NTEC Module: Water Reactor Performance and Safety

Lecture 5: Introduction to two-phase flow

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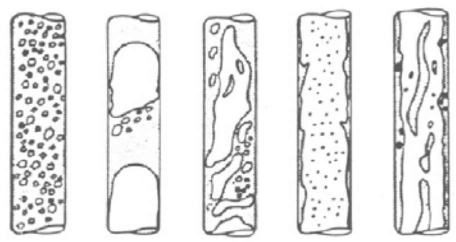
Two-phase flow regimes in vertical tubes



Bubble Flow | Slug or Plug Flow | Churn Flow | Annular Flow | Wispy Annular Flow

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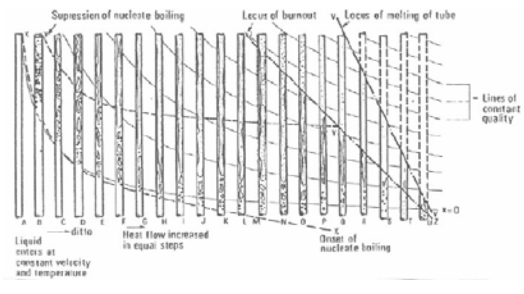
Forced convective boiling: Regions of boiling and flow



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Introduction to nomenclature

New international nomenclature

(i) Capital letters: *M*, mass
V, volume
Q, quantity of heat

(ii) Dotted variables: $\dot{M}$, mass rate of flow
$\dot{V}$, volume rate of flow

(iii) Lower case variables: *h*, enthalpy; c_p, specific heat — Specific (per unit mass)

(iv) Lower case dotted variable (per unit area): $\dot{q}$, heat flux
$\dot{m}$, mass flux

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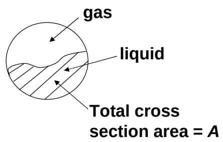
Definitions of quantities



Total mass rate of flow = $\dot{M}$ (Gas $\dot{M}_G$, Liquid $\dot{M}_L$)

Total mass rate of flow = $\dot{V}$ (Gas $\dot{V}_G$, Liquid $\dot{V}_L$)

Mass flux = $\dfrac{\dot{M}}{A} = \dot{m}$

Fraction of cross section occupied by gas phase ("void fraction") = ε_G

Fraction occupied by liquid phase (holdup) = $\varepsilon_L = (1 - \varepsilon_G)$

"Superficial velocity": $U = \dfrac{\dot{V}}{A}, U_G = \dfrac{\dot{V}_G}{A}, U_L = \dfrac{\dot{V}_L}{A}$

Velocities: $u_G = \dfrac{U_G}{\varepsilon_G}, u_L = \dfrac{U_L}{\varepsilon_L}$ **Slip ratio:** $S = \dfrac{u_G}{u_L}$

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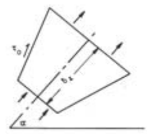
Basic equations:
The homogeneous model: Introduction



Homogeneous flow model
- treats fluid as single fluid cf. single phase flow
- assumes equal velocities for two phases

Homogeneous density

$$\rho_H = \frac{\dot{M}}{\dot{V}} = \frac{\dot{m}A}{\dfrac{\dot{m}Ax}{\rho_G} + \dfrac{\dot{m}A(1-x)}{\rho_L}}$$

$$= \frac{\rho_L \rho_G}{x\rho_L + (1-x)\rho_G}$$

Void fraction:

$$\varepsilon_G = \frac{\dot{V}_G}{\dot{V}} = \frac{x}{x + (1-x)\rho_G/\rho_L}$$

Slip ratio:

$$S = u_G / u_L = 1$$

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Basic equations:
Homogeneous continuity (mass) equation

For channel element (Slide 5)

Rate of creation of mass = 0 = Mass outflow rate - Mass inflow rate + Mass storage rate

$$0 = \left[U\rho_H A + \delta z \frac{\partial}{\partial z}\left(U\rho_H A\right)\right] - U\rho_H A + A\delta z \frac{\partial \rho_H}{\partial t}$$

U = total volume flux

Rearranging gives:

$$\frac{\partial}{\partial z}\left(U\rho_H A\right) + A\frac{\partial \rho_H}{\partial t} = 0$$

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Basic equations:
Homogeneous momentum equation

Rate of creation of momentum = Momentum outflow rate - Momentum Inflow rate + Momentum storage rate

$$= \left[\dot{m}UA + \delta z \frac{\partial}{\partial z}\left(\dot{m}UA\right)\right] - \dot{m}UA + \frac{\partial}{\partial t}\left(\dot{m}A\delta z\right)$$

= sum of forces on element

= sum of forces to pressure gradient, gravity and wall shear

$$= pA - \left(pA + \delta z A \frac{\partial p}{\partial z}\right) - g\rho_H A\delta z \sin\alpha - \tau_o \delta z P$$

p = fluid pressure (assumed constant over cross section);

P = channel periphery; $U = \dfrac{\dot{m}}{\rho_H}$

Rearranging gives homogeneous momentum equation:

$$\frac{\partial \dot{m}}{\partial t} + \frac{1}{A}\frac{\partial\left(\dot{m}^2 A/\rho_H\right)}{\partial z} = -\frac{\partial p}{\partial z} - g\rho_H \sin\alpha - \frac{\tau_o P}{A}$$

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Basic equations: Homogeneous energy equation

Rate of creation of energy = 0 = Energy outflow rate - Energy Inflow rate + Energy storage rate

$$0=\left[UA\rho_H e+\delta z\frac{\partial}{\partial z}\left(UA\rho_H e\right)\right]-\left[UA\rho_H e+\left(\dot{q}P+\dot{q}_v A\right)\delta z\right]+\left[A\delta z\frac{\partial}{\partial t}\left(\rho_H\mu+\frac{U^2\rho_H}{2}\right)\right]$$

$e=$ energy convected per unit mass of fluid $=h+\frac{U^2}{2}+gz\sin\alpha$

$h=$ enthalpy $=\mu+\frac{p}{\rho_H}$

$\mu=$ internal energy of fluid

$\dot{q}=$ wall heat flux

$\dot{q}_v=$ volumetric heat generation rate

Rearranging gives homogeneous energy equation:

$$\rho_H\left(\frac{\partial e}{\partial t}+U\frac{\partial e}{\partial z}\right)=\frac{\dot{q}P}{A}+\dot{q}_v+\frac{\partial p}{\partial t}$$

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Homogeneous model: Components of pressure gradient

Homogeneous momentum equation (Slide 8)

$$\frac{\partial\dot{m}}{\partial t}+\frac{1}{A}\frac{\partial\left(\dot{m}^2A/\rho_H\right)}{\partial z}=-\frac{\partial p}{\partial z}-g\rho_H\sin\alpha-\frac{\tau_o P}{A}$$

For constant cross section and steady flow

$$-\frac{\partial p}{\partial z}=\frac{\tau_o P}{A}+\dot{m}^2\frac{d}{dz}\left[\frac{1}{\rho_H}\right]+g\rho_H\sin\alpha$$

Total	Frictional	Acceleration	Gravitational
$-\frac{dp}{dz}$ =	$-\frac{dp_F}{dz}$	$-\frac{dp_a}{dz}$	$-\frac{dp_g}{dz}$

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Frictional pressure drop calculation: Homogeneous model

From slide 9

$$-\frac{dp_F}{dz}=\frac{\tau_o P}{A}\qquad\left(\frac{P}{A}=\frac{\pi D}{\pi D^2/4}=\frac{4}{D}\ \text{for round tubes}\right)$$

Define f_{TP} from

$$f_{TP}=\frac{\tau_o}{1/2\left(\dot{m}^2/\rho_H^2\right)\rho_H}$$

Hence

$$-\frac{dp_F}{dz}=\frac{2f_{TP}\dot{m}^2}{D\rho_H},\quad\rho_H=\frac{\rho_G\rho_L}{x\rho_L+(1-x)\rho_G}$$

$f_{TP}=fn\left(\mathrm{Re}_{TP}\right)$ from standard curves

$\mathrm{Re}_{TP}=\frac{\dot{m}D}{\eta_{TP}},\ \frac{1}{\eta_{TP}}=\frac{x}{\eta_G}+\frac{(1-x)}{\eta_L}$ (McAdams et al., 1942)

(usually very poor predictions)

McAdams et al., TASME 64, 193 (1942)

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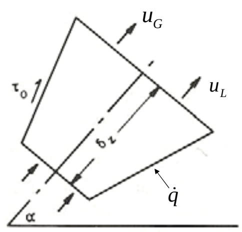
Basic equations: Separated flow model: Introduction



Two fluids flow in separate regions each with a given but unequal velocity:

Thus: $u_G\neq u_L,\ S\neq 1$

Mean fluid density in element:

$\rho_{TP}=\rho_L\left(1-\varepsilon_G\right)+\rho_G\varepsilon_G$

Void fraction / slip ratio relationship:

$$\varepsilon_G=\frac{x}{x+S\left(1-x\right)\rho_G/\rho_L}$$

$x=$ quality

(fraction of mass flow flowing as vapour)

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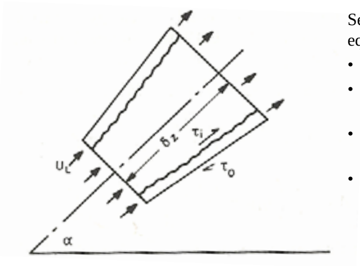
Basic equations: Balance element for Separated flow model



Separated flow model (six equation model). Main features:

- Two flow regions
- Continuity, momentum and (energy) balances written
- Equations written for each phase
- Equations may be summed to give overall balances.

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Conservation equations: Continuity equation for the liquid phase

Rate of creation of mass = 0 = mass outflow rate – mass in flow rate + mass storage rate

$$\left\{\rho_L(1-\varepsilon_G)u_L A + \delta z\frac{\partial}{\partial z}\left[\rho_L(1-\varepsilon_G)u_L A\right] + \dot{m}_e\delta z\right. \quad \text{(outflow)}$$

$$-\rho_L(1-\varepsilon_G)u_L A \quad \text{(inflow)}$$

$$\left.+\frac{\partial}{\partial t}\left[\rho_L(1-\varepsilon_G)A\delta z\right]\right\} \quad \text{(storage)}$$

$$=0$$

ε_G **= void fraction**

u_L **= liquid phase velocity**

A **= cross sectional area**

$\dot{m}_e$ **= rate of conversion of liquid to vapour per unit length**

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Conservation equations: Continuity equation for the gas phase

Rate of creation of mass = 0 = mass outflow rate – mass in flow rate + mass storage rate

$$\left\{\rho_G\varepsilon_G u_G A + \delta z\frac{\partial}{\partial z}\left[\rho_G\varepsilon_G u_G A\right]\right. \quad \text{(outflow)}$$

$$-\rho_G\varepsilon_G u_G A - \dot{m}_e\delta z \quad \text{(inflow)}$$

$$\left.+\frac{\partial}{\partial t}\left[\rho_G\varepsilon_G A\delta z\right]\right\} \quad \text{(storage)}$$

$$=0$$

ε_G **= void fraction**

u_L **= liquid phase velocity**

A **= cross sectional area**

$\dot{m}_e$ **= rate of conversion of liquid to vapour per unit length**

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Conservation equations: Continuity equation: Liquid, gas, combined

Simplifying from previous slide gives liquid phase continuity equation:

$$\frac{\partial}{\partial t}\left[\rho_L(1-\varepsilon_G)A\right] + \frac{\partial}{\partial z}\left[\rho_L u_L(1-\varepsilon_G)A\right] = -\dot{m}_e$$

Similarly for gas phase:

$$\frac{\partial}{\partial t}\left[\rho_G\varepsilon_G A\right] + \frac{\partial}{\partial z}\left[\rho_G\varepsilon_G u_G A\right] = \dot{m}_e$$

Adding the equations and noting that:

$$\dot{m} = \rho_L u_L(1-\varepsilon_G) + \rho_G\varepsilon_G u_G$$

$$\rho_{TP} = \varepsilon_G\rho_G + (1-\varepsilon_G)\rho_L$$

We have:

$$\frac{\partial}{\partial t}\left[\rho_{TP}A\right] + \frac{\partial}{\partial z}\left[\dot{m}A\right] = 0$$

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Conservation equations: Momentum equation for liquid phase

Rate of creation of momentum = Momentum outflow rate - Momentum Inflow rate + Momentum storage rate

= Sum of forces acting on control volume (next slide)

$$= \left[\dot{M}_L u_L + \delta z \frac{\partial}{\partial z}\left(\dot{M}_L u_L\right)\right] - \dot{M}_L u_L + \frac{\partial}{\partial t}\left[u_L \rho_L \left(1-\varepsilon_G\right) A \delta z\right]$$

$$= \delta z \left\{ \frac{\partial}{\partial z}\left[u_L^2 \rho_L \left(1-\varepsilon_G\right) A\right] + \frac{\partial}{\partial t}\left[u_L \rho_L \left(1-\varepsilon_G\right) A\right] \right\}$$

(since $\dot{M}_L = u_L \rho_L \left(1-\varepsilon_G\right) A$)

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Momentum equation for liquid phase: Forces on element of fluid

$$p\left(1-\varepsilon_G\right)A - \left\{ p\left(1-\varepsilon_G\right)A + \delta z \frac{\partial}{\partial z}\left[p\left(1-\varepsilon_G\right)A\right] \right\}$$

(Net pressure force on ends of element)

$$-\left\{-p\delta z \frac{\partial}{\partial z}\left[\left(1-\varepsilon_G\right)A\right]\right\}$$

(Pressure force on resolved area of sloping liquid surface)

$$-g\rho_L\left(1-\varepsilon_G\right)A\delta z \sin\alpha$$

(gravitational force)

$$-\tau_o P \delta z + \tau_i P_i \delta z$$

(shear forces)

τ_o **= wall shear stress**

τ_i **= interfacial shear stress**

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Momentum equation for liquid phase: Equating momentum creation with forces

$$-(1-\varepsilon_G)\frac{\partial p}{\partial z} - \rho_L g(1-\varepsilon_G)\sin\alpha - \frac{\tau_0 P}{A} + \frac{\tau_i P_i}{A}$$

$$= \frac{\partial}{\partial t}\left[\rho_L u_L (1-\varepsilon_G)\right] + \frac{1}{A}\frac{\partial}{\partial z}\left[\rho_L A u_L^2 (1-\varepsilon_G)\right]$$

Steady state, constant area duct

$$-(1-\varepsilon_G)\frac{dp}{dz} - \rho_L g(1-\varepsilon_G)\sin\alpha - \frac{\tau_0 P}{A} + \frac{\tau_i P_i}{A}$$

$$= \frac{d}{dz}\left[\rho_L u_L^2 (1-\varepsilon_G)\right]$$

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Momentum equation for gas phase: (Similar derivation to that for liquid)

$$-\varepsilon_G \frac{\partial p}{\partial z} - g\rho_G \varepsilon_G \sin\alpha - \frac{\tau_i P_i}{A} =$$

$$\frac{\partial}{\partial t}(\rho_G \varepsilon_G u_G) + \frac{1}{A}\frac{\partial}{\partial z}(\rho_G A \varepsilon_G u_G^2)$$

Steady state, constant area duct:

$$-\varepsilon_G \frac{\partial p}{\partial z} - g\rho_G \varepsilon_G \sin\alpha - \frac{\tau_i P_i}{A} = \frac{\partial}{\partial z}(\rho_G \varepsilon_G u_G^2)$$

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Mixture momentum equation

Adding the liquid (slide 19) and gas (slide 20) momentum equations we have:

$$-\frac{\partial p}{\partial z} - g\rho_{TP}\sin\alpha - \frac{\tau_o P}{A}$$
$$= \frac{\partial}{\partial t}\left[\rho_L u_L\left(1-\varepsilon_G\right) + \rho_G u_G \varepsilon_G\right]$$
$$+ \frac{1}{A}\frac{\partial}{\partial z}\left[\rho_L A u_L^2\left(1-\varepsilon_G\right) + \rho_G A \varepsilon_G u_G^2\right]$$

$$\rho_{TP} = \varepsilon_G \rho_G + \left(1-\varepsilon_G\right)\rho_L$$

Mixture momentum equation: Alternative form

Putting:

$$\dot{m} = \rho_L u_L\left(1-\varepsilon_G\right) + \rho_G \varepsilon_G u_G$$
$$u_L = \dot{m}\left(1-x\right)/\rho_L\left(1-\varepsilon_G\right)$$
$$u_G = \dot{m}x/\rho_G\varepsilon_G$$

Gives mixture momentum equation in form:

$$-\frac{\partial p}{\partial z} - g\rho_{TP}\sin\alpha - \frac{\tau_0 P}{A} = \frac{\partial \dot{m}}{\partial t} + \frac{1}{A}\frac{\partial}{\partial z}\left\{\dot{m}^2 A\left[\frac{\left(1-x\right)^2}{\rho_L\left(1-\varepsilon_G\right)} + \frac{x^2}{\rho_G\varepsilon_G}\right]\right\}$$

For steady state flow in a duct of constant A:

$$-\frac{\partial p}{\partial z} = \frac{\tau_o P}{A} + \dot{m}^2\frac{\partial}{\partial z}\left\{\left[\frac{\left(1-x\right)^2}{\rho_L\left(1-\varepsilon_G\right)} + \frac{x^2}{\rho_G\varepsilon_G}\right]\right\} + g\rho_{TP}\sin\alpha$$

Combined conservation equations for separated flows

Continuity:

$$\frac{\partial}{\partial t}\left[\rho_{TP}A\right] + \frac{\partial}{\partial z}\left[\dot{m}A\right] = 0 \qquad \left[\rho_{TP} = \varepsilon_G\rho_G + \left(1\text{-}\varepsilon_G\right)\rho_L\right]$$

Momentum:

$$-\frac{\partial p}{\partial z} - g\rho_{TP}\sin\alpha - \frac{\tau_o P}{A}$$
$$= \frac{\partial \dot{m}}{\partial t} + \frac{1}{A}\frac{\partial}{\partial z}\left[\dot{m}^2 A\frac{\left(1-x\right)^2}{\rho_L\left(1-\varepsilon_G\right)} + \frac{x^2}{\rho_G\varepsilon_G}\right]$$

Energy:

$$A\frac{\partial}{\partial t}\left[\rho_L h_L\left(1-\varepsilon_G\right) + \varepsilon_G h_G\right] + \frac{\partial}{\partial z}\left\{\dot{m}A\left[\left(1-x\right)h_L + xh_G\right]\right\}$$
$$= \dot{q}P + \dot{q}_v A - \frac{\partial}{\partial z}\left\{\frac{\dot{m}^3 A}{2}\left[\frac{\left(1-x\right)^3}{\rho_L^2\left(1-\varepsilon_G\right)^2} + \frac{x^3}{\rho_G^2\varepsilon_G^2}\right]\right\} + A\frac{\partial p}{\partial t}$$

Correlations for steady state channel flows (constant cross section)

HOMOGENEOUS MODEL $\rightarrow$ τ_o correlation

$$-\frac{dp}{dz} = \frac{\tau_o P}{A} + \frac{d\left(\dot{m}^2/\rho_H\right)}{dz} + g\rho_H\sin\alpha$$

$$-\frac{dp}{dz} = -\frac{dp_F}{dz} \qquad -\frac{dp_a}{dz} \qquad -\frac{dp_g}{dz}$$

Friction — Acceleration — Gravity

$$-\frac{dp}{dz} = \frac{\tau_o P}{A} + \dot{m}^2\frac{d}{dz}\left[\frac{\left(1-x\right)^2}{\rho_L\left(1-\varepsilon_G\right)} + \frac{x^2}{\rho_G\varepsilon_G}\right] + g\rho_{TP}\sin\alpha$$

SEPARATED FLOW MODEL $\rightarrow$ τ_o and ε_G correlation

Frictional pressure gradient

Frictional pressure gradient in a round tube:

$$-\frac{\mathrm{d}p_f}{\mathrm{d}z} = \frac{\tau_o P}{A} = \frac{\tau_o(\pi D)}{(\pi D^2/4)} = \frac{4\tau_o}{D}.$$

Pressure drop multipliers:

$$-\frac{\mathrm{d}p_f}{\mathrm{d}z} = -\phi_G^2\left(\frac{\mathrm{d}p_f}{\mathrm{d}z}\right)_G = -\frac{\phi_G^2 2x^2\dot{m}^2}{\rho_G D}f_G,$$

$$-\frac{\mathrm{d}p_f}{\mathrm{d}z} = -\phi_{GO}^2\left(\frac{\mathrm{d}p_f}{\mathrm{d}z}\right)_{GO} = -\frac{\phi_{GO}^2 2\dot{m}^2}{\rho_G D}f_{GO},$$

$$-\frac{\mathrm{d}p_f}{\mathrm{d}z} = -\phi_L^2\left(\frac{\mathrm{d}p_f}{\mathrm{d}z}\right)_L = -\frac{\phi_L^2 2\dot{m}^2(1-x)^2}{\rho_L D}f_L,$$

$$-\frac{\mathrm{d}p_f}{\mathrm{d}z} = -\phi_{LO}^2\left(\frac{\mathrm{d}p_f}{\mathrm{d}z}\right)_{LO} = -\frac{\phi_{LO}^2 2\dot{m}^2}{\rho_L D}f_{LO}.$$

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Gravitational pressure gradient

Gravitational component of pressure gradient given by:

$$-\frac{\mathrm{d}p_g}{\mathrm{d}z} = g\rho_{TP} = g[\rho_L(1-\varepsilon_G) + \rho_G\varepsilon_G].$$

Definition of slip ratio:

$$S = \frac{u_G}{u_L} = \frac{x(1-\varepsilon_G)\rho_L}{(1-x)\varepsilon_G\rho_G}$$

Void fraction/slip ratio relationship:

$$\varepsilon_G = \frac{x}{x + S(1-x)\rho_G/\rho_L}$$

Void fraction in homogeneous flow:

$$\varepsilon_G = \frac{U_G}{U_G + U_L} = \frac{x\rho_L}{x\rho_L + (1-x)\rho_G} = \beta$$

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Typical correlation for void fraction (Premoli et al , 1971)

$$S = 1 + E_1\left(\frac{Y}{1+YE_2} - YE_2\right)$$

where

$$Y = \frac{\beta}{1-\beta} = \left(\frac{x}{1-x}\right)\frac{\rho_L}{\rho_G} \qquad Re = \frac{\dot{m}D}{\eta_L}$$

Parameters E_1 and E_2 are given by

$$We = \frac{\dot{m}^2 D}{\sigma\rho_L}$$

$$E_1 = 1.578Re^{-0.19}\left(\frac{\rho_L}{\rho_G}\right)^{0.22}$$

$$E_2 = 0.0273\,WeRe^{-0.51}\left(\frac{\rho_L}{\rho_G}\right)^{-0.08}$$

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Typical correlation for friction: Freidel, 1979

$$\phi_{LO}^2 = E + \frac{3.24\ FH}{Fr^{0.045}\ We^{0.035}}$$

$$E = (1-x)^2 + x^2\left[\frac{\rho_L f_{GO}}{\rho_G f_{LO}}\right] \qquad We = \frac{\dot{m}^2 D}{\rho_{TP}\sigma},$$

$$F = x^{0.78}(1-x)^{0.24},$$

$$H = \left(\frac{\rho_L}{\rho_G}\right)^{0.91}\left(\frac{\eta_G}{\eta_L}\right)^{0.19}\left[1-\frac{\eta_G}{\eta_L}\right]^{0.7} \qquad \rho_{TP} = \left[\frac{x}{\rho_G} + \frac{(1-x)}{\rho_L}\right]^{-1}$$

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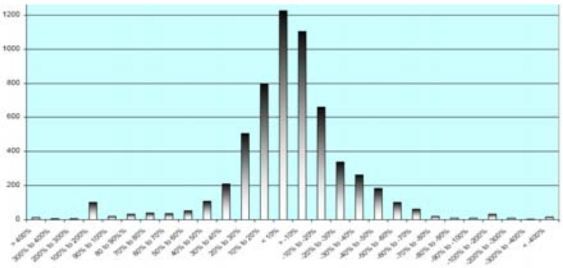
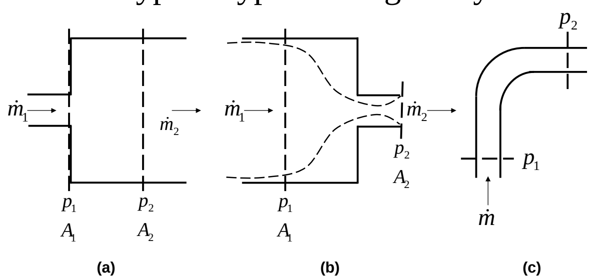
Distribution of errors for Combination: Premoli et al (1971)/Freidel (1979)



Expect large errors with empirical correlations

Pressure drop in singularities: Typical types of singularity



Pressure drop in singularities: Homogeneous model for singular pressure drops

Sudden enlargement

$$p_2 - p_1 = \frac{\dot{m}_1^2 \sigma (1-\sigma) \psi_H}{\rho_L}$$

Sudden contraction

$$p_1 - p_2 = \frac{\dot{m}_2^2}{2\rho_L}\left[\left(\frac{1}{C_c}-1\right)^2 + 1 - \frac{1}{\sigma^2}\right]\psi_H$$

$$\sigma = \frac{A_1}{A_2},\; C_c = \text{contraction coefficient}$$

$$C_c = \frac{1}{0.639\left[1-\left(\frac{1}{\sigma}\right)\right]^{1/2} - 1} \quad \text{(Chisholm)}$$

90° bend

$$p_1 - p_2 = k_B\left[\frac{\dot{m}^2}{2\rho_L}\right]\psi_H$$

$$k_B \approx 0.15$$

Homogeneous multiplier

$$\psi_H = \left[1 + x\left(\frac{\rho_L}{\rho_G} - 1\right)\right]$$

Phenomenological approach: General principles

Stages:

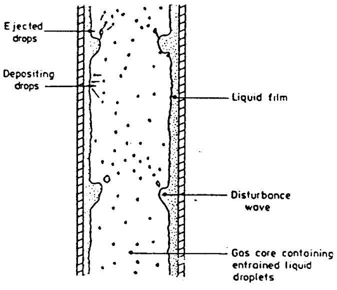
(1) Identify the type of interfacial distribution – i.e. FLOW REGIME

(2) Observe detailed phenomena and make appropriate measurements.

(3) Construct physical models of theoretical or semi-theoretical type to describe the phenomena.

(4) Integrate the local models to achieve a complete system description.

Phenomenological approach: Example: Annular flow I



PREDICTION PROBLEMS

- Liquid film behaviour
- Liquid deposition and entrainment
- Interfacial friction (waves)
- Effect of heat flux on local phenomena

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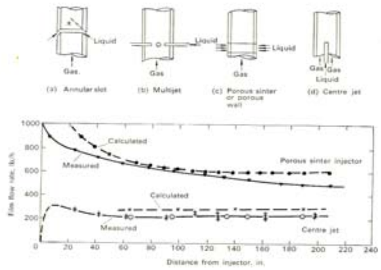
Phenomenological approach: Example: Annular flow II



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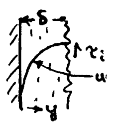
Phenomenological approach: Example: Annular flow III

1. TRIANGULAR RELATIONSHIP



Calculate $\tau = (y, \tau_i)$

Calculate $u = (u(y)$

Calculate $\dot{m}_{LF} = \frac{4}{\pi\, d^2} (\int_0^\delta \pi (d-y) \rho$

Establish "triangular relationship"

$\dot{m}_{LF} = \dot{m}_{LF}(\delta, \tau_i) = \dot{m}_{LF}(\delta, dp/dz)$

2. INTERFACIAL ROUGHNESS

Effective roughness (ϵ) or friction factor (f_i) of interface function of δ/d ("Geometrical similarity")

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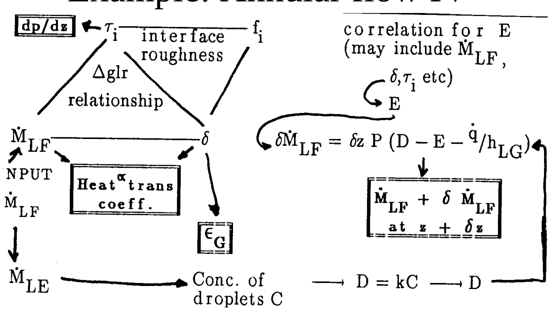
Phenomenological approach: Example: Annular flow IV



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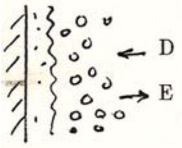
Phenomenological approach: Example: Annular flow V

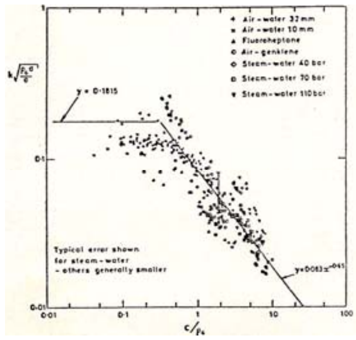


Equilibrium flow
D = E
Non–equilibrium flow
D ≠ E
∴ correlation for both required

Usual form:
D = kC
k = deposition mass transfer coefficient (m/s)

C = Homogeneous concentration of drops in core (kg/m³)

Phenomenological approach: Annular flow VI
Correlation for deposition rate



Correlation

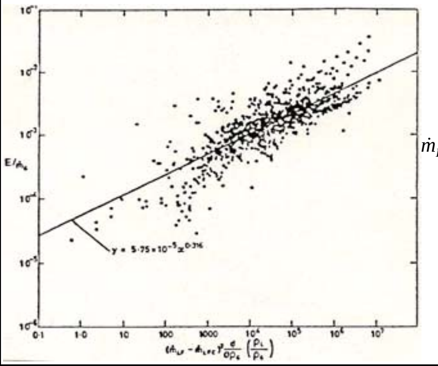
$k\sqrt{\frac{\rho_G d}{\sigma}} = 0.18$ if $C/\rho_G < 0.3$

$k\sqrt{\frac{\rho_G d}{\sigma}} = 0.83\,(C/\rho_G)^{[illegible]}$ if $C/\rho_G > 0.3$

D = kC

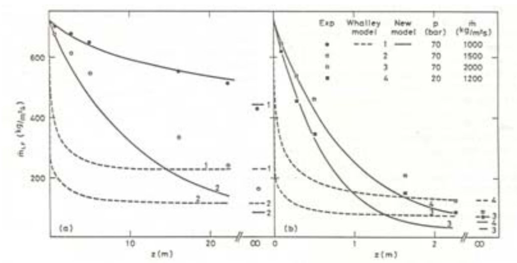
See Hewitt, Invited Lecture, ASME 1990, Winter Annual Meeting, Dallas

Phenomenological approach: Annular flow VII
Correlation for entrainment rate



$\dot{m}_{LFC}$ = critical film flow for onset of entrainment

Phenomenological approach: Example: Annular flow V



Prediction of Nigmatulin (1978) high pressure film flow data (Hewitt & Govan, 1990)