Reference:
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
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
Two Phase Flow Patterns

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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
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 as 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 \(\Delta z\), 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.

\[ u_f = \frac{Q_f}{A_f}, \quad u_g = \frac{Q_g}{A_g} \]

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

\[ j_f = \frac{Q_f}{A}, \quad j_g = \frac{Q_g}{A} \]
Vertical, Co-current, Upward Flow
Vertical, Co-current, Upward Flow
**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.
Vertical Co-current Flow (Adiabatic)

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

Liquid, $Q_L$ → Mixer → Gas, $Q_G$ → Camera
Horizontal, Co-current – Low Liquid Flow Rate

(a) Stratified Smooth

(b) Stratified Wavy

(c) Slug

(d) Annular/Dispersed

\( Q_G \)
Horizontal, Co-current – High Liquid Flow Rate

(a) Bubbly

(b) Dispersed Bubbly

(c) Plug/Elongated Bubble

(d) Annular/Dispersed
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.
Horizontal, Co-current
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 depend on
   • geometry: size, shape, aspect ratio of channel, flow disturbances
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3. There could be multitude of subtle flow regimes.
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 ($100 \mu m \leq D \leq 1 mm$)
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

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

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

\[ G_l = \frac{\text{Liquid Mass Flow Rate}}{\text{Tube Crosssectional Area}} \]
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 $\lambda$ and liquid-phase parameter $\psi$

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

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

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- Properties of air and water are evaluated at standard atmospheric pressure and room temperature
- Standard dimensionless parameters \(\lambda\) and \(\psi\) 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
\[ Fr_g = \frac{G_g}{[\rho_g (\rho_l - \rho_g) D g]^{1/2}} \]

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

\[ K = Fr_g Re_f^2 \]

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

\[ Re_f = \frac{G_f D}{\mu_f}, f \text{ is either } g \text{ or } l \]

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

\[ f_f = \begin{cases} 
\frac{16}{Re_f}, & \text{Re}_f \leq 2000 \\
\frac{0.079}{Re_f}, & \text{Re}_f > 2000 
\end{cases} \]
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.

\[
\rho_l = 850 \text{ kg/m}^3, \quad \rho_g = 10 \text{ kg/m}^3, \quad \mu_l = 128 \times 10^{-6} \text{ Pa s}, \quad \mu_g = 16 \times 10^{-6} \text{ Pa s}
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**Vertical Upflow:**

\[
G = \frac{4}{\pi \cdot 0.1^2/4} = 509 \text{ kg/m}^2\text{s}
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\[
G_g = xG = 102 \text{ kg/m}^2\text{s}
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G_l = (1-x)G
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Problem: Flow Pattern in Vertical and Horizontal

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