EN634 Nuclear Reactor Thermal Hydraulics
Flow Patterns

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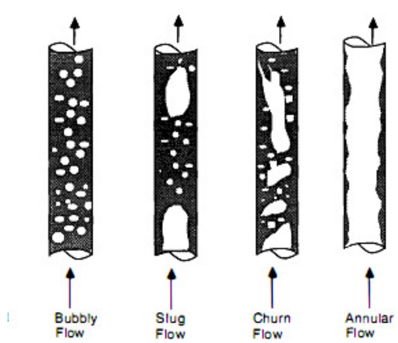
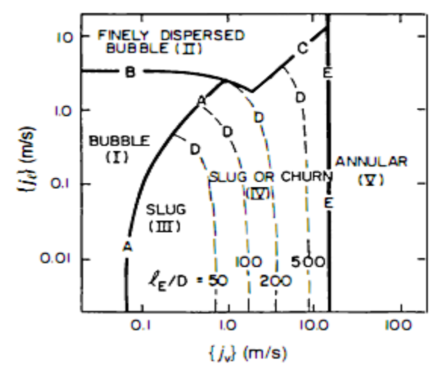
Motivation for this lecture

- We had understood the patterns encountered in horizontal systems
- All patterns were assumed to originate from the instability of stratified flow
- Many empirical arguments had been used in the process of delineation
- In dealing with vertical flows, the arguments are mostly empirical
- We shall touch upon it briefly

The Patterns Encountered



Taitel-Dukler's Map



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Taitel-Dukler's Model-I

- In horizontal systems we had put the map in the non-dimensional planes with χ as the fundamental parameter and with F, T and K as the deciding parameters
- In vertical systems such a treatment is absent
- All arguments are dimensional
- Usually it is plotted in j_g-j_l plane
- We can assume the properties that may decide the flow patterns are j_g, j_l, D, ρ_l, ρ_g, μ_l, μ_g, σ and g.
- With 9 variables, we can get 6 π groups. Thus, ideally it will be a complex map.

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Taitel-Dukler's Model-II

- However, the state of the art is far from satisfactory
- There have been many papers
- Taitel-Dukler's model seems rational (AIChE J, 26, 345, 1980)
- Discussions are fairly complete in Kazimi and Todreas
- We shall briefly look at the arguments.

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Bubbly-Slug Transition-I

- In fully developed flow, there is a constant slip.
- In stationary liquid systems the final velocity reached by the gas bubbles is called the bubble rise velocity.
- From large number of studies, it has been established that the bubble rise velocity can be expressed as

$$V_\infty = 1.53\left(\frac{g\Delta\rho\sigma}{\rho_l^2}\right)^{\frac{1}{4}} \qquad (1)$$

- When liquid velocity is superimposed, we can write

$$V_g - V_l = V_\infty \qquad (2)$$

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Bubbly-Slug Transition-II

- From basic relations, we can write

$$V_g = \frac{V_{gs}}{\alpha}, \quad V_l = \frac{V_{ls}}{1-\alpha} \qquad (3)$$

- From equations 1, 2 and 3, we can write

$$\frac{V_{ls}}{1-\alpha} = \frac{V_{gs}}{\alpha} - 1.53\left(\frac{g\Delta\rho\sigma}{\rho_l^2}\right)^{1/4} \qquad (4)$$

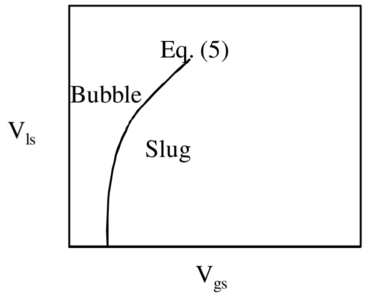
- They argued that,
  - Bubble collision frequency $\rightarrow\infty$ as $\alpha\rightarrow 0.3$
  - Bubbles wobble and coalesce at $\alpha = 0.25$

Bubbly-Slug Transition-III

- Substituting α = 0.25 in Eq. (4) and rearranging, we get,

$$\frac{V_{ls}}{V_{gs}} = 3 - \frac{1.15}{V_{gs}}\left(\frac{g\Delta\rho\sigma}{\rho_l^2}\right)^{1/4} \quad (5)$$

Although the equation is linear, in a log-log plot it is non-linear



- It has been observed that in very small tubes, bubbly flow is not seen.
- Taitel and Dukler rationalised as follows
  - It is knon that Taylor bubble velocity can be expressed as $V = 0.35\ (gD)^{0.5}$
  - If the bubble rise velocity is larger than the Taylor bubble velocity, then the bubble will rise and coalesce into a Taylor bubble
  - Hence the condition for bubbly flow not to exist is to equate the bubble rise velocity to Taylor bubble velocity

$$0.35\sqrt{gD} \le 1.53\left(\frac{g\Delta\rho\sigma}{\rho_l^2}\right)^{\frac{1}{4}} \Rightarrow \left(\frac{\rho_l^2 gD^2}{\Delta\rho\sigma}\right)^{\frac{1}{4}} \le 4.36 \quad (6)$$

Bubble-Dispersed Bubble Transition-I

- As discussed in horizontal systems, if there is high liquid shear it will tear larger bubbles into smaller ones.
- However, gravity will have no role in this case.
- Taitel and Dukler took the study of Hinze (1955) on bubble development in agitated flows. Hinze showed that maximum diameter of the bubble to be

$$d_{max} = k\left(\frac{\sigma}{\rho_l}\right)^{\frac{3}{5}} \varepsilon^{-\frac{2}{5}}$$

where, ε is energy dissipated per unit mass,

k = 0.725

Bubble-Dispersed Bubble Transition-II

- The dissipation rate can be treated as follows

$$\frac{power}{mass} = \frac{\Delta pQ}{A\rho\Delta x} = \frac{dp}{dx}\frac{V_m}{\rho_m}$$

$$\frac{dp}{dx} = \frac{4f}{2D}\rho_m V_m^2 \quad \text{with} \quad f = 0.046\left(\frac{V_m D}{\nu_l}\right)^{-0.2}$$

- Further, when the bubbles are too small, they do not coalesce. Brodkey (1967) had shown that the critical diameter wbove which coalescence happens can be given as

$$d_{crit} = \left(\frac{0.4\sigma}{\Delta\rho g}\right)^{0.5}$$

Bubble-Dispersed Bubble Transition-III

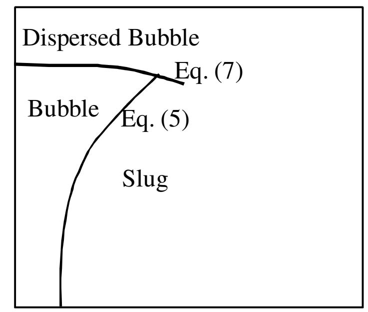
- Taitel argued that for isolated bubbles to exist, $d_{max} > d_{crit}$
- Substituting the expressions arrived for the dmax and d crit and equating the gives

$$\left[\frac{\left(\frac{\rho_l}{g\Delta\rho}\right)^{0.5} \nu_l^{0.08}}{\left(\frac{\sigma}{\rho_l}\right)^{0.1} D^{0.48}}\right](V_{ls}+V_{gs})^{1.12} = 3 \qquad (7)$$

- Kazimi and Todreas gets RHS as 4.72
- Barnea has modified it as

$$RHS -= 3 + 17\left(\frac{V_{gs}}{(V_{ls}+V_{gs})}\right)^{0.5}$$

Bubble-Dispersed Bubble Transition-IV

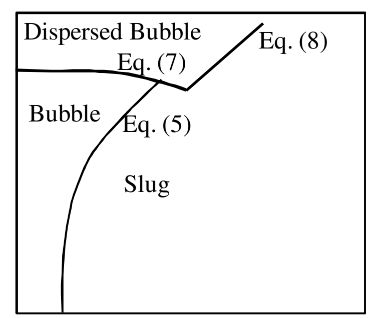


Dispersed Bubble-Slug Transition-I

- If we have spheres in a cubic lattice, the maximum packing one can obtain is 0.52. This implies that it is physically impossible to have bubbly flow beyond $\alpha = 0.52$
- Further, in dispersed bubble flow, one can expect homogeneous model to be valid. Hence, we can write

$$\alpha = \beta = \frac{V_{gs}}{(V_{ls}+V_{gs})} = 0.52 \qquad (8)$$

Dispersed Bubble-Slug Transition-I



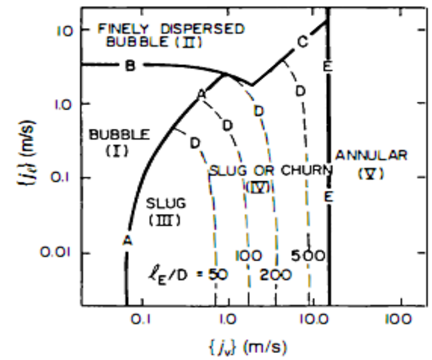
Slug-Churn Flow-I

- Taitel and Dukler argued that Churn flow occurs before stabilization of the slug
- Thus churn flow was looked at as an entrance phenomenon. If the entrance length is large, then the entire pipe will have churn flow.
- Using several empirical arguments they came out with an expression for the entrance length as

$$\frac{l_e}{D} = 42.6\left(\frac{(V_{ls} + V_{gs})}{\sqrt{gD}} + 0.29\right)$$

- Thus, the transition line will depend on l/D of the pipe. First it will be churn followed by slug

Slug-Churn Flow-II



Transition to Annular Flow

- Taitel and Dukler proposed that annular flow will result if the drag overcomes the weight of a fragmented drop
- They used the data of Hinze on the fragmented drop size, used the value of coefficient of drag as 0.44 and finally assuming that $V_g \sim V_{gs}$, they arrived at the transition criterion as

$$\frac{V_{gs}\rho_g^{\,0.5}}{(\sigma g \Delta\rho)^{0.25}} = 3.1$$

- Note that this will be a vertical line in V_{gs}-V_{ls} plot
- Refer to figure in previous slide