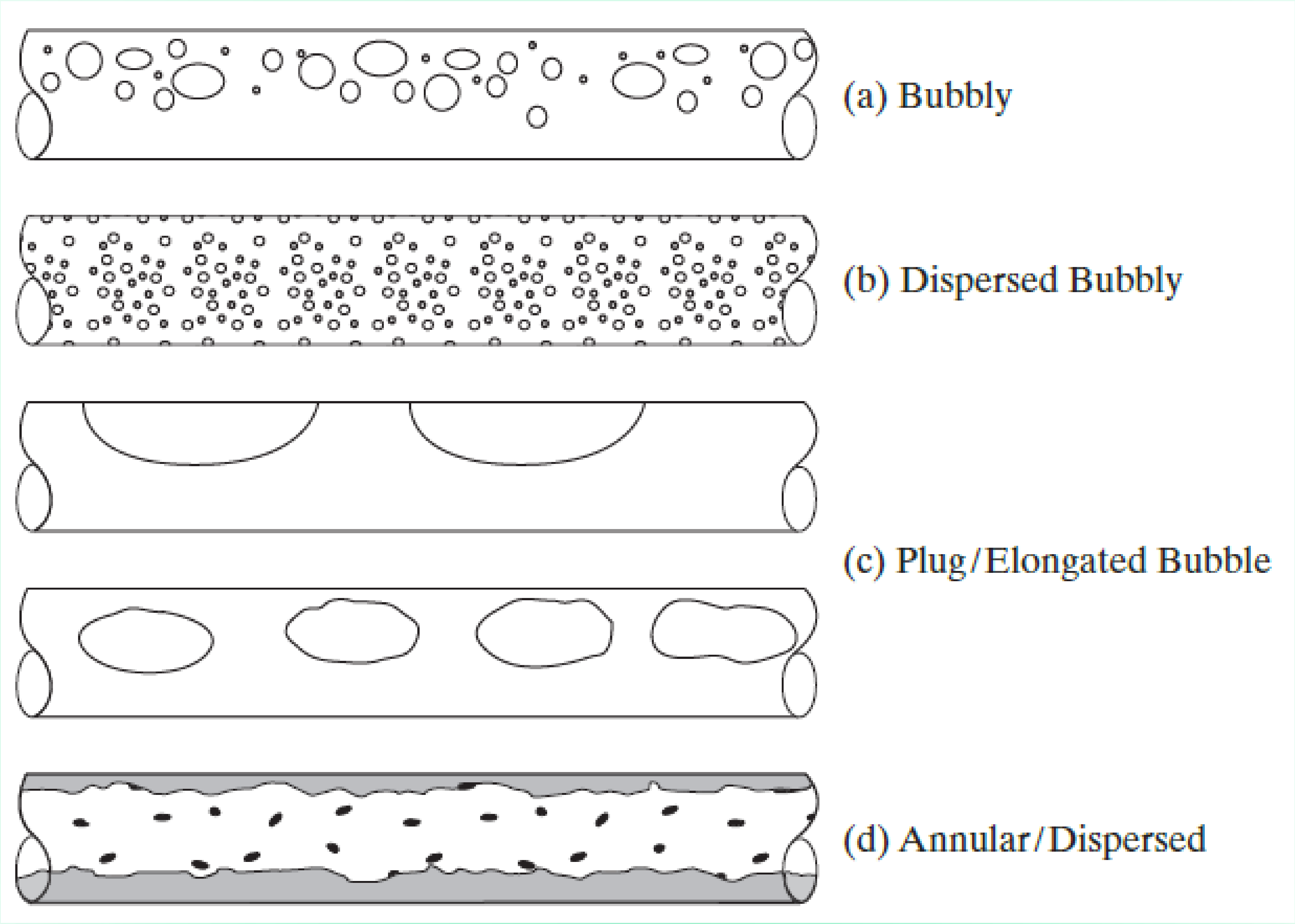
Horizontal, Co-current



Horizontal, Co-current – Low Liquid Flow Rate



Horizontal, Co-current – High Liquid Flow Rate



Horizontal Co-current Flow (Adiabatic)

Bubbly – bubbles flows on top

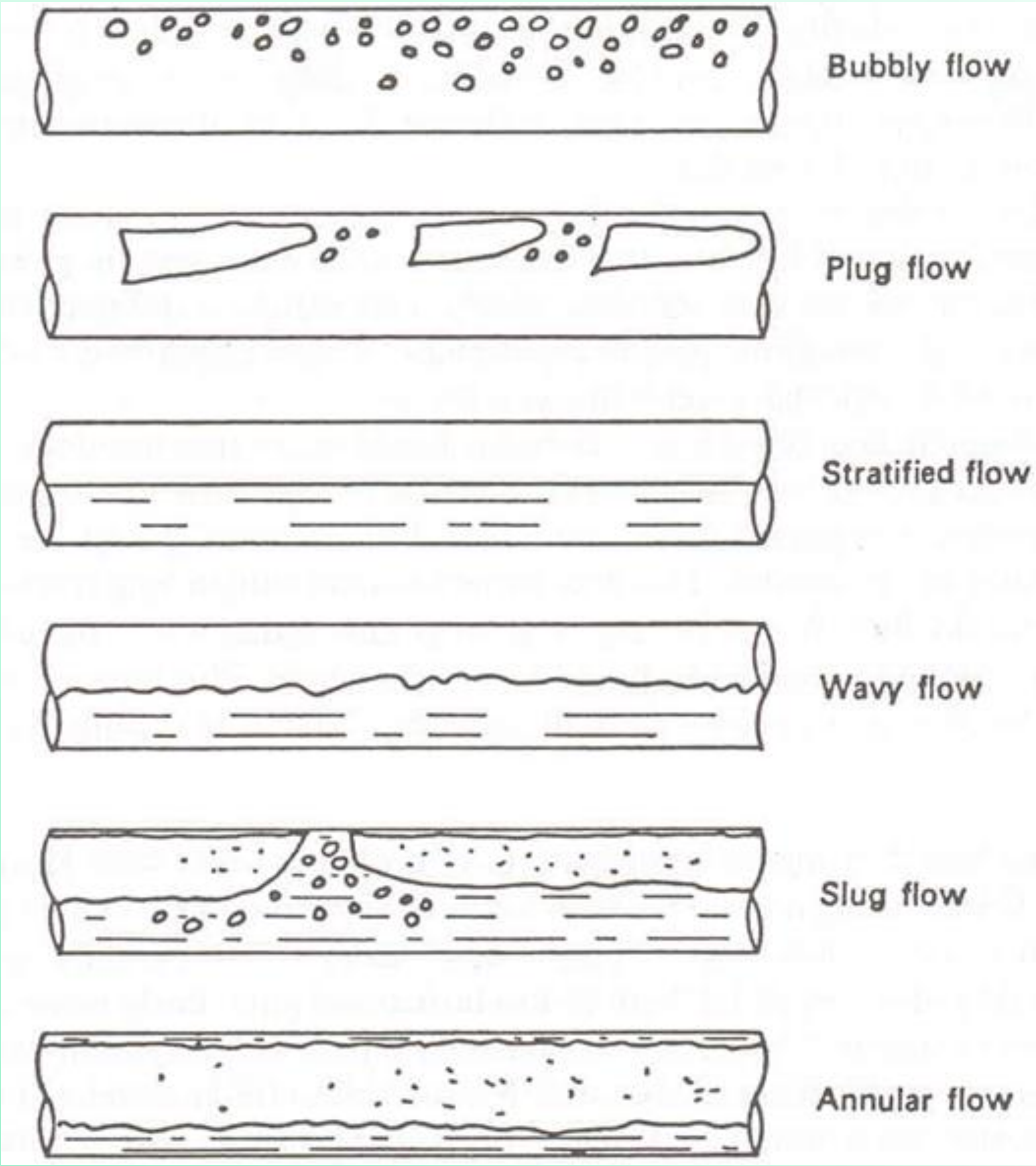
Plug – Small bubbles have coalesced to produce long plugs

Stratified – interface is smooth. This doesn't occur usually

Wavy – wave amplitude increases as the gas velocity increases

Slug – wave amplitude is so large that the wave touches top of tube

Annular – similar to vertical annular flow except that the liquid film is much thicker at the bottom of the tube than at the top.



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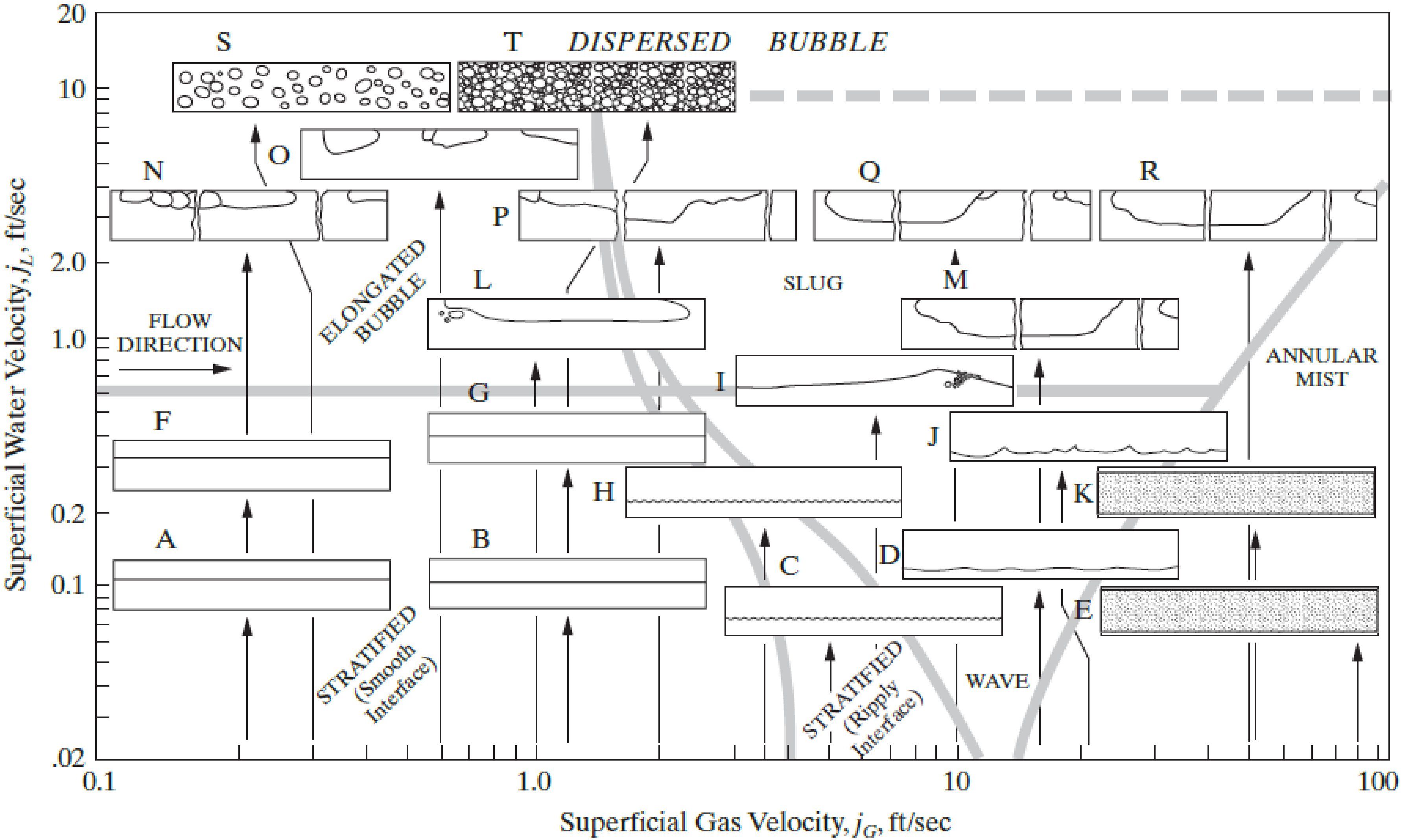
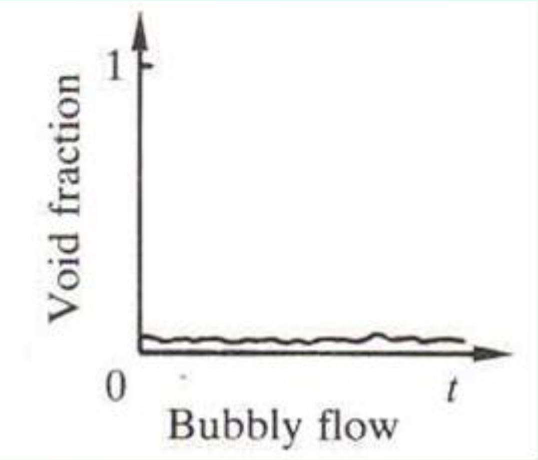
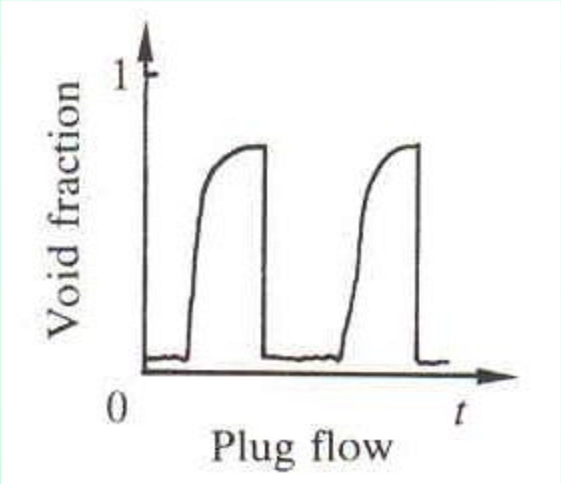
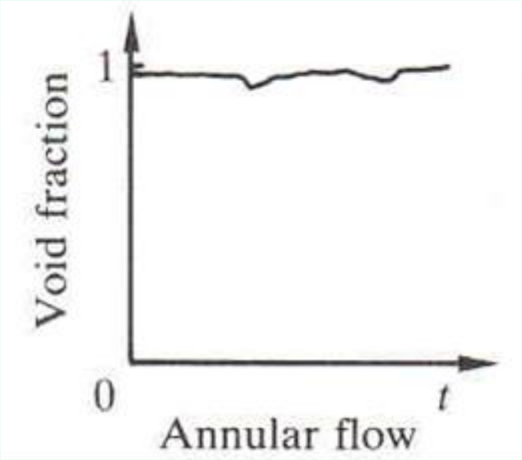


Idealized Response of a Void Fraction Probe







Various instruments like gamma ray densitometry, capacitance probe and resistance probes give the distribution of void fraction

Results are rarely so conclusive

Summary

1. Flow regimes and conditions depends on
   - geometry: size, shape, aspect ratio of channel, flow disturbances
   - liquid properties: σ, μ, ρ_l/ρ_g

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4. The regime change boundaries are generally difficult to define due to the occurrence of extensive “transitional” regimes
5. Bubbly, plug/slug, churn, annular flows also occur in minichannels (100 μm ≤ D ≤ 1 mm)
6. Regimes in phase change are significantly different from adiabatic

Flow Pattern Maps

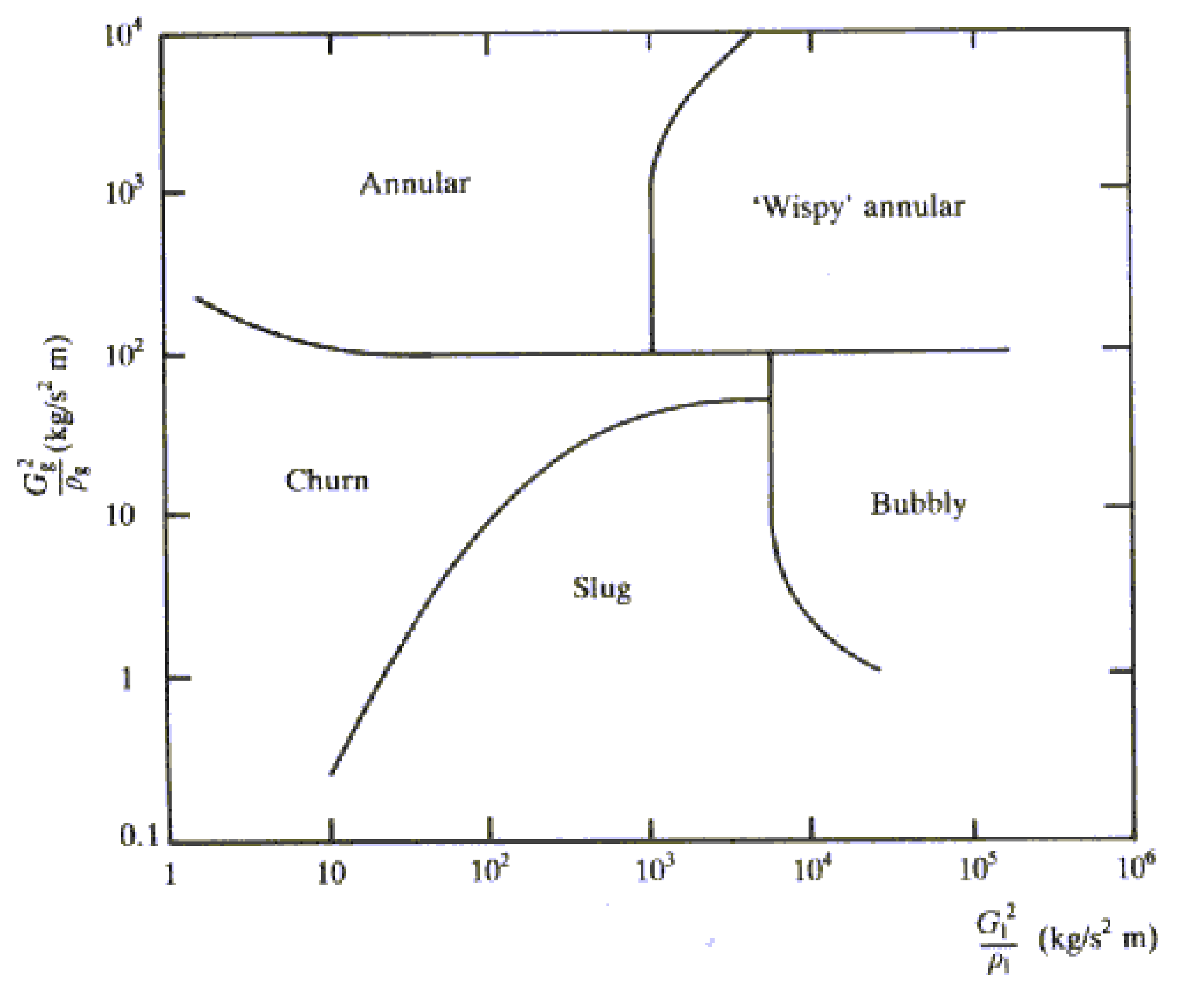
Flow pattern maps are 2D graphs to separate the space into areas corresponding to the various flow patterns

Hewitt and Roberts Map – Vertical upflow in a tube

Baker Map – Horizontal flow

Taitel and Dukler Map – Horizontal flow

Vertical, Co-current: Hewitt and Roberts



$$G_g = \frac{\text{Gas Mass Flow Rate}}{\text{Tube Cross sectional Area}}$$

$$G_l = \frac{\text{Liquid Mass Flow Rate}}{\text{Tube Cross sectional Area}}$$

This map works reasonably well for water-air and water-steam systems over a range of pressures, again in small diameter tubes

Baker’s Map (1954) - Modified Scott (1963)

- One of the earliest flow pattern maps for horizontal adiabatic flow
- Developed based on air-water data
- Identifies stratified, plug, slug, wavy, annular, bubbly flow patterns

Procedure to Use Baker's Map (1954)

Determine mass velocities of the liquid (G_l) and vapor (G_g)

Calculate gas-phase parameter λ and liquid-phase parameter ψ

$$\lambda = \left(\frac{\rho_g \rho_l}{\rho_{\text{air}} \rho_{\text{water}}}\right)^{0.5}$$

$$G_g = \frac{\text{Gas Mass Flow Rate}}{\text{Tube Crosssectional Area}}$$

$$\psi = \frac{\sigma_{\text{water}}}{\sigma}\left[\frac{\mu_l}{\mu_{\text{water}}}\left(\frac{\rho_{\text{water}}}{\rho_l}\right)^2\right]^{\frac{1}{3}}$$

$$G_l = \frac{\text{Liquid Mass Flow Rate}}{\text{Tube Crosssectional Area}}$$

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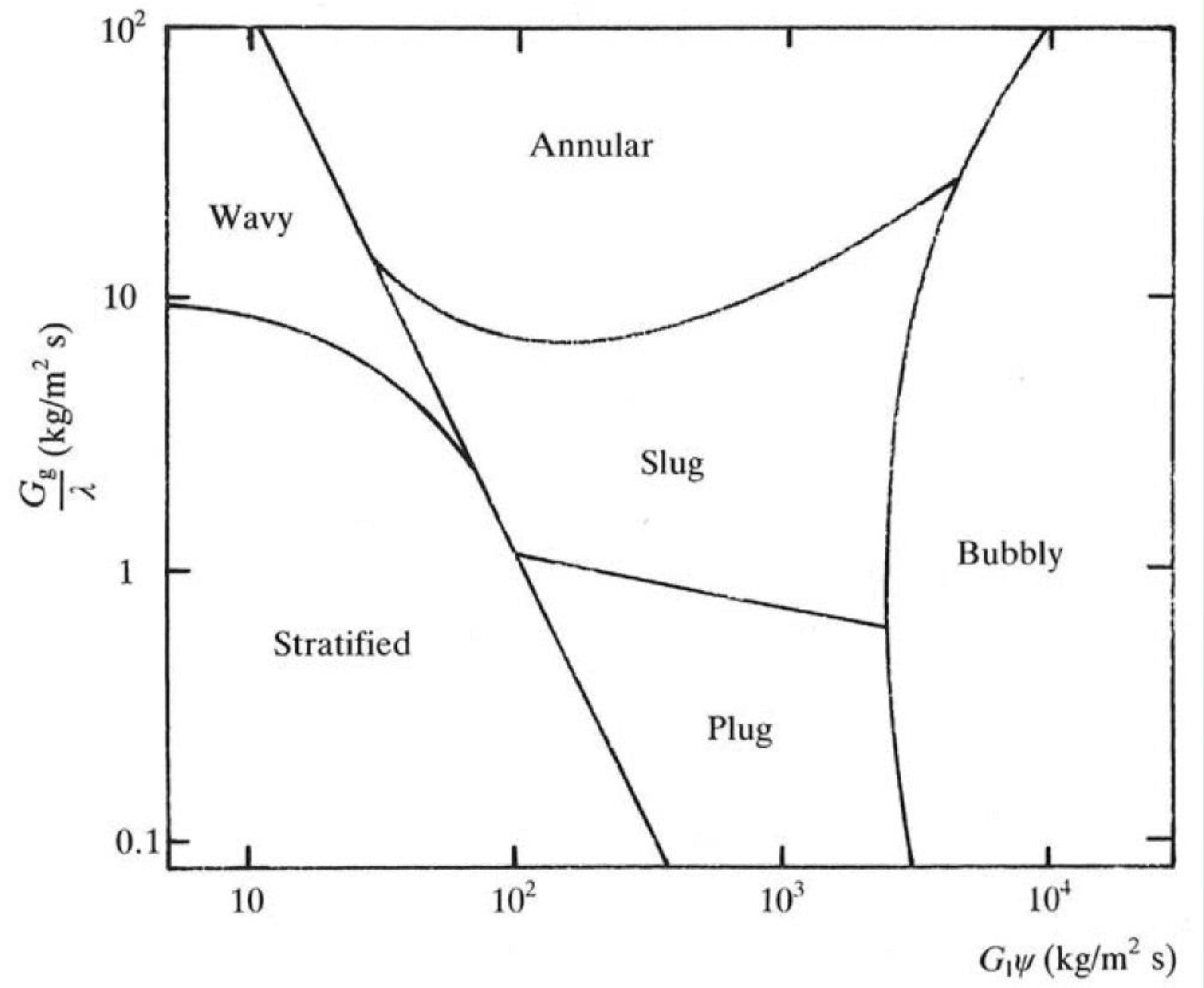
- Properties of air and water are evaluated at standard atmospheric pressure and room temperature
- Standard dimensionless parameters λ and ψ take into account the variation in the properties of the fluid

Horizontal, Co-current: Baker (1954)



Works for R12 in 8 mm diameter horizontal tube

Taitel and Dukler Map, 1976

- Proposed in 1976 for horizontal flow in tube
- Originally developed for adiabatic flow with no phase change
- The map uses Martinelli parameter (X_{tt}) the gas Froude number (Fr_G) and the parameters T and K

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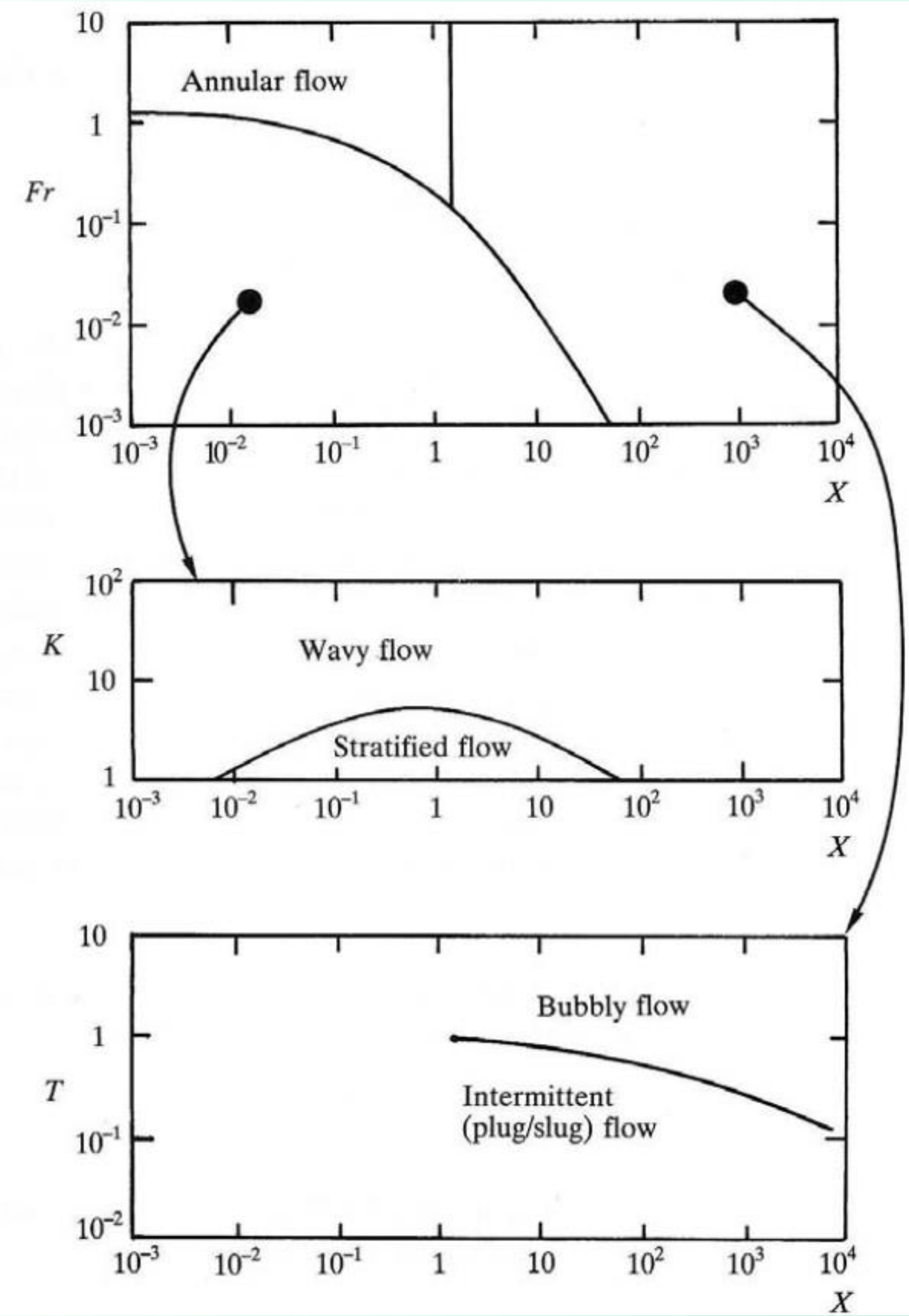
Procedure

- If (Fr_g, X) falls in **annular flow regime**, then the flow is
- If (Fr_g, X) falls in the lower left zone
  - Using (K, X), identify **stratified-wavy or fully stratified**
- If (Fr_g, X) falls in the right zone
  - Using (T, X), identify **bubbly or intermittent (plug/slug)**

The map was tested for condensation with water, methanol, propanol, R113, N-pentane in 24.4 mm tube



$$Fr_g = \frac{G_g}{\left[\rho_g(\rho_l - \rho_g)Dg\right]^{\frac{1}{2}}}$$

$$T = \left[\frac{|(dp/dz)_L|}{g(\rho_l - \rho_g)}\right]^{\frac{1}{2}}$$

$$K = Fr_g Re_l^{\frac{1}{2}}$$

$$X = \left[\frac{(dp/dz)_l}{(dp/dz)_g}\right]^{\frac{1}{2}}$$

$$\mathrm{Re}_f = \frac{G_f D}{\mu_f}, f \text{ is either } g \text{ or } l$$

$$(dp/dz)_f = \frac{2 f_f G_f^2}{\rho_f D}$$

$$f_f = \begin{cases} \dfrac{16}{\mathrm{Re}_f}, \mathrm{Re}_f \leq 2000 \\ \dfrac{0.079}{\mathrm{Re}_f}, \mathrm{Re}_f > 2000 \end{cases}$$

Problem: Flow Pattern in Vertical and Horizontal

Find the flow pattern when 4 kg/s of steam-water mixture of quality 20% at 20 bar flows in a 0.1 m circular tube.

ρ_l = 850 kg/m^3, ρ_g = 10 kg/m^3, μ_l = 128×10^{-6} Pa s, μ_g = 16×10^{-6} Pa s

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Vertical Upflow:

$$G = \frac{4}{\pi\, 0.1^2/4} = 509\ \text{kg/m}^2\text{s}$$

$$G_g = xG = 102\ \text{kg/m}^2\text{s}$$

$$G_l = (1 - x)G$$

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