MULTI PHASE FLOWS
(Flow Regimes & Flow maps)

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Introduction

Multiphase flow is simultaneous flow of:

- Materials with different states or phases (i.e. gas, liquid or solid).
- Materials with different chemical properties but in the same state (oil droplets in water).
Need to study two phase system

- Design of boilers: two-phase flow heat-transfer and pressure drop behaviour
- Nuclear reactor use two phase water system as coolant (removal heat from the reactor core)
- Pump cavitation
- Multiphase flow is important in many industrial processes:
  - Riser reactors.
  - Bubble column reactors.
  - Fluidized bed reactors.
  - Scrubbers, dryers, etc.
Flow patterns

- Single Phase: Laminar & Turbulent flows

- Multi phase flow: Internal Phase distribution ("flow patterns" or "flow regimes")

- Two-phase mixture of a gas or vapor and a liquid flowing together in a channel, different internal flow geometries or structures can occur that depend on
  - the size or orientation of the flow channel
  - relative magnitudes of these flow parameters
  - fluid properties of the two phases
Flow Patterns (vertical flow)

**System**: co-current upflow of gas & liquid in vertical pipe

1. **Bubble Flow** (*least gas void fraction*)
   - Gas phase in form of discrete bubbles
   - Continuous liquid phase
   - Bubbles – nearly spherical, smaller than tube diameter

2. **Slug Flow**
   - *Concentration of gas void fraction goes up*
   - Bubbles coalesce
   - Bubble diameter approaches that of the tube.
   - Characteristics: bullet shaped bubbles
   - Bubbles separated by liquid slugs which may contain smaller bubbles
Flow Patterns (vertical flow)

3. Churn Flow-
   - Increasing flow velocity makes flow unstable
   - Gravity & Shear forces act in opposite directions
   - an oscillatory motion of the liquid upwards & downwards leads to a *churned* flow
   - Intermediate between Slug and Annular flow
   - Churn Flow to be avoided
   - *(destructive consequence on the piping system)*
Flow Patterns (vertical flow)

4. **Annular Flow** - liquid flows on the wall as a film
   - Gas phase as the centre core
   - Interface disturbed by waves & ripples
   - Liquid phase is entrained as small droplets in the gas core

5. **Wispy annular flow** -
   - Increase in liquid flow rate
   - Entrained droplets may form clouds or *Wisps* of liquid

6. **Mist Flow** –
   - Very high gas flow rates destroy liquid film by shear
   - All liquid entrained as droplet in vapour core
   - Inverse of Bubbly Flow
Flow Patterns (horizontal flow)

- Liquid distribution influenced by gravity
- It stratifies liquid to the bottom of the tube
- **Bubbly Flow** - The bubbles tend to flow at the top of the tube due to buoyancy

- **Stratified flow** - at low liquid and gas velocities
  - complete separation by gravity
  - Undisturbed horizontal interface
- **Wavy flow** - Increasing gas velocity in stratified flow large surface waves are formed on the gas liquid interface giving the wavy flow regime.
Flow Patterns (horizontal flow)

- **Intermittent flow** – increasing gas velocity
- Large amplitude waves, *top of tube always wetted*
- **Subcategories:** Plug flow & Slug flow

**Plug flow** - also called ‘Elongated bubble flow’
- Liquid phase continuous along the bottom

**Slug flow** - Large amplitude waves
- Liquid slugs separating elongated bubbles
Flow Patterns (horizontal flow)

- **Annular flow** - Increased gas velocity pierces the liquid slugs
- Gas core & annular flow with a thicker film at the bottom
- Interface disturbed by small amplitude waves

- Mist flow – All liquid stripped from the wall
- Entrained as droplet in the continuous gas core
FLOW REGIME MAPS

- To predict the flow-pattern for any set of operating conditions
- Usual way of presenting results of observations of flow patterns:
  i. To plot them on a graph (axes represent certain flow parameter eg. Mass fluxes, void fraction etc.)
  ii. Lines represent the boundaries between the various regimes of flow.

The resultant diagram is called a “flow regime map”.
Flow regime maps (Baker Map, 1954)

- Two phase horizontal flow (Adiabatic flow)

- Parameters:
  Mass flux of liquid and vapor phase

- Stratified flow at lower mass flux
- Bubbly flow at lower void fraction
- Plug – slug – annular (as vapor velocity increases)

\[
\psi = \left( \frac{\sigma_{\text{water}}}{\sigma} \right) \left( \frac{\mu_L}{\mu_{\text{water}}} \right) \left( \frac{\rho_{\text{water}}}{\rho_L} \right)^2 \right)^{1/3}
\]

\[
\lambda = \left( \frac{\rho_G}{\rho_{\text{air}}} \frac{\rho_L}{\rho_{\text{water}}} \right)^{1/2}
\]

\(\rho\) is the density, \(\sigma\) is surface tension, \(\mu\) is the viscosity
Flow Patterns (experimental Observation)

- Stratified flow
- Stratified Wavy
- Churn Flow
- Annular Flow
Baker Map

\[ \frac{\sigma_{\text{water}}}{\sigma} \left[ \left( \frac{\mu_{L}}{\mu_{\text{water}}} \right) \left( \frac{\rho_{\text{water}}}{\rho_{L}} \right)^2 \right]^{1/3} \]

\[ \lambda = \left( \frac{\rho_{G}}{\rho_{\text{air}}} \frac{\rho_{L}}{\rho_{\text{water}}} \right)^{1/2} \]

are used for translation from air water data to gas oil systems.

- Flow regimes were observed in photographs Baker looked at data form various sources & came up with a map.

- Suffers from lack of basis of mechanism that are responsible for the transition of flow regime.
Flow Regime Maps (Taitel & Dukler 1976)

- **Horizontal Flow**
- Based on analysis of flow transition mechanism together with empirical selection of several parameter.
  1. Martinelli parameter $X$
     \[
     X = \left[ \frac{(dp/\,dz)_L}{(dp/\,dz)_G} \right]^{1/2}
     \]
  2. Gas Froude number $Fr$
     \[
     Fr_G = \frac{\dot{m}_G}{\sqrt{\frac{\rho_G(\rho_L - \rho_G)d_i g}}}
     \]
     \[
     K = Fr_G \text{Re}_L^{1/2}
     \]
     \[
     T = \left[ \frac{|dp/\,dz|_L}{g(\rho_L - \rho_G)} \right]^{1/2}
     \]
Flow Pattern Maps (Taitel & Dukler 1976)

Pressure Gradient

\[
\left( \frac{dp}{dz} \right)_k = -\frac{2f_k m_k^2}{\rho_k d_i} \quad (f \text{ – friction factor})
\]

\[
f_k = \frac{16}{Re_k} \quad (\text{for } Re < 2000)
\]

\[
f_k = \frac{0.079}{Re_k^{1/4}} \quad (\text{for } Re > 2000)
\]

- lower gas and liquid phase velocity – stratified flow
- Gas velocity increases – stratified wavy
- Further increase lead to annular flow
Flow Regime Maps (Taitel & Dukler 1976)

- Compared successfully with a large amount of experimental data
- One of the best results actually available as it considers influence of pipe diameter

- Results often extrapolated to diabatic process of evaporation and condensation with not so reliable results
- *Evaporation & condensation need different treatment*
Void fraction & Diabatic system

- Channel average void fraction $\langle \alpha \rangle$ is defined as ratio of vapor area to total cross section area
  \[
  \langle \alpha \rangle = \frac{A_g}{A_G + A_L}
  \]

- Vapor quality ($X$) : ratio of the mass flow rate
  \[
  \alpha = \frac{A_g}{A} = \frac{1}{1 + \frac{\dot{m}_l \rho_g u_g}{\dot{m}_g \rho_l u_l}} = \frac{1}{1 + \frac{1 - x \rho_g u_g}{x \rho_l u_l}}
  \]

  **Phase velocity** : ratio of volume flow rate and phase cross sectional area
  \[
  u_g = \frac{\dot{m}_g}{\rho_g A_g}
  \]

  **Superficial Velocity** : ratio of volume flow rate and total cross sectional area of the tube
  \[
  V_g = \frac{\dot{m}_g}{\rho_g A} = u_g \frac{A_g}{A} = u_g \alpha
  \]

  **Slip ratio** : ratio of the phase velocities
Flow Regime Map for Evaporation (Kattan-Thome-Favrat map) (1998)

- Plotted for mass flux versus vapor fraction (void fraction)
- For condensation flow regimes are similar
Flow pattern map for Evaporation (Kattan-Thome-Favrat map) (1998)

• Vapor quality is the vapor mass fraction (high void fraction - mist flow)

• Developed for a refrigerant (R – 134)
Dry out Zone

- Dry out in horizontal tube takes place over range of vapor qualities
- Starts as an annular flow & ending when fully developed mist flow regime is reached
- Horizontal movement in Kattan-Thome-Favrat map
Sharp change in heat transfer coefficient indicates the inception of the dryout.

End of this decrease of h.t coefficient marks the end of dryout and beginning of mist flow.
**Vertical evaporation**

- **Local boiling** - super heated liquid layer next to the wall
- Bulk may be sub-cooled
- Next to the super heated layer is 2 phase bubble layer (with bubbles attached to wall or carried along the stream)

- **Bulk boiling section**: all the liquid has attained saturation
- Bubbles concentrate in the central, high velocity region (Bernoulli effect) & annular pattern forms
- Same pressure gradient, less dense attains more velocity
Void fractions for vertical flow

- Void fraction: very important in nuclear reactor safety
- Gill et al. measured the two-phase void distribution
- Observations: large void fractions – void concentrates at the centre & forms a vapor core

- Low void fractions: void concentrates away from the centre & forms a bubbly layer at the wall
Simulation techniques (background):

- The primary and secondary phases:
  - One of the phases is continuous (primary) while the other(s) (secondary) are dispersed within the continuous.
  - A diameter has to be assigned for each secondary phase to calculate its interaction (drag) with the primary phase.
Modeling approach

- **Algebraic slip model.**
  - Treats the system as a single entity
  - Solve one momentum equation for the mixture.

- **Two-fluids theory (multi-fluids).**
  - Eulerian models.
  - Solve as many momentum equations as there are phases.

- Fully resolved and coupled.
Algebraic slip model (ASM)

- Solves one set of momentum equations for the mass averaged velocity and tracks volume fraction of each fluid throughout domain.
- Assumes an empirically derived relation for the relative velocity of the phases.
- The ASM model can be used to model in FLUENT 5.
- Less expensive than Eulerian models
ASM equations (2)

- Average density: \( \rho_m = \alpha_1 \rho_1 + \alpha_2 \rho_2 \)

- Mass weighted average velocity: \( \vec{u}_m = \frac{\rho_1 \alpha_1 \vec{u}_1 + \rho_2 \alpha_2 \vec{u}_2}{\rho_1 \alpha_1 + \rho_2 \alpha_2} \)

- Velocity and density of each phase: \( \vec{u}_1, \vec{u}_2, \rho_1, \rho_2 \)

- Effective viscosity: \( \mu_{eff} = \mu_1 \alpha_1 + \mu_2 \alpha_2 \)
Example: bubble column design

A bubble column is a liquid pool sparged by a process stream.

Liquid Pool

Sparger

Gas

Gas Inlet

Liquid/Slurry Inlet

Liquid

Gas

2 < L/D < 20

$U_{G,\text{sup}}$ up to 50 cm/s

$U_{G,\text{sup}} >> U_{L,\text{sup}}$
Bubble columns: flow regimes

Bubbly Flow

Churn-Turbulent Flow

Flow Regime Map (Deckwer, 1980)
Bubble column results

- 3D modeling of dynamic behavior of an air-water churn turbulent bubble-column using the ASM model.
- Constant bubble size is used.

Fig 1: Iso-contours of gas volume fraction

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Fig 2: Unstable flow in a 3-D bubble column with rectangular cross section.
Summary

- Multiple phase flow study is important with its application in industry & safety of Nuclear reactors.
- Dependence of flow patterns on the void fraction is most significant.
- Different analysis for evaporation & adiabatic flows.
- Huge scope for development both in analytical and modeling sections.
References

- Boiling Heat Transfer and Two Phase Flow, L.S. Tong and Y.S. Tang
- Two Phase Flow and Heat Transfer, Butterwooth and Hewitt
- Annular Two-Phase Flow, G.F. Hewitt and N.S. Hall-Taylor
- Two Phase Flow and Heat Transfer, P.B. Whalley
- Engineering Data Book III, Chapter 12, Wolverine Tube, Inc (2007)
Thanks a lot for your attention
Back up slides

- Pressure
- Analytical treatment
- Correlations
Modeling two phase flow

1. Homogeneous model/drift flux model
   - Treats mixture as a whole
   - Physical properties are averaged as per void fraction
   - *Slip velocity neglected ( same velocity for both the phases )*
   - Solved similar to the single phase flow
   - Failed ( neglects slip velocity )
Modeling two phase flows

- Separate - phase model ( two – fluid model )
- Assumption : equality of the mean pressure of the two phases
- Separate conservation equations for the two phases
- Interfacial conditions

\[ \sum_{i=L,G} \phi_i = 0 \]

\[ \sum_{i=L,G} \phi_i - \text{div} \sigma \bar{U} - \sigma n_G \left( \frac{2}{R} \right) = 0 \]

Where:

- \( \phi_i \) = mass flux across the interface
- \( \sigma \) = surface tension
- \( \bar{U} \) = metric tensor of the space
- \( n_G \) = normal vector in gas-phase direction

\[ \sum_{i=L,G} \phi_i - \text{div} \sigma u_i \bar{U} - \sigma u_i \left( \frac{2}{R} \right) n_G = 0 \]
Pressure Drop (homogeneous flow model)

\[ \Delta p_{\text{total}} = \Delta p_{\text{static}} + \Delta p_{\text{mom}} + \Delta p_{\text{frict}} \]

\[ \Delta p_{\text{static}} = \rho_H g H \]

\[ \rho_H = \rho_L (1 - \varepsilon_H) + \rho_G \varepsilon_H \]

Average density

\[ \varepsilon_H = \frac{1}{1 + \left( \frac{u_G (1-x)}{u_L} \frac{\rho_G}{\rho_L} \right)} \]

Void fraction

\[ \left( \frac{dp}{dz} \right)_{\text{mom}} = \frac{d(\dot{m}_{\text{total}} / \rho_H)}{dz} \]

\[ f_{tp} - \text{two phase friction factor} \]

\[ \Delta p_{\text{frict}} = \frac{2 f_{tp} \dot{m}_{\text{total}}^2}{d_i \mu_{tp}} \]

\[ \mu_{tp} = x \mu_G + (1-x) \mu_L \]

\[ f_{tp} = \frac{0.079}{\text{Re}^{0.25}} \]

\[ \text{Re} = \frac{\dot{m}_{\text{total}} d_i}{\mu_{tp}} \]
Separated flow models

- Two phases to be separated into 2 flows
- Velocity constant for a given phase within the zone occupied by the phase
- P static same as before

\[
\Delta p_{\text{mom}} = \dot{m}_{\text{total}}^2 \left\{ \left[ \frac{(1-x)^2}{\rho_L (1-\varepsilon)} + \frac{x^2}{\rho_G \varepsilon} \right]_{\text{out}} - \left[ \frac{(1-x)^2}{\rho_L (1-\varepsilon)} + \frac{x^2}{\rho_G \varepsilon} \right]_{\text{in}} \right\}
\]

\[
\varepsilon = \frac{x}{\rho_G} \left[ (1+0.12(1-x)) \left( \frac{x}{\rho_G} + \frac{1-x}{\rho_L} \right) + \frac{1.18(1-x)\left[g\sigma(\rho_L - \rho_G)\right]^{0.25}}{\dot{m}_{\text{total}}^2 \rho_L^{0.5}} \right]^{-1}
\]

- Frictional pressure drop same as single phase (done twice and summed up)
Pressure drop (experimental & correlations)
Analytical treatment for pressure drop in Stratified flow

Assumptions:

1. That the shear stress at the interface is equal to the shear of the gas at the wall
2. That the wall shear stress can be calculated on the basis of fully developed pipe flow correlation, provided the correct hydraulic diameter is used

\[ A_G \left( \frac{\Delta P}{L} \right) = \tau_{wG} \tilde{p}_G + \tau_i w_i \]

\[ \tilde{p}_G, \tilde{p}_L = \text{perimeters for the gas and liquid phases, respectively} \]

\[ A_G, A_L = \text{flow cross section of the gas and liquid phases, respectively} \]

\[ \tau_i, w_i = \text{interfacial stress and interfacial area width, respectively} \]

\[ A_L \left( \frac{\Delta P}{L} \right) = \tau_{wL} \tilde{p}_L - \tau_i w_i \]
Analytical treatment for pressure drop in Stratified flow

- Gas phase wall stress given in terms of usual friction factors

For the liquid phase, Cheremisinoff and Davis (1979) solved the momentum equation using von Karman’s and Deissler’s eddy viscosity expressions.

The dimensionless liquid flow rate, $W^*$, can be expressed as

$$W^* = \frac{W_L}{\mu_L R}$$

$$= \frac{2}{\sqrt{\pi}} \int_0^{\frac{y^+}{R^+}} \frac{u^+ (y^+)}{R^+} \left( 1 - \frac{y^+}{R^+} \right) dy^+ d\theta$$

(3-124)

where dimensionless radius

$$\times R^+ = \frac{u^* R}{\nu_L}$$

friction velocity

$$\times u^* = \left( \frac{\tau_{\text{wL}}}{\rho_L} \right)^{1/2}$$

position of the interface in nondimensional form

$$\times y^+ = \frac{y u^*}{\nu}$$
Equation (3-124) has been integrated numerically, and results can be presented. Figure 3.41 is a plot of liquid holdup $E_L$ versus $W^*$ for various values of the parameter $R^*$. 

**Figure 3.41** The in-situ liquid volume fraction as a function of dimensionless liquid flow rate $W^*$ and dimensionless tube size parameter $R^*$. (From Cheremisinoff and Davis, 1979. Copyright © 1979 by American Institute of Chemical Engineers, New York. Reprinted with permission.)
Analytical treatment for pressure drop in Stratified flow

For interfacial shear stress the following expression is used

\[ \tau_i = \frac{C_{f,i} \rho_G \overline{U_G}^2}{2} \]

\[ C_{f,i} = 0.0080 + 2.00 \times 10^{-5} \text{Re}_L \]  \hspace{1cm} (3-126)

for \( 100 \leq \text{Re}_L \leq 1,700 \), where \( \text{Re}_L = \Gamma_L / \nu_L \) and \( \Gamma_L = \) volumetric flow per unit width of parallel-plate channel.
Analytical treatment for pressure drop in Stratified flow

An iterative procedure to calculate the pressure drop was suggested by Cherymisinoff and Davis (1979) for turbulent/turbulent stratified flow:

1. Choose a trial value of the holdup $E_L$ and calculate the geometric parameters $D_{eG}$, $D_{eL}$, $\tilde{p}_G$, $\tilde{p}_L$, and $w_i$ for the tube diameter under consideration.
2. Calculate $W^+ = W_L/\mu_L R$ from the liquid mass flow rate $W_L$ and determine $R^+$ by interpolation from Figure 3.41.
3. Calculate the friction velocity and then $\tau_{wL}$ from $R^+$ and compute $\tau_i$ and $\tau_{wG}$ from Eqs. (3-125) and (3-122).
4. Solve Eqs. (3-120) and (3-121) separately for $(\Delta P/L)$. If the two calculated values do not agree to within some specified accuracy, a new value of $E_L$ is assumed, and the procedure is repeated.
Measurement of void fraction

Radiation attenuation techniques In this approach a gamma or X ray is used that gives the average fluid density along the path of the beam. The source and detector can be located external to the flow channel to measure an average reading across the width of the channel. A traversing mechanism can also be used to vary the relative location of the source, the detector, and the channel, thereby measuring an average over a selected chordal distance (Schrock, 1969; Hsu and Graham, 1976).

Capacitance or conductance measurement This method is applied where the working fluid acts as a capacitive or conductive element in a circuit (Jones et al., 1981). Use of fiber optics sensors has been developed recently (Moujaes and Dougall, 1987, 1990). These methods are used to measure film thickness in annular flow. Further discussion appears in Section 3.3.4.4. For other regimes, the use of the electrical impedance imaging method has also been introduced (Lin et al., 1991).

Measurement based on heat flux effects This approach uses local probing devices such as hot-wire anemometers and microthermocouples. The hot-wire anemometer can be either a constant-temperature system or a constant-heat-flux system. Because of the difference in heat transfer between the exposed fluid (liquid or gas)
Measurement of void fraction

and the wire, the variation of heat flux or temperature will settle on two distinctly different levels. In this manner, both the void fraction and the local velocity of each phase may be measured simultaneously. This technique provides a very clear signal for slug flow and for bubbly flow with large bubbles (Hsu et al., 1963).

Figure 3.29  Microthermocouple probe and responses to the passing of bubbles. (From Stefanovic et al., 1970. Copyright © 1970 by Hemisphere Publishing Corp., New York. Reprinted with permission.)