Micro-scale two-phase flow dynamics

Lecture 04 Gas-liquid two-phase flow

陈 斌

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Outline

- Two-Phase Flow Regimes
- Concept terminology, and Notations
- Flow regime / Pattern / Map (gas-liquid two-phase flow)
- Flow in Micro-channels
- Flow Pattern Identification

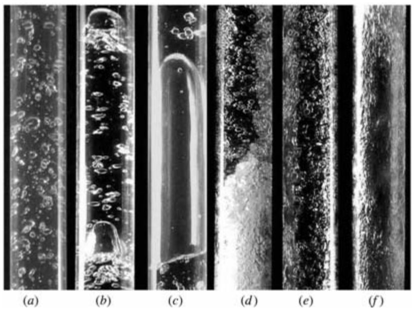
Two-Phase Flow Regimes

- liquid-vapor (gas), where the volume fraction of one phase relative to the other results in different flow regimes
- Two-component liquid-gas systems where the gas is non-condensable; these include air/water flow in aeration, deaeration, and humidification or dehumidification processes.
- In the case of a single-component two-phase flow, such as forced convective condensation or evaporation, continuous mass transfer occurs between the vapor and liquid phases. Examples of liquid-gas flow processes include distillation, fractionation, flashing, spray-drying, stripping, and absorption.

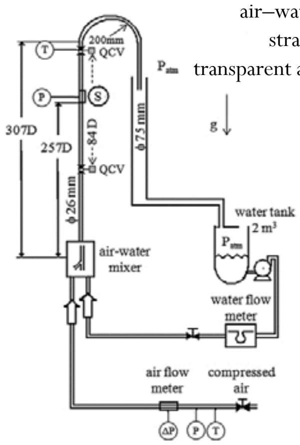
Two-Phase Flow Regimes

- liquid-vapor (gas) flow is the most complex because the interfaces are deformable and the vapor or gas phase is more common. Furthermore, the interfacial configurations in two-phase flow are also very complicated due to heat and mass transfer and can vary over a wide range. The interfacial distribution in the liquid-vapor (gas) flow can be classified into a number of categories known as flow patterns or flow regimes.
- Each regime in liquid-vapor (gas) two-phase flow has a characteristic flow behavior that can substantially affect both pressure drop and heat transfer. In different regimes of two-phase flow, the pressure drop and heat transfer characteristics are significantly different, so it is necessary to identify the conditions corresponding to the flow regimes.

Upward Two-Phase Flow



(a) bubbly; (b) spherical cap; (c) stable slug;
(d) unstable slug; (e) semi-annular and (f) annular



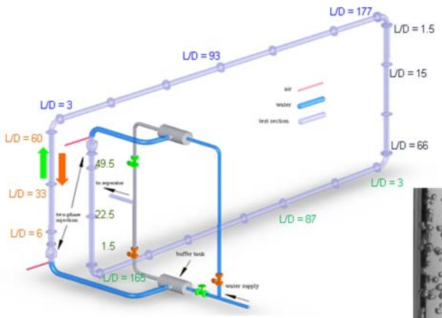
air–water flow in a straight vertical transparent acrylic tube, 26 mm ID

307D long

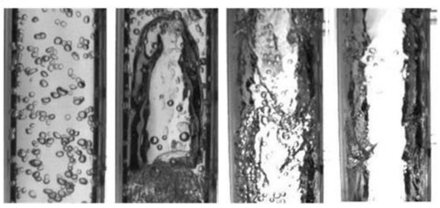
E S Rosa et al 2012 *Meas. Sci. Technol.* 23 055304

Mechanical Engineering Faculty, State University of Campinas, São Paulo, Brazil

Upward Two-Phase Flow



PENNSTATE



Bubbly Slug Churn-Turbulent Annular

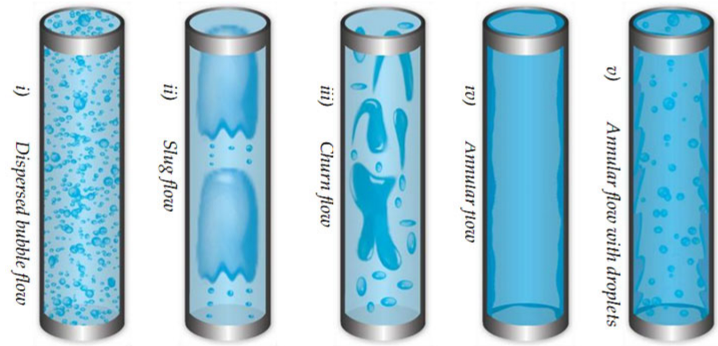
- 50.8 mm inner diameter acrylic pipes
- vertical section: 66D
- horizontal section:180D

Yadav, Mohan S., Master Thesis 2009

Advanced Multi-Phase Flow Laboratory

Department of Mechanical and Nuclear Engineering

Two-Phase Flow Regimes



泡状流　弹状流/塞状流　块状流　环状流　雾状流

http://www.drbratland.com/PipeFlow2/chapter1.html

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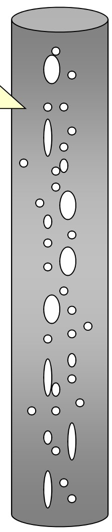
Dispersed bubble flow

characterized by small size bubbles, high liquid flow velocity and low to high gas flow velocity.

http://www.thermopedia.com/content/2/



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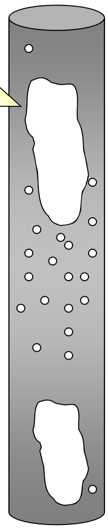
www.ux.uis.no/~s-skj

Slug/Plug flow

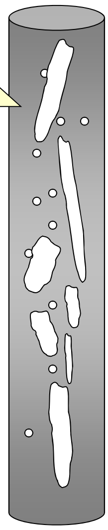
Liquid flow at low to moderate velocity and moderate velocity for gas flow. Slug flow is characterized with large bullet shaped Taylor bubbles and small bubbles flowing in-between.



http://www.thermopedia.com/content/2/

Churn flow

Liquid flow at low to moderate velocity and high velocity for gas flow. Churn flow is characterized with large thin bubbles and small bubbles flowing in-between.

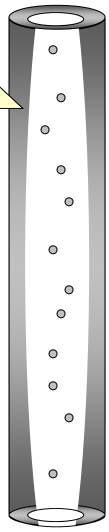


http://www.thermopedia.com/content/2/

Annular flow

Gas flow at very high velocity and low to very high velocity for liquid flow. Annular flow is characterized with a layer of liquid on the walls of the pipe and small bubbles of liquid in the middle gas zone.

http://www.thermopedia.com/content/2/

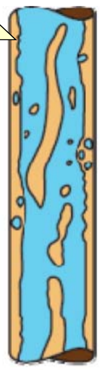


www.ux.uis.no/~s-skj

Wispy Annular Flow

As the liquid flow rate is increased, the concentration of drops in the gas core increases, leading to the formation of large lumps (团) or streaks (wisps, 缕) of liquid.

http://www.thermopedia.com/content/2/



The wispy annular flow regime was first identified by Bennett, A. W., Hewitt, G. F.; et al. in 1965 (Proc. Inst. Mech. Eng. 1965, 180 (3C), No. 5)

Downward two-phase flow

Afshin J. Ghajar

http://ghajar.ceat.okstate.edu/

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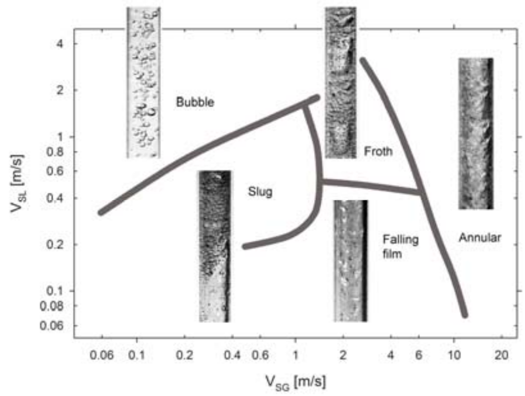
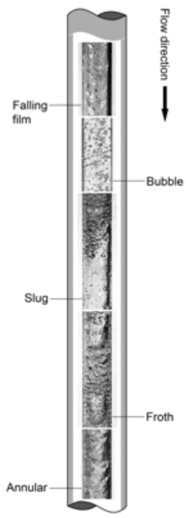
Downward two-phase flow





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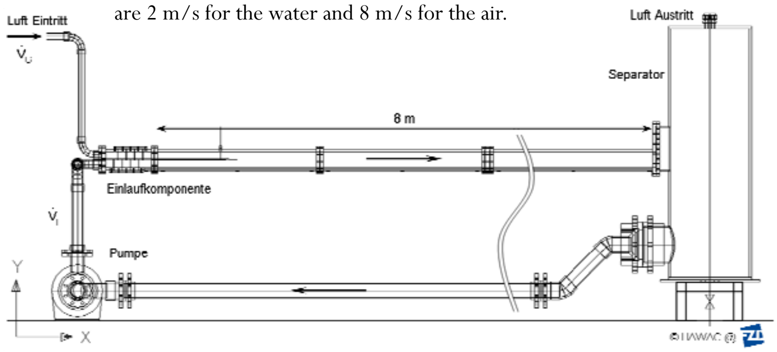
Horizontal Two-Phase Flow

rectangular cross-section of 100 x 30 mm² (height x width)

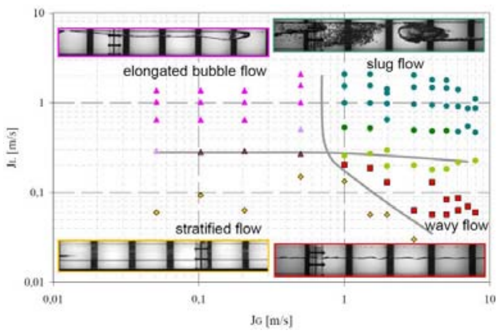
The maximum superficial velocities achieved in the test-section are 2 m/s for the water and 8 m/s for the air.



Helmholtz-Zentrum Dresden-Rossendorf 德国德累斯顿亥姆霍兹研究中心

http://www.hzdr.de/db/Cms?pOid=24089&pNid=3016

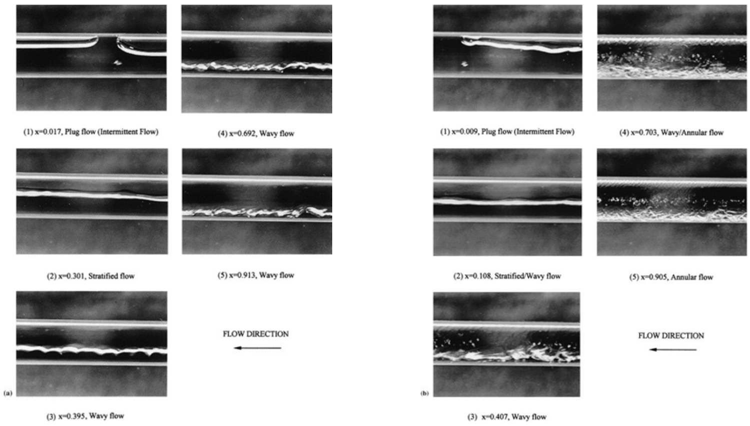
Horizontal Two-Phase Flow



Helmholtz-Zentrum Dresden-Rossendorf 德国德累斯顿亥姆霍兹研究中心

http://www.hzdr.de/db/Cms?pOid=24089&pNid=3016

Horizontal Two-Phase Flow



C.-C. Wang et al. / Int. J. Heat and Fluid Flow 19 (1998) 259-269

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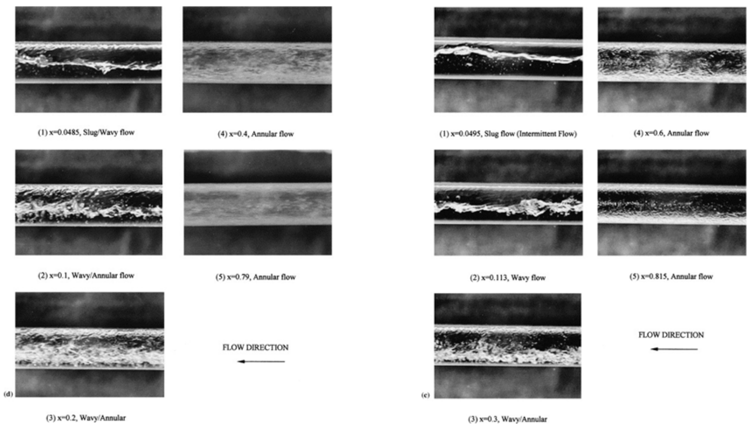
Horizontal Two-Phase Flow



C.-C. Wang et al. / Int. J. Heat and Fluid Flow 19 (1998) 259-269

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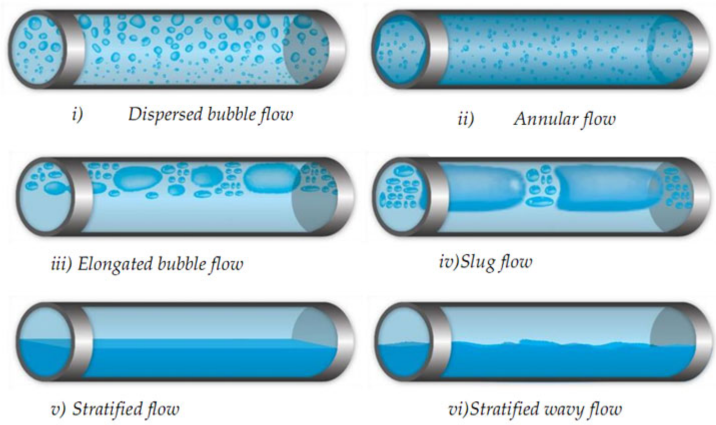
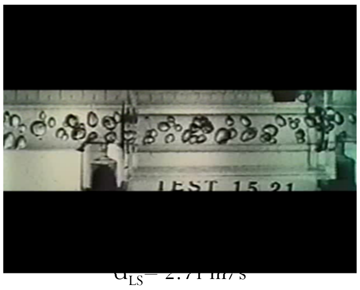
Horizontal Two-Phase Flow



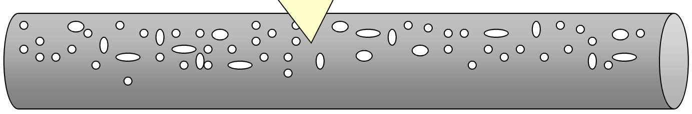
http://www.drbratland.com/PipeFlow2/chapter1.html

Dispersed bubble flow

Very high liquid velocity, and the gas velocity can vary from very low to very high. Characterized by small bubbles of gas moving mostly in the upper zone of the liquid.



http://microgravity.grc.nasa.gov/6712/2phase_flow/2phase.html

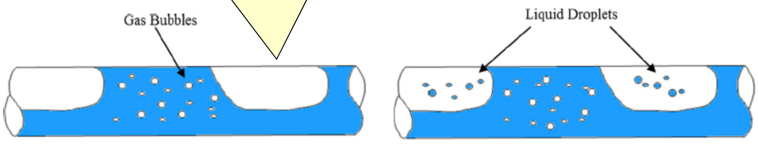


www.ux.uis.no/~s-skj

Plug flow / Elongated bubble flow

An increase of quality, moderate liquid flow velocity and low gas flow velocity. Characterized by bullet-shaped plugs / large bubbles in the upper zone of the liquid phase.

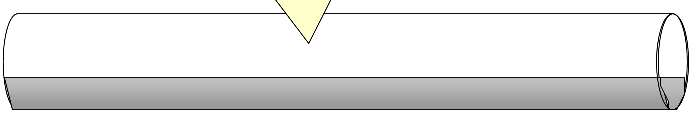
$U_{LS} = 0.3$ m/s
$U_{GS} = 0.005$ m/s



J. Energy Resour. Technol. 136(1), 012901

Stratified smooth flow

Flow at very low velocity for both gas and liquid, the quality is relatively high. Stratified smooth flow is characterized with a clear distinguished line between gas and liquid.



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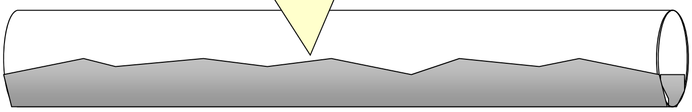
Stratified wavy flow

Low liquid velocity and mediocre gas velocity. Since gas velocity is slightly higher then the liquid velocity, its causing the liquid flow to create waves. This characterize stratified wavy flow.

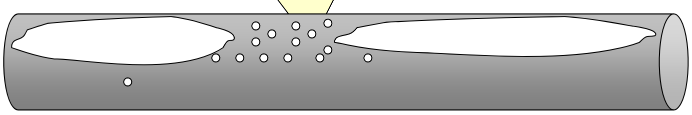
U_{LS} = 0.05 m/s
U_{GS} = 5.00 m/s



Slug flow

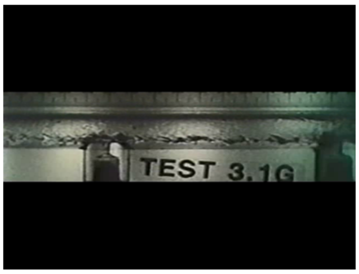
The amplitude of the waves increases as the liquid flow rate increases. The crests can span the entire tube, and a bridge starts to develop, separating the slugs from one another.

http://www.thermopedia.com/content/2/

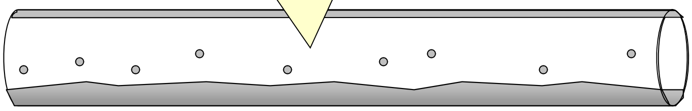


Annular flow

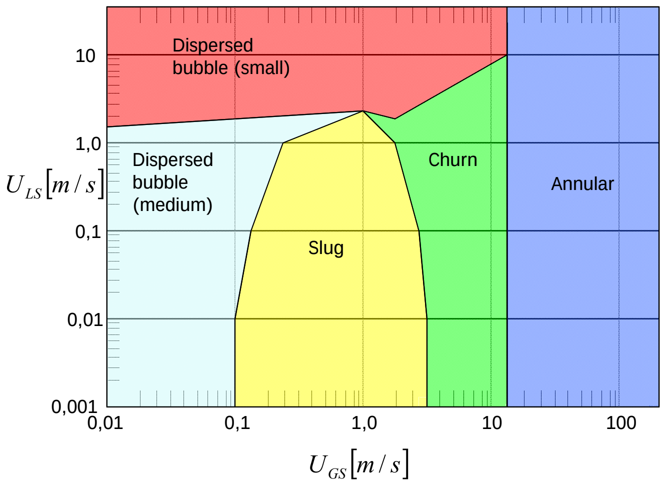
Very high gas velocity, and the liquid velocity can vary from very low to very high. Characterized by a thin layer of liquid along the walls of the pipe, with bubbles of liquid moving in the middle gas zone.



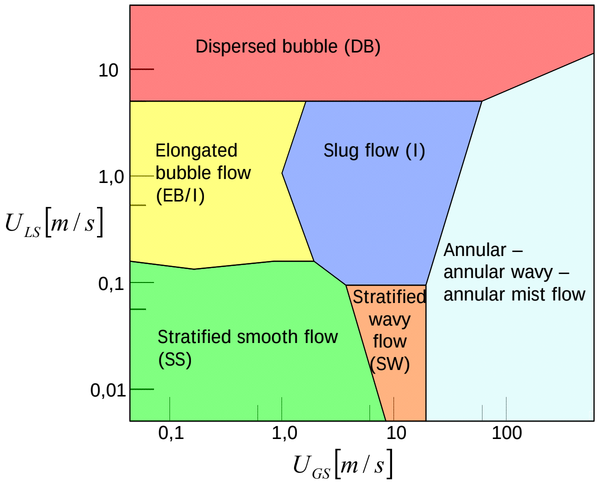
http://microgravity.grc.nasa.gov/6712/2phase_flow/2phase.html



Vertical flow



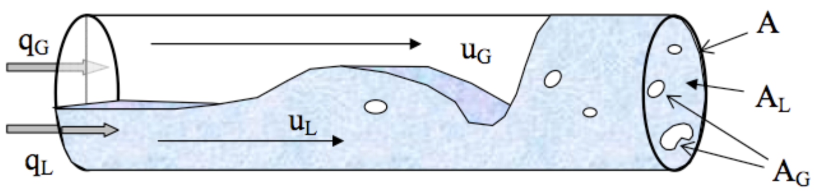
Horizontal flow



Outline

- Two-Phase Flow Regimes
- Concept terminology, and Notations
- Flow regime / Pattern / Map (gas-liquid two-phase flow)
- Flow in Micro-channels
- Flow Pattern Identification

Concept terminology, and Notations



Marius Aarskog. Extending a Drift - Flux Model for More Realistic Prediction of Transient Flow in UBO

Concept terminology, and Notations

- *void fraction (holdup)* (含气率/持液率) represents the time-averaged volumetric fraction of gas/vapor (liquid) in a two-phase mixture

$$\alpha = \frac{\int_{V_g} dV}{\int_V dV} = \frac{V_g}{V_g + V_l}$$

- For a pipe with equal cross-section

$$\alpha = \frac{\Delta z \int_{A_g} dA}{\int_A dA} = \frac{A_g}{A_g + A_l}$$

- Physical properties of the two-phase mixture:

$$\rho = \frac{\int_{V_g} \rho_g dV + \int_{V_l} \rho_l dV}{V_g + V_l} = \alpha\rho_g + (1-\alpha)\rho_l$$

Concept terminology, and Notations

- The *total mass flow rate* (质量流率) is the sum of the mass flow rate of each phase

$$\dot{m} = \dot{m}_g + \dot{m}_l$$

- The *total volumetric flow rate* (体积流率) is the sum of the volumetric flow rate of each phase

$$\dot{Q} = \dot{Q}_g + \dot{Q}_l = \frac{\dot{m}_g}{\rho_g} + \frac{\dot{m}_l}{\rho_l}$$

- The *total mass flux* (质量通量) of the flow is defined the total mass flow rate divided by the pipe cross-sectional area

$$G = \frac{\dot{m}}{A}$$

Concept terminology, and Notations

- The *phase velocity* (相速度) is the mean velocity of each phase and is defined as the volumetric flow rate of that phase through its cross-sectional area

$$\langle\omega_g\rangle = \frac{\dot{Q}_g}{A_g} \qquad \langle\omega_l\rangle = \frac{\dot{Q}_l}{A_l}$$

- The *superficial velocity* (表观速度) of gas phase flow is the velocity if the gas is flowing alone in the pipe. It is defined as the volumetric flow rate of gas divided by the pipe cross-sectional area

$$j_g = \frac{\dot{Q}_g}{A} \qquad j_l = \frac{\dot{Q}_l}{A} \qquad j_g = \alpha\langle\omega_g\rangle$$

$$j_l = (1-\alpha)\langle\omega_l\rangle$$

Concept terminology, and Notations

- The *volumetric flow fraction* (体积含气率) is defined as the volumetric flow rate of the vapor divided by the total volumetric flow rate

$$\beta = \frac{\dot{Q}_g}{\dot{Q}_g + \dot{Q}_l} = \frac{j_g}{j_g + j_l} \qquad j_g = \frac{\dot{Q}_g}{A} \qquad j_l = \frac{\dot{Q}_l}{A}$$

- A *slip ratio* (滑移率) is defined as the ratio of the phase velocity of the gas to that of the liquid

$$s = \frac{\langle\omega_g\rangle}{\langle\omega_l\rangle} = \frac{\dot{Q}_g}{\dot{Q}_l}\frac{A_l}{A_g} = \frac{\frac{A_l}{A_g}}{\frac{\dot{Q}_l}{\dot{Q}_g}} = \frac{\frac{A - A_g}{A_g}}{\frac{\dot{Q} - \dot{Q}_g}{\dot{Q}_g}} = \frac{\frac{1}{\alpha} - 1}{\frac{1}{\beta} - 1}$$

- For homogeneous flow, $s = 1$, $\alpha = \beta$

Concept terminology, and Notations

- Armand in 1946 fitted from experimental data

$$\frac{\alpha}{\beta} = C_A = 0.833 \qquad \text{For } \beta < 0.9$$

- Massena in 1960 extended this fit for $\beta > 0.9$ as

$$\frac{\alpha}{\beta} = [C_A + (1 - C_A)x]\beta = 0.833$$

- 水平或上升流动中，s总大于1，即 $\alpha < \beta$
- 下降流中，s可能大于1也可能小于1

Concept terminology, and Notations

- The *quality* (*dryness fraction*, 干度) is defined as the ratio of the mass flow rate of gas phase to the total mass flow rate

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

- *The volumetric quality* (容积干度/容积含气率) is defined as the ratio of the volumetric flow rate of gas phase to the total volumetric flow rate

$$\beta = \frac{\dot{Q}_g}{\dot{Q}} = \frac{\rho_g \dot{m}_g}{\rho_g \dot{m}_g + \rho_l \dot{m}_l} = \frac{x\rho_g}{x\rho_g + (1-x)\rho_l} = \frac{1}{1 + \left(\frac{1-x}{x}\right)\frac{\rho_g}{\rho_l}}$$

$$s = \frac{\langle \omega_g \rangle}{\langle \omega_l \rangle} = \frac{\dot{Q}_g}{\dot{Q}_l}\frac{A_l}{A_g} = \frac{\rho_g}{\rho_l}\frac{\dot{m}_g}{\dot{m}_l}\frac{1-\alpha}{\alpha} = \frac{\rho_g}{\rho_l}\frac{x}{1-x}\frac{1-\alpha}{\alpha}$$

Concept terminology, and Notations

- The *superficial mass flux* or *mass velocity* (表观质量通量) of liquid and gas/vapor is defined as

$$G_g = \frac{\dot{m}_g}{A} = \rho_g \frac{\dot{Q}_g}{A} = \rho_g j_g = \rho_g \langle \omega_g \rangle \alpha \qquad \langle \omega_g \rangle = \frac{\dot{Q}_g}{A_g}$$

$$G_l = \frac{\dot{m}_l}{A} = \rho_l \frac{\dot{Q}_l}{A} = \rho_l j_l = \rho_l \langle \omega_l \rangle (1-\alpha) \qquad j_g = \frac{\dot{Q}_g}{A}$$

- The *total mass flux* is

$$\dot{m}'' = G_g + G_l = \rho_g j_g + \rho_l j_l$$

- so

$$x = \frac{\dot{m}_g}{\dot{m}} = \frac{G_g}{\dot{m}''}$$

Concept terminology, and Notations

- The *superficial momentum flux* (表观动量通量) of liquid and gas/vapor is defined as

$$\rho_g j_g^2 = \rho_g \frac{G_g^2}{\rho_g^2} = \frac{x^2 G^2}{\rho_g}$$

$$\rho_l j_l^2 = \rho_l \frac{G_l^2}{\rho_l^2} = \frac{(1-x^2)G^2}{\rho_l}$$

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Flow regime / Pattern / Map

- To predict the local flow pattern in a tube, a **flow pattern map** is used.
- It's a diagram that displays the **transition boundaries** between the flow patterns and is typically plotted on **log-log axis using dimensionless parameters** to represent the liquid and gas velocities

Flow regimes

- Better predictions of ΔP and Holdup (volume fraction), if flow regime is known.
- Flow regime prediction is not only important for reliable design, but for pipeline operability.
- Phenomena like pipe corrosion and erosion depend on flow regimes.
- Flow regime at pipe outlet affects gas-liquid separation efficiency.

Typical Velocities (1" pipe)

Regime	Liquid Velocity (ft/s)	Vapor Velocity (ft/s)
Dispersed	Close to vapor	> 200
Annular	<0.5	>20
Stratified	<0.5	0.5-10
Slug	Less than vapor vel.	3-50
Plug	2	< 4
Bubble	5-15	0.5-2

http://users.rowan.edu/~savelski/temporary_storage/two-phase-1.ppt

Flow-Pattern Transitions

- **Semi-empirical correlations** based on the experimental and operational data that have been collected over the decades by various investigators. (subjectivity, not always easy to distinguish)
- **Analytical models** that are based on physical concepts are often used to derive one-dimensional continuity, momentum, and energy balances for simple boundary conditions and steady state systems.
- In transient systems and more complex systems where boundary conditions are not exact, **numerical models** based on physical concepts are used to predict two-phase flow. (accurate, difficult)

The coordinates used in flow maps

- **Phase velocities or fluxes**: gas and liquid superficial velocities j_g and j_l (m/s) or gas and liquid superficial mass fluxes G_g and G_l (kg/m^2 s) and gas and liquid mass flow rates m_g and m_l (kg/s). Use of these parameters, while undoubtedly being the most convenient, does not ensure creation of a universal flow-pattern map for different two-phase mixtures.
- **Quantities referring to the two-phase flow homogeneous model** are the transformations of the parameters from group 1 such as total velocity j, total mass flux G, Froude number based on total velocity Fr, void fraction α, and quality x. They are only useful for the description of some flow-pattern maps.
- **Parameters including the physical properties of phases** such as liquid and gas Reynolds numbers ReL and ReG, Baker correction factors λ and ψ, gas and liquid kinetic energies EG and EL, and others; this formulation gives the best possibility for attaining a universal flow-pattern map.

Applied Mechanics Reviews 2008, Vol. 61 / 050802-5

Flow-Pattern Transitions

Table 2.3 Flow-Pattern Maps for Vertical Upward Two-Phase Flow Systems Based on Generalized Coordinate Parameters

Author	Fluids	Pipe Diameter	Coordinate Parameters
Kosterin (1949)	Air-Water	1 in.	β, j
Kozlov (1954)	Air-Water	1 in.	$\beta, j^2/gD)^{1/2}$
Galegar et al. (1954)	Air-Water, -Kerosene	0.5 & 2 in.	G_g, G_f
Ueda (1958)	Air-Water	2 in.	W_g, W_f
Hewitt & Roberts (1969)	Air-Water	1.25 in.	$\rho_f j_f^2, \rho_g j_g^2$
Nishigawa et al. (1969)	Air-Water	1 in.	j_f, j_g
Govier & Aziz (1972)	Air-Water	Data from Others	Yj_f, Xj_g
Oshinowa & Charles (1974)	Natural Gas-Oil		$(\beta/1-\beta)^{1/2}$, Fr_{TP}/Æ
Spedding & Nguyen (1980)	Air-Water	4.55 mm	$j/(gD)^{1/2}, j_f/j_g$
Weisman & Kang (1981)	Freon-113 Vapor-Liquid	1 in.	$j_g/\Phi1, j_f/\Phi2$

Michael L. Corradini, Department of Engineering Physics, University of Wisconsin

Vertical upward two-phase flow

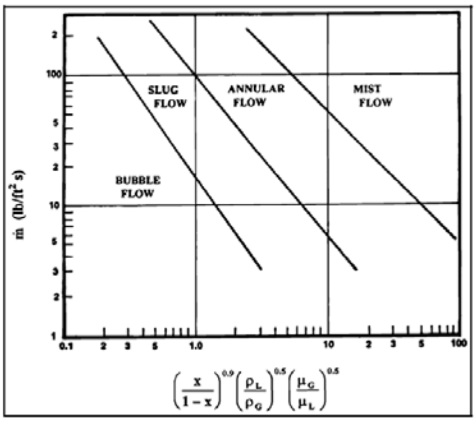
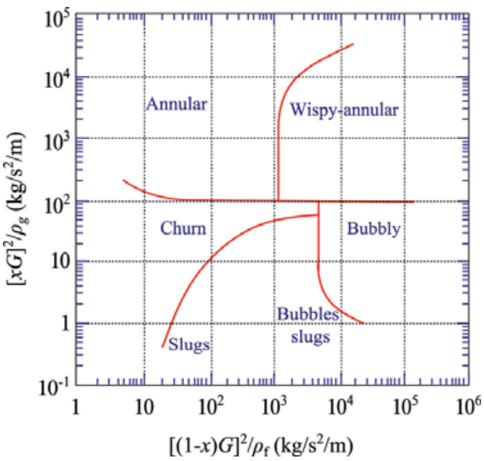


Figure 12.4. Two-phase flow pattern map of Fair (1960) for vertical tubes.

- Calculate the value of the x-axis and the mass velocity (lb/ft^{2}s) for the particular application at hand
- Fair, J. R. (1960) What you need to know to design thermosyphon reboilers (热虹吸式再沸器), Petroleum Refiner, Vol. 39, NO. 2, pp.105

Vertical upward two-phase flow



One of the leading empirical flow-pattern maps for vertical upflows

Research Complex at Harwell

Working across the life and physical sciences

Founder and Head of Heat Transfer & Fluid Flow Service (1968-1982), Harwell Laboratory, Oxfordshire

Hewitt and Roberts. *AERE-M* 2159 (1969)

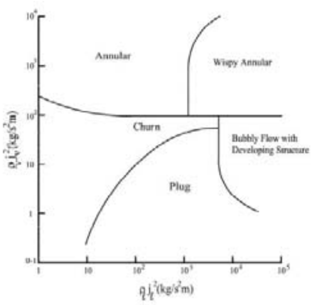
西安交通大学动力工程多相流国家重点实验室 陈斌 Geoffrey F. Hewitt. *Energy & Fuels* 2012, 26, 4067−4077

Two-Phase Flow Regimes

- **Professor Geoffrey F. Hewitt**
- Imperial College London， UK
- Fellow, Royal Society of Chemistry
- Fellow, Royal Academy of Engineering
- Fellow, Royal Society

- Hewitt, G. F. (1982), Handbook of Multiphase Systems (Ed. G. Hetsroni), Hemisphere Publishing Corporation, New York.

Example



Example 11.1 Determine the flow regime for vertical upward flow of 0.8 Kg/s of R134a in a vertical 0.1 m diameter tube at -20 °C and 25% quality.

Solution: The mass flow rate is $\dot{m} = 0.8$ kg/s, and the diameter of the tube is $D = 0.1$m. Therefore, the mass flux of the R11 in the tube is

$$\dot{m}'' = \frac{\dot{m}}{A} = \frac{4\dot{m}}{\pi D} = \frac{4 \times 0.8}{\pi \times 0.1^2} = 101.86 \text{ kg/m}^2\text{-s}$$

The densities of liquid and vapor R-134 at T= –20 °C can be found from the Table B.34 as $\rho_\ell = 1358$ kg/m³ and $\rho_v = 6.785$ kg/m³. The superficial velocities of the vapor and liquid are obtained from eqs. (11.24) and (11.25), i.e.,

$$j_\ell = \frac{\dot{m}''(1-x)}{\rho_\ell} = \frac{101.86 \times (1-0.25)}{1358} = 0.0562 \text{ m/s}$$

$$j_v = \frac{\dot{m}'' x}{\rho_v} = \frac{101.86 \times 0.25}{6.785} = 3.75 \text{ m/s}$$

The superficial momentum of the liquid and vapor phases are, respectively:

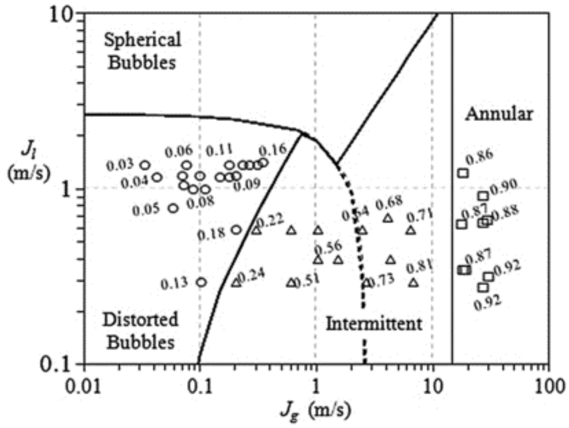
$$\rho_\ell j_\ell^2 = 1358 \times 0.0562^2 = 4.30 \text{ kg/s}^2\text{-m}$$

$$\rho_v j_v^2 = 6.785 \times 3.75^2 = 95.4 \text{ kg/s}^2\text{-m}$$

It can be found from Fig. 11.2 that the flow regime is churn flow.

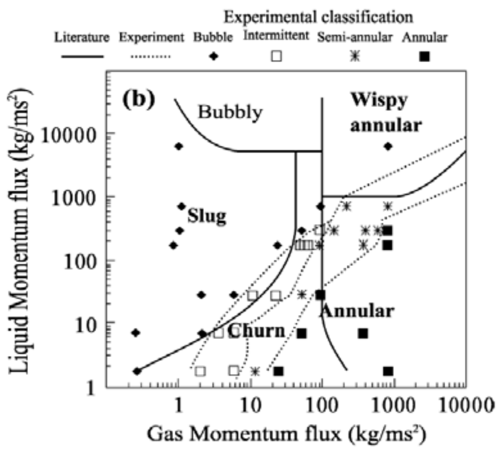
http://www.thermalfluidscentral.org/e-books/book-viewer.php?b=42&s=94

Upward Two-phase flow



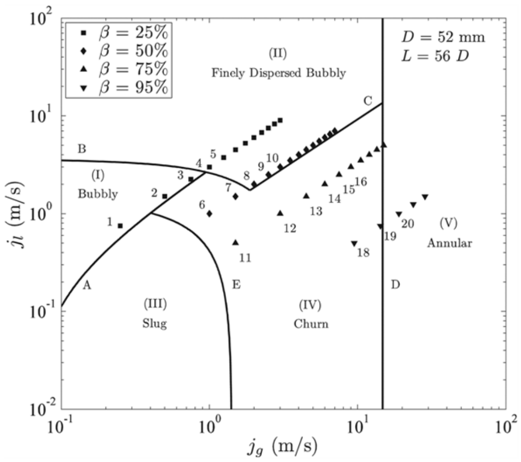
Taitel Y, Barnea D and Dukler A E 1980 Modelling flow pattern transitions for steady upward gas–liquid flow in vertical tubes AIChE J. 26 345–54

Upward vertical two-phase flow



Nitrogen-naptha (石脑油) flows at 90 bar pressure (Omebere-Iyari et al., AIChE J. 2007, 53, 2493−2504). These data are typical of flows encountered in wells and risers in hydrocarbon (烃) recovery.

Upward vertical flow



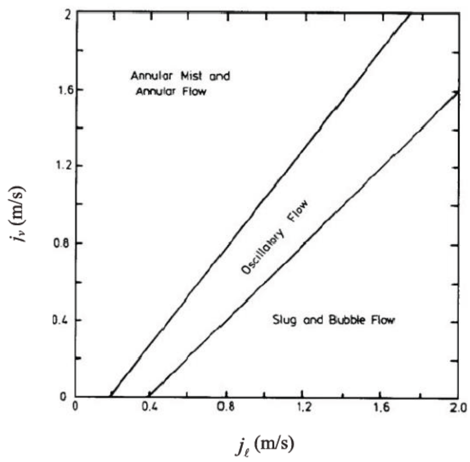
Michel J. Pettigrew
Polytechnique Montréal

- a 52 mm diameter U-bend tube
- A new two-phase flow pattern map, based on existing transition models and validated using our own local void fraction measurements

J. Pressure Vessel Technol. 135(3), 030907

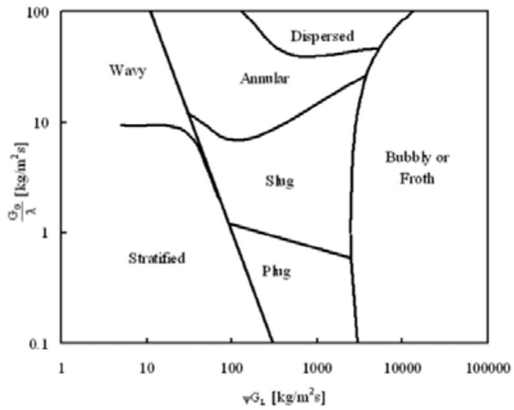
Vertical downward flow

- Although downward two-phase flow finds application in many areas, especially in condensation, it has received very little attention from investigators.
- The difference with upward flow is that the downward-acting shear force, gravitational force, and imposed pressure gradient eliminate the churn flow regime.
- Annular flow regime is dominant



Golan and Stenning, 1969
Low pressure air-water flow data

Horizontal flow



$$\lambda = \left(\frac{\rho_G}{\rho_A}\frac{\rho_L}{\rho_W}\right)^{1/2}$$

$$\psi = \left(\frac{\sigma_W}{\sigma}\right)\left[\left(\frac{\mu_L}{\mu_W}\right)\left(\frac{\rho_W}{\rho_L}\right)^2\right]^{1/3}$$

- Both λ and ψ reduce to 1 for water/air mixtures at standard conditions.
- The Baker map is reasonably well for water/air and oil/gas mixtures in small diameter (< 0.05 m) pipes.

One of the best known empirical flow-pattern maps for horizontal flow, This map was first suggested by Baker (1954), and was subsequently modified by Scott (1964).

Baker, O., 1954, “Simultaneous Flow of Oil and Gas,” Oil Gas J., 53, pp. 185–190.

Shortcomings

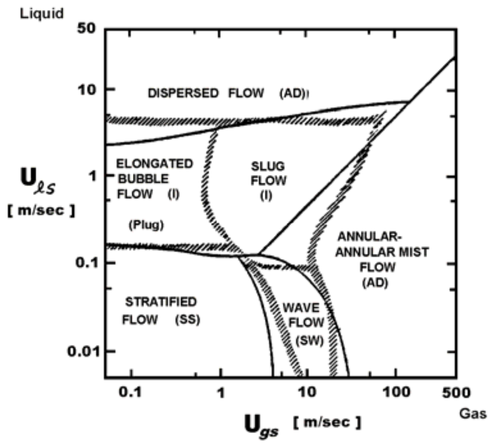
- Claimed that the Baker correlation overestimates the effect of fluid properties.
- Claimed that a plot with superficial velocities rather than superficial mass velocities is better.
- Suggested a slight correction for fluid properties by using a corrected superficial gas velocity:

$$V_G^{'} = f(x, y)V_G \qquad x = \left[\left(\frac{\rho_G}{0.0013}\right)^{0.2}\left(\frac{\rho_L 72.4}{\sigma}\right)^{0.25}\left(\frac{\mu_G}{0.018}\right)^2\right] \qquad y = \left[\left(\frac{\rho_L 72.4}{\sigma}\right)^{0.25}\mu_L^{\ 0.2}\right]$$

Mandhane Plot (Mandhane et al., 1974)

Horizontal flow

- low-pressure system without a large change in the gas density
- Water-air
- 25°C, 1 atm.
- 2.5 cm. diam.



Mandhane, J. M., Gregory, G. A., and Aziz, K., 1974, Int. J. Multiphase Flow., 1, pp. 537–553

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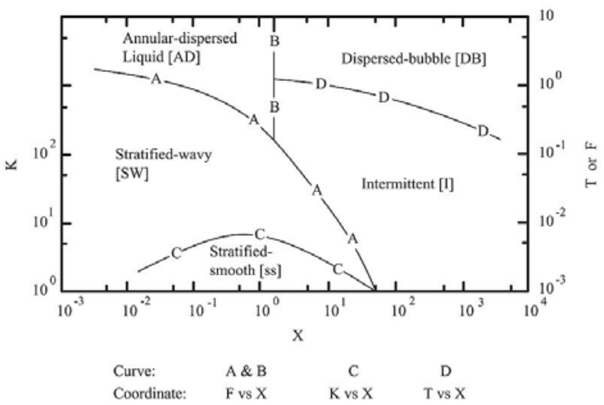
Horizontal flow



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

$$F = \sqrt{\frac{\rho_v}{\rho_l - \rho_v}}\frac{j_v}{\sqrt{Dg\cos\theta}}$$

$$K = F \cdot Re_l^{0.5} = \left[\frac{\rho_v j_v^2}{(\rho_l - \rho_v)Dg\cos\theta}\frac{Dj_l}{\nu_l}\right]^{1/2}$$

$$T = \left[\frac{|(dp/dz)_l|}{(\rho_l - \rho_v)g\cos\theta}\right]^{1/2}$$

The **most comprehensive treatment** of flow pattern transitions in horizontal flow on a semitheoretical basis (Taitel, Y., and Dukler, A.E., 1976, AIChE Journal, Vol. 22, pp. 47- 55)

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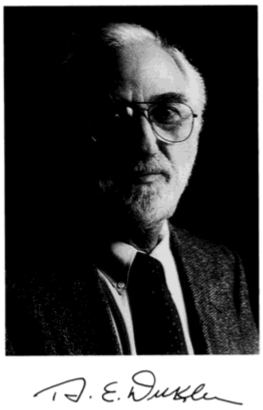
Horizontal flow

Prof. Yehuda Taitel
Tel Aviv University



A. E. DUKLER
1925-1994
Member of NAE
U. Huston

Taitel, Y., and Dukler, A.E., 1976, "A Model for Predicting Flow Regime Transitions in Horizontal and Near Horizontal Gas-Liquid Flow," AIChE Journal, Vol. 22, pp. 47- 55.

Horizontal flow

- The Taitel and Dukler (1976) map is the most widely used flow pattern map for horizontal two-phase flow.
- This map is based on a semi-theoretical method, and it is computationally more difficult to use than other flow maps.
- It should be noted that the Taitel and Dukler (1976) map was obtained for adiabatic two-phase flow; however, the transition boundaries between various flow regimes depend on the heat flux. Nevertheless, this flow map is often used to determine the flow patterns for evaporation and condensation inside pipes, for which external heating or cooling is required.

Shortcomings of the Taitel - Dukler flow regime_models

- Poor prediction of stratified flow for inclined pipes.
- Poor prediction of high pressures and low surface tension fluids.
- Near vertical flow regime better predicted than near horizontal.
- Viscosity effect not properly described.
- Out of 10,000 gas liquid flow pattern observations over the last 30 years, only 67% of all observations were predicted correctly. (Shell Research - Development, 1999)

Horizontal flow

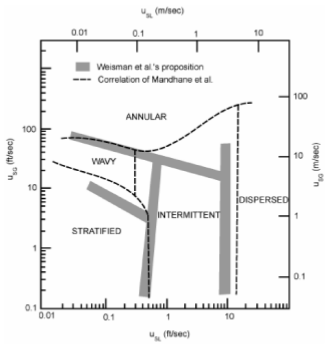


Figure 6. Weisman et al. (1979) map for horizontal flow.

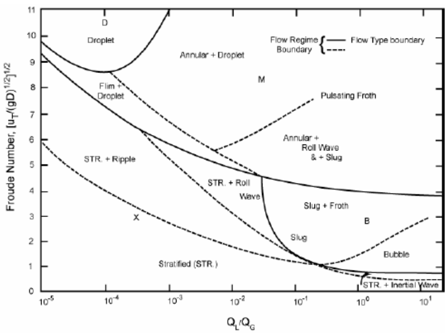


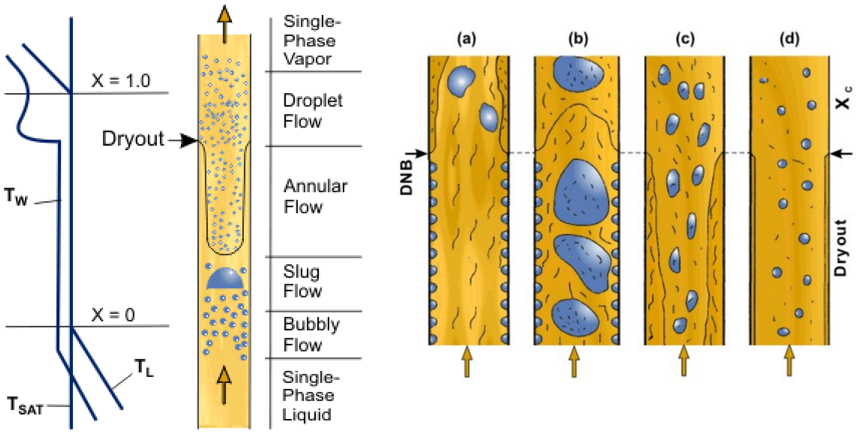
Figure 7. Spedding and Nguyen (1980) map for horizontal flow.

Weisman et al. (1979) studied the effects of fluid properties (liquid viscosity, liquid density, interfacial tension, and gas density) and pipe diameters [(0.5in to 2in) I.D.] on flow patterns in horizontal pipes.

Spedding and Nguyen (1980) map for horizontal flow.

A. J. Ghajar. J. Braz. Soc. Mech. Sci. & Eng. vol.27 no.1 Rio de Janeiro Jan./Mar. 2005

Convective boiling in vertical tube



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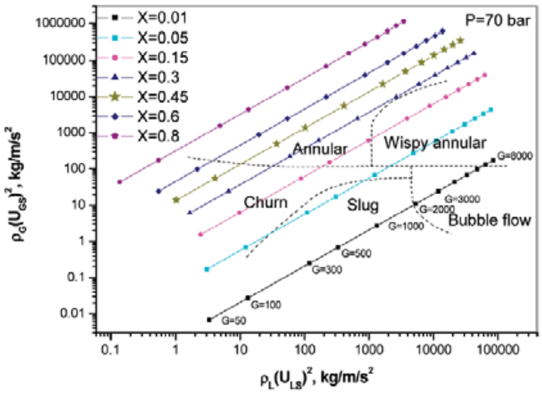
CHF vs Flow regime

evaporation of water in vertical round tubes



CHF data obtained from the Groeneveld et al. (Nucl. Eng. Des. 2007, 237, 1909–1922.) plotted on the flow regime map by Hewitt and Roberts (data obtained by Ahmad (Ph.D. Thesis, Imperial College))

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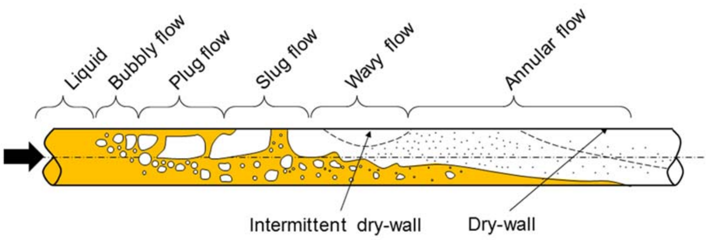
Convective boiling in horizontal tube



https://www.htri.net/modeling-twophase-flow-with-phase.aspx

Convective boiling in horizontal tube

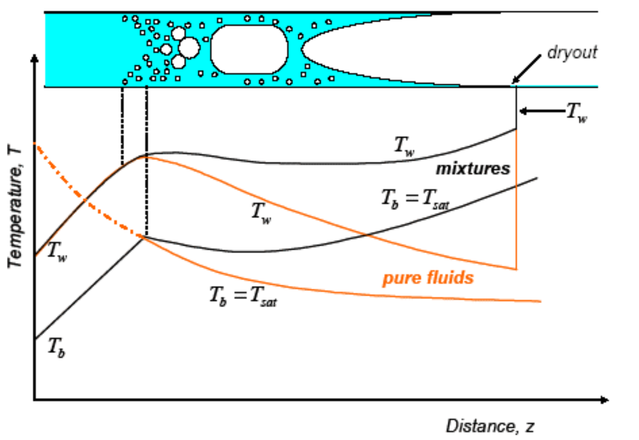


Figure 9. Temperature profiles and boiling regimes for convective evaporation (Thome and Shock, 1984).

binary and multicomponent evaporating systems

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Flow regime

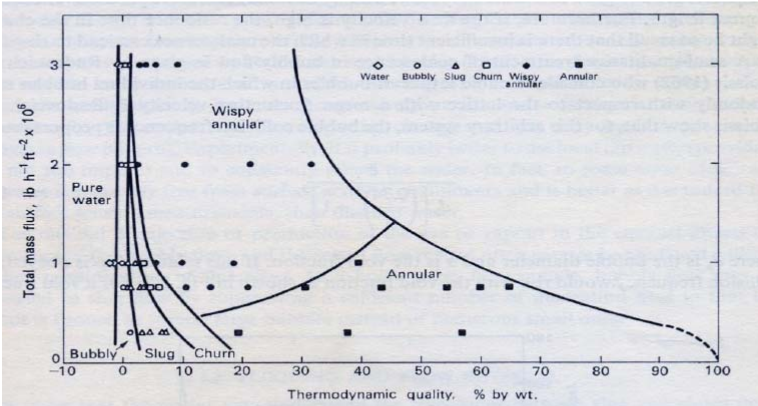
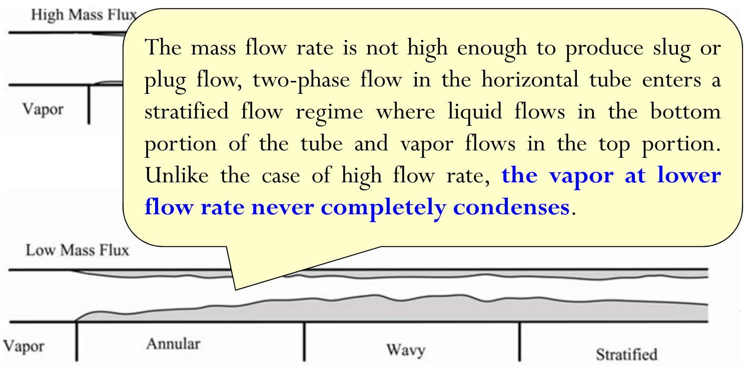


FIG. 2.6. Results of Bennett *et al.* (1965) for flow patterns produced by boiling in a $\frac{1}{2}$ in. bore tube at 1000 p.s.i.a.

Forced convective condensation

- Condensation in a vertical tube is relatively simple, because gravity acts parallel to the flow direction and, consequently, an annular liquid film forms on the inner surface of the tube. Therefore, the flow pattern for condensation in a vertical tube is limited to annular flow, and an analytical solution can easily be obtained.

Forced convective condensation

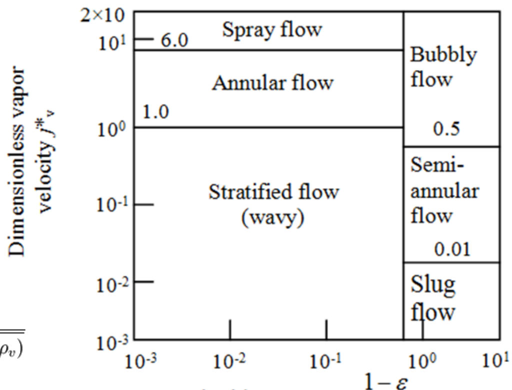


The mass flow rate is not high enough to produce slug or plug flow, two-phase flow in the horizontal tube enters a stratified flow regime where liquid flows in the bottom portion of the tube and vapor flows in the top portion. Unlike the case of high flow rate, **the vapor at lower flow rate never completely condenses**.

(b) Lower mass flow rate

Hewitt, G.F., 1998, "Multiphase Fluid Flow and Pressure Drop," Heat Exchanger Design Handbook, Vol. 2, Begell House, New York, NY

Forced convective condensation



$$j_v^* = \frac{x\dot{m}''}{\sqrt{gD\rho_v(\rho_\ell - \rho_v)}}$$

$$\frac{1-\varepsilon}{\varepsilon}$$

Tandon, T.N., Varma, H.K., and Gupta, C.P., 1982, ASME Journal of Heat Transfer, Vol. 104, pp. 763-768

Different Inclination Angles

0° to ±90° orientation experimental setup

http://ghajar.ceat.okstate.edu/

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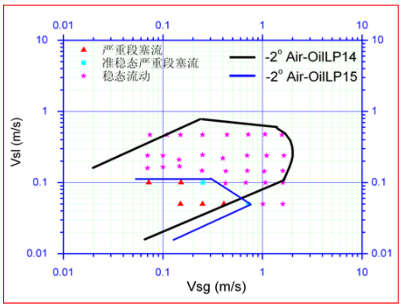
Different Inclination Angles



L: 2100m Oil: 29m³/h water: 29m³/h gas: 1020 Nm³/h Pressure: 35MPa Temperature: 3~70°C Power: 1500kW

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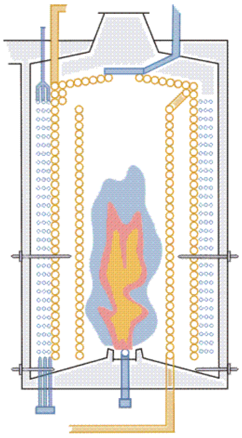
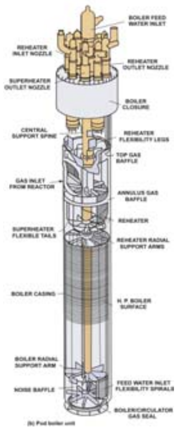
Helical Coiled Tubes

160馬力雙迴路閉式循環汽輪發動機，航程大於20km，下潛深度大於800m，潛航速度為30節，戰鬥部裝填炸藥重40kg。



Coiled tube boiler



Coiled tube pod boilers used in advanced gas cooled reactor

http://www.thermopedia.com/content/638/

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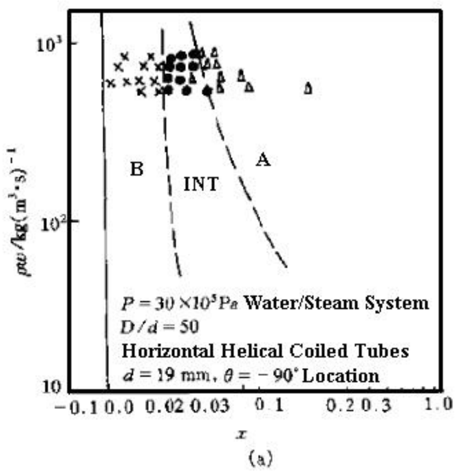
Helical Coiled Tubes



- the pressure ranging from 0.1MPa to 15.0MPa
- working media including single component two-phase fluid (water and steam) and two component two-phase fluid (water and air)
- the ratio of diameter helical coils to inner diameter of tube ranging from 12 to 50

L. J. Guo, Ph. D Thesis, 1989

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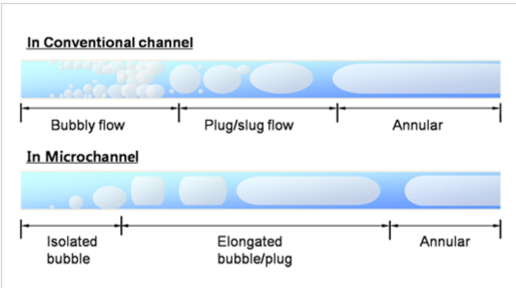
Outline

- Two-Phase Flow Regimes
- Concept terminology, and Notations
- Flow regime / Pattern / Map (gas-liquid two-phase flow)
- Flow in microchannels
- Flow Pattern Identification

Microchannel

- Microchannel has several benefits in thermal-hydraulic system. (ex: Higher heat dissipation rate, Fast response of reaction)
- However, there are many different behaviors from that in conventional size due to the ratio between surface and volume.



http://twophase.postech.ac.kr/02research/research04.htm

Microchannel

hydraulic diameter of 500 μm

Mass flux 25 kg/m^2 s, Heat flux 120 kW/m^2 in hydrophilic (疏水) channel

Mass flux 25 kg/m^2 s, Heat flux 120 kW/m^2 in hydrophobic (亲水) channel

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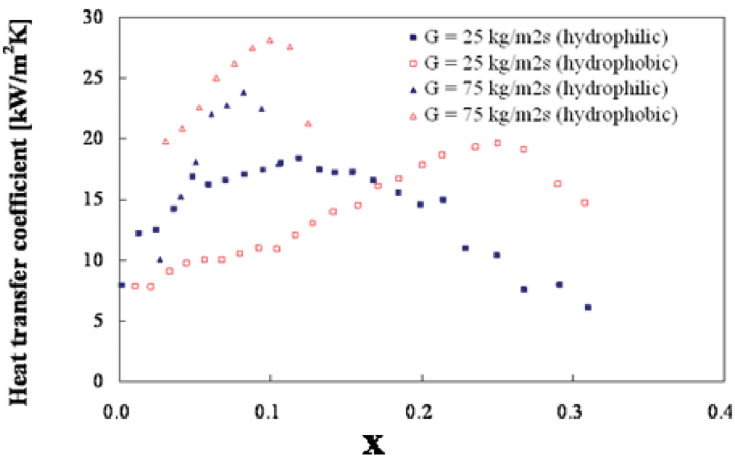
Microchannel

hydraulic diameter of 500 μm



http://twophase.postech.ac.kr/02research/research04.htm

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Outline

- Two-Phase Flow Regimes
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- Flow in microchannel
- Flow Pattern Identification

Flow Pattern Identification

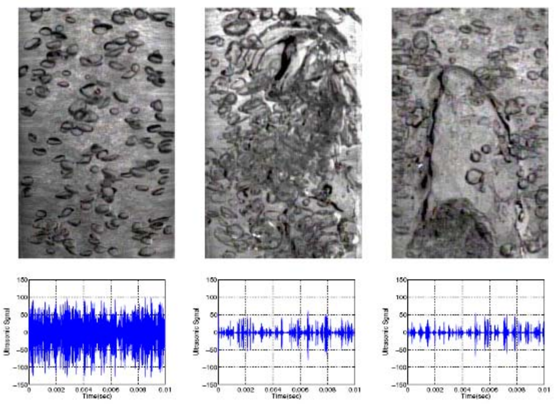
- Two-phase flow is generally a complex phenomenon; therefore, to obtain a reasonable analytical prediction, a number of approximations must be made while solving the momentum and energy balances.
- Generally, the pressure drop across the flow channel and/or heat transfer coefficients are calculated to determine the flow characteristics at a given point and allow prediction of the flow regime.
- To that end, prediction methods based on heat transfer coefficients and pressure drop correlations are developed.

Flow Pattern Identification

- x-ray absorption spectrometers
- Resistance sensors (Moreira, 1989)
- Tomography techniques (Lehner and Wirth, 1999)
- Capacitance electrical tomography (Ostrowski et al., 2000)
- Ultrasonic tomography (Xu and Xu, 1997)

Flow Pattern Identification

Objective Flow Regime Identification via Ultrasound



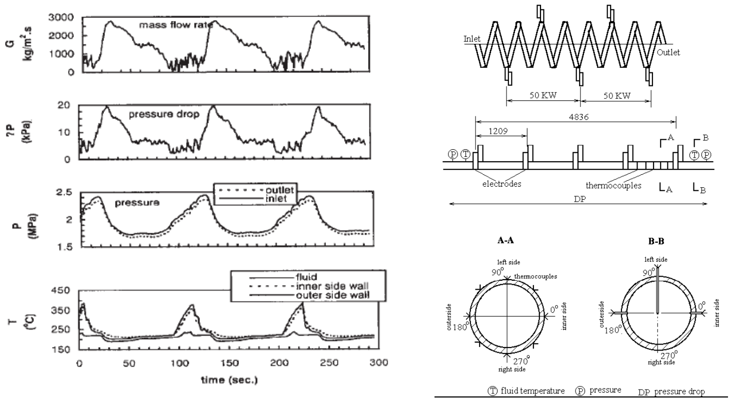
http://www2.mne.psu.edu/amfl/research/fru/

Flow Pattern Identification

- pressure-drop is frequently associated with a change of flow regime (Wambsganss et al.,1994)
- Lin and Hanraty (1987) used pressure measurements to detect the intermittent flow regime
- Osman and Aggour (2002) introduced a neural network model to predict the pressure drop in horizontal multiphase flow.

Flow Pattern Identification

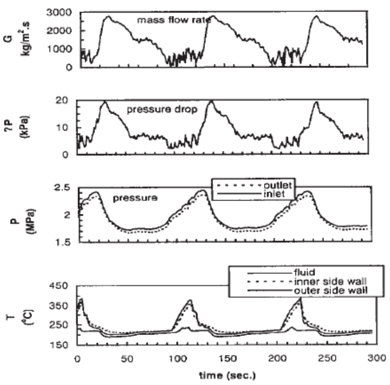
Pressure drop oscillation of steam-water two-phase flow in a helically coiled tube

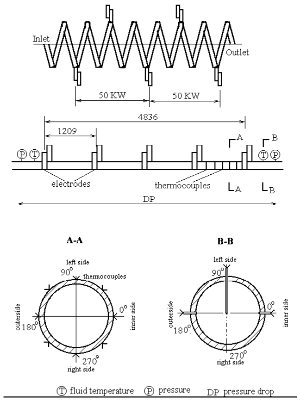


L.-J. Guo et al. / International Journal of Heat and Mass Transfer 44 (2001) 1555-1564

Flow Pattern Identification

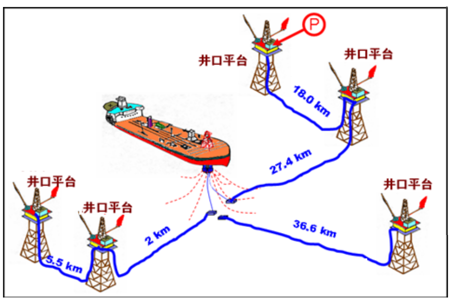
Pressure drop oscillation of steam-water two-phase flow in a helically coiled tube



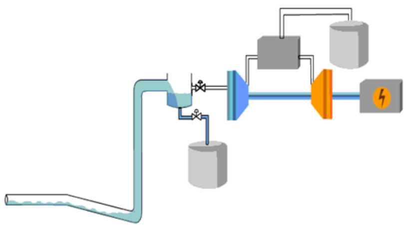


L.-J. Guo et al. / International Journal of Heat and Mass Transfer 44 (2001) 1555-1564

Flow Pattern Identification

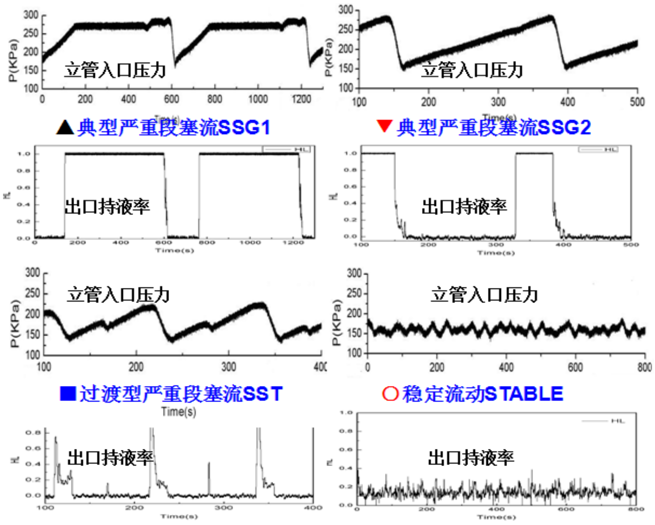


深水（>500m）油气生产的集输-立管系统



➢液塞长度大于立管高度时发生严重段塞流动：井口高回压影响产量；燃油压缩机频繁启动；平台分离器溢流事故等

Flow Pattern Identification



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Flow Pattern Identification

观察流型	测试的流型				
	SSG1	SSG2	SST	ST	识别率
SSG1	47	2	1	0	94.0%
SSG2	0	21	4	0	84.0%
SST	0	0	40	4	90.9%
ST	0	0	3	36	92.3%

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Exercise 05

$$s = \frac{\frac{1}{\alpha} - 1}{\frac{1}{\beta} - 1} \qquad \beta = \frac{1}{1 + \left(\frac{1-x}{x}\right)\frac{\rho_g}{\rho_l}} \qquad s = \frac{\rho_g}{\rho_l}\frac{x}{1-x}\frac{1-\alpha}{\alpha}$$

$$x = \frac{\dot{m}_g}{\dot{m}} = \frac{G_g}{\dot{m}"}$$

Exercise 06

- A two-phase fluid is flowing upwards in a vertical pipe of internal diameter of 1.0 in. The fluid properties are as follows: liquid density = 60 lb/ft^3; vapor density = 2 lb/ft^3; liquid viscosity = 0.4 cp; vapor viscosity = 0.01 cp. If the vapor quality is 0.2 and the total flow rate of liquid and vapor is 3600 lb/h, using the Fair flow pattern map, what is the local flow pattern expected to be?

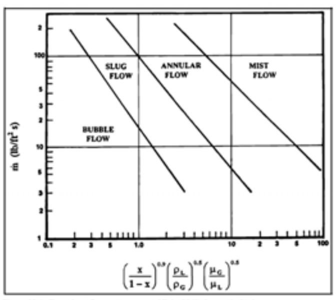


Figure 12.4. Two-phase flow pattern map of Fair (1960) for vertical tubes.

Exercise 07

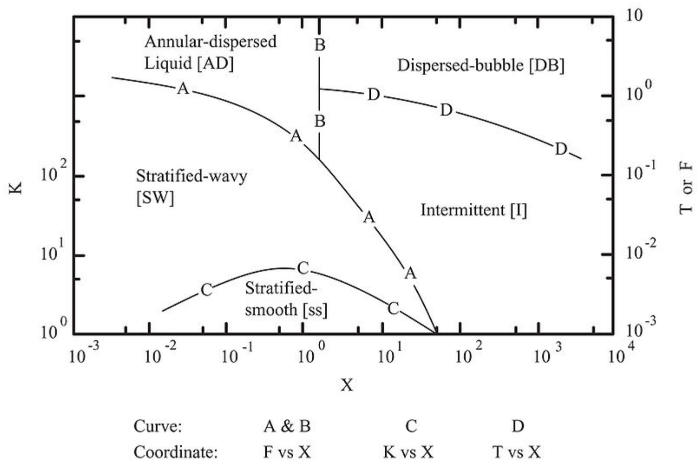
- Use the Taitel-Dukler flow map to determine the flow regime for a flow of 8 kg/s of water-stream at 15% quality and 180°C in a 0.1m ID horizontal tube (θ = 0°).
- (ρ_w = 887.31 kg/m^3, ρ_v = 5.1597 kg/m^3, μ_w = 1493×10^{-7} Ns/m^2, μ_w = 149×10^{-7} Ns/m^2)

$$X = \left[\frac{(dp_F/dz)_l}{(dp_F/dz)_v}\right]^{1/2} \qquad F = \sqrt{\frac{\rho_v}{\rho_l-\rho_v}}\frac{j_v}{\sqrt{Dg\cos\theta}}$$

$$K = F \cdot Re_l^{0.5} = \left[\frac{\rho_v j_v^2}{(\rho_l-\rho_v)Dg\cos\theta}\frac{D j_l}{\nu_l}\right]^{1/2}$$

$$-\left(\frac{dp_F}{dz}\right)_v = \frac{2 f_v \dot{m}''^2 x^2}{D\rho_v} \qquad -\left(\frac{dp_F}{dz}\right)_l = \frac{2 f_l \dot{m}''^2 (1-x)^2}{D\rho_l} \qquad f = 0.079 Re^{0.25}$$

Exercise 07



To be continued……

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