Two-Phase flow with phase change in conventional and miniature channels

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Lecture - 02

Flow Regimes and Flow Regime Maps

Welcome back to the course on Two-Phase flow with phase change in conventional and miniature channels. Today we will discuss Flow Regimes in two phase flow.

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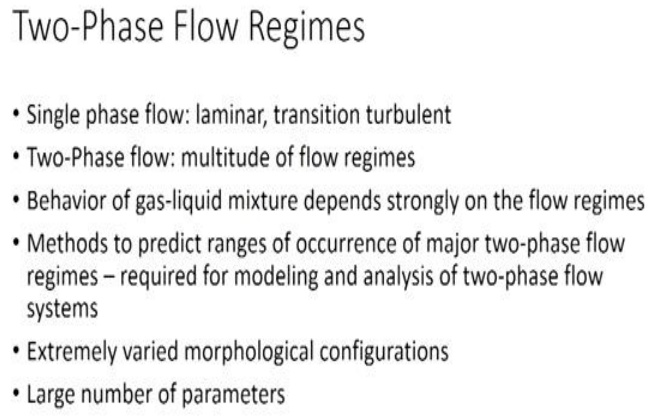

Two-Phase Flow Regimes

- Single phase flow: laminar, transition turbulent
- Two-Phase flow: multitude of flow regimes
- Behavior of gas-liquid mixture depends strongly on the flow regimes
- Methods to predict ranges of occurrence of major two-phase flow regimes – required for modeling and analysis of two-phase flow systems
- Extremely varied morphological configurations
- Large number of parameters

In single phase flow, there are only two flow regimes laminar and turbulent and in between there is a transition regime. But in two phase flow there are many flow regimes or multitude of flow regimes and between any two flow regimes, there is a transition range. The behavior of gas liquid mixture depends strongly on the flow regimes. Therefore, it is important to study the flow regimes and to predict the conditions under which different flow regimes will occur. The methods to predict ranges of occurrence of major two phase flow regimes are required for modeling and analysis of two phase flow systems. In two phase flows, there are extremely varied morphological configurations; that means, the liquid and vapor phases can have many different shapes and there are large number of parameters which effect the flow regimes.

In single phase flow, there is only one parameter Reynolds number and by checking the value of Reynolds number, we can predict whether it will be laminar flow or turbulent flow or in between transition. But in two phase flow there are many parameters and we have to check many parameters to predict which flow regime will occur under certain given conditions. Some physical factors which cause morphological variations are the following.

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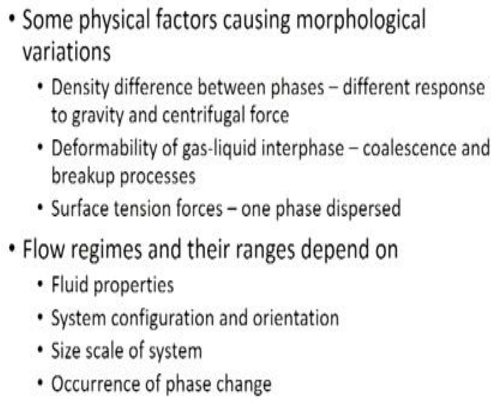

- Some physical factors causing morphological variations
  - Density difference between phases – different response to gravity and centrifugal force
  - Deformability of gas-liquid interphase – coalescence and breakup processes
  - Surface tension forces – one phase dispersed
- Flow regimes and their ranges depend on
  - Fluid properties
  - System configuration and orientation
  - Size scale of system
  - Occurrence of phase change

- **Density difference between the phases:** Usually there is large density difference the liquid density is much higher than the gas density because of this the two phases have different responses to gravity and centrifugal force.
- **Deformability of interphase:** The gas liquid interphase can deform and because of that there can be coalescence breakup processes of bubbles and drops.
- **Surface tension forces:** At the surface at the liquid gas interphase there is surface tension force and because of that one of the phases is usually dispersed and both phases are not continuous.

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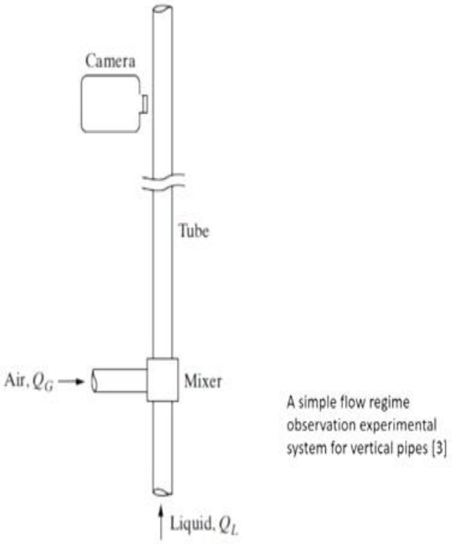

A simple flow regime observation experimental system for vertical pipes [3]

Flow regimes and their ranges depend on many factors. Fluid properties; they depend on fluid properties, they depend on system configuration and orientation. For example, whether it is vertical flow or horizontal flow or inclined flow and it depends on the size scale of the system in conventional channel we observe certain flow patterns, but in small channels miniature channels or micro channels, we offer we observe

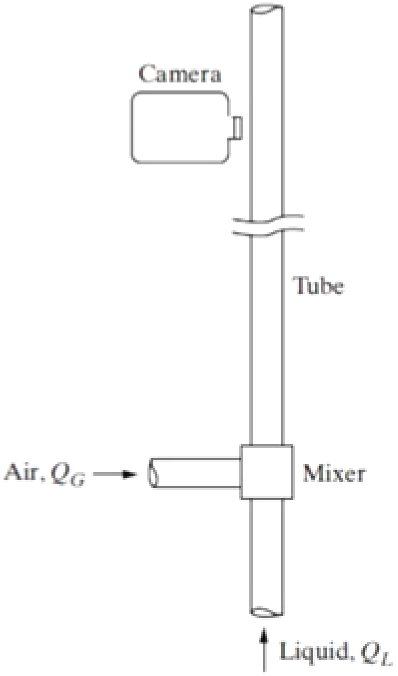

Figure 1: A simple flow regime observation experimental system for vertical pipes (image source: internet)

some different flow patterns. Then there is occurrence of phase change if the system is a single component two phase system, then there is possibility of phase change the liquid can get converted into vapor and vapor can get converted into liquid and because of that there is another factor which affects the flow regimes.

Figure 1 shows a simple experimental set up to observe flow regimes in vertical pipes. There is at one inlet at there is liquid and at another liquid inlet, there is gas and they are mixed in a mixture and then the mixture flows through the tube and then there is a camera through which pictures are taken to observe the flow patterns.

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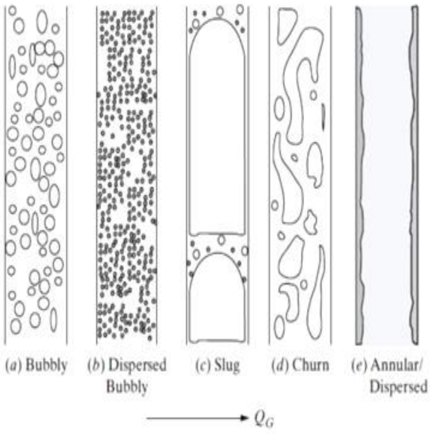

Major flow regimes in vertical upward pipe flow [3]

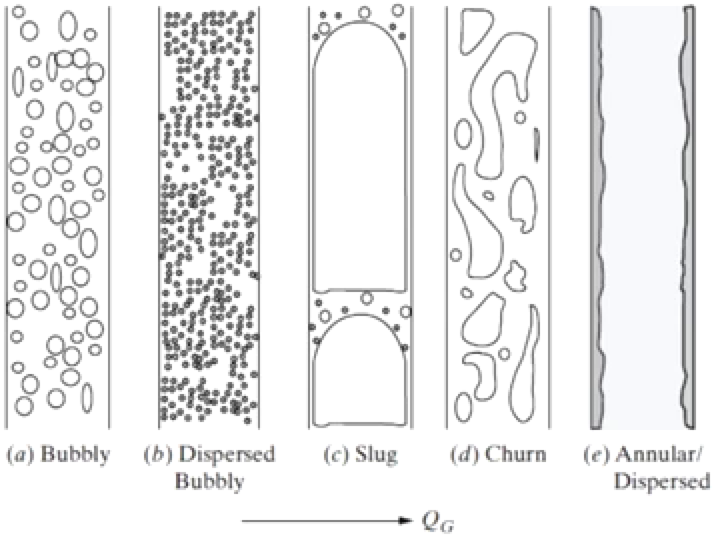

Figure 2: Major flow regimes in vertical upward pipe flow (image source: internet)

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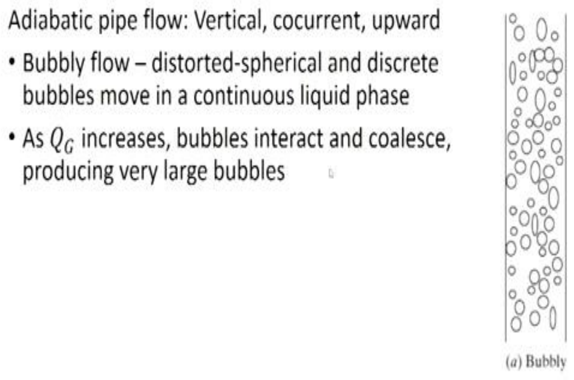

Adiabatic pipe flow: Vertical, cocurrent, upward

- Bubbly flow – distorted-spherical and discrete bubbles move in a continuous liquid phase
- As Q_G increases, bubbles interact and coalesce, producing very large bubbles

In figure 2, major flow regimes in vertical upward pipe flow are shown. There is bubbly flow in which the liquid phase is continuous and the gas is in the form of bubbles, then there is dispersed bubbly flow in which bubbles are small and spherical shaped and almost of equal size. Then there is slug flow in which bubbles are large approximately of the size of the channel itself and the bubble has a hemispherical head and cylindrical body and it looks like bullet. These bubbles are called Taylor bubbles. There is a liquid film between the bubble and the wall and between bubbles, there is mostly liquid which is called slug, but the liquid slug may contain some bubbles of vapor also. Then there is churn flow in which bubbles are of

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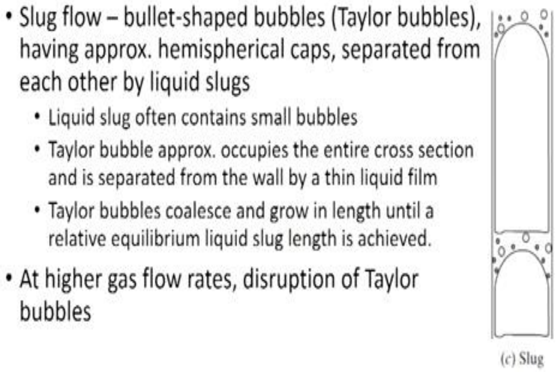

- Slug flow – bullet-shaped bubbles (Taylor bubbles), having approx. hemispherical caps, separated from each other by liquid slugs
  - Liquid slug often contains small bubbles
  - Taylor bubble approx. occupies the entire cross section and is separated from the wall by a thin liquid film
  - Taylor bubbles coalesce and grow in length until a relative equilibrium liquid slug length is achieved.
- At higher gas flow rates, disruption of Taylor bubbles

(c) Slug

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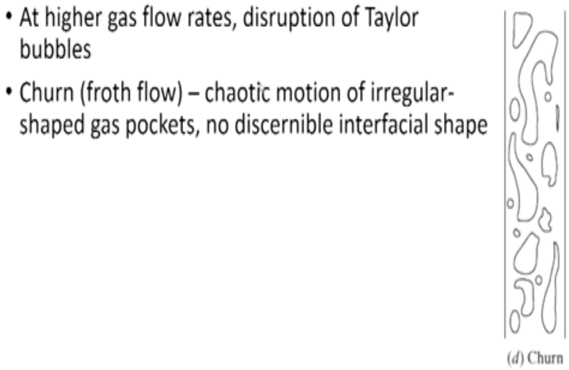
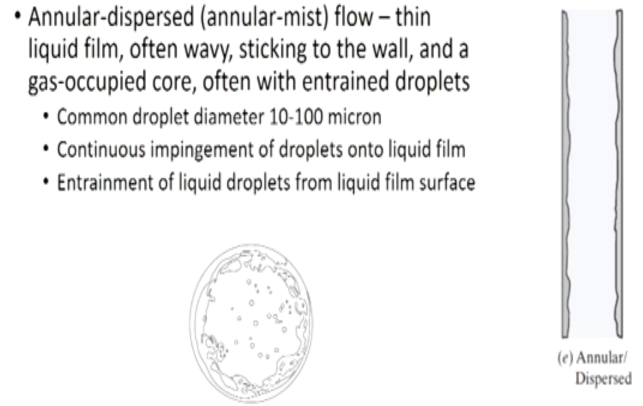


- At higher gas flow rates, disruption of Taylor bubbles
- Churn (froth flow) – chaotic motion of irregular-shaped gas pockets, no discernible interfacial shape

(d) Churn

irregular shape and size and the shape of the bubble keeps on changing in with time. So, therefore, that is why it is called churn flow, there is continuously churning of the flow. Then there is annular flow and annular dispersed flow in which there is a liquid annulus at the walls and at the center, there is a vapor core. The vapor core may contain entrained liquid droplets also and liquid film may contain some vapor (Refer Slide Time: 09:14)



- Annular-dispersed (annular-mist) flow – thin liquid film, often wavy, sticking to the wall, and a gas-occupied core, often with entrained droplets
  - Common droplet diameter 10-100 micron
  - Continuous impingement of droplets onto liquid film
  - Entrainment of liquid droplets from liquid film surface

bubbles. These flow regimes are shown as the volumetric flow rate (Q_G) of the liquid of the gas increases. So, from left to right Q_G is increasing. When Q_G is low, we get bubbly flow; when Q_G increases, the bubbles becomes small and spherical. They break into small bubbles and we get dispersed bubbly flow and at higher values of Q_G, we get slug flow the bubbles coalesce and they form large bubbles. At still higher Q_G, these bubbles will break and there is churn flow and at still higher volumetric flow rate of gas there is annular flow. So, in bubbly flow, there are distorted spherical and discrete bubbles which move in a continuous liquid phase. Here bubbly flow is shown. As Q_G increases bubbles interact and coalesce and produce very large bubbles. And then we get slug flow. In slug flow, there are bullet shaped bubbles or Taylor bubbles and they have spherical cap separated from each other by liquid slugs. The liquid slug often contains small bubbles. The Taylor bubble approximately occupies the entire cross section and this separated from the wall by a thin liquid film. Taylor bubbles coalesce and grow in length until a relative equilibrium liquid slug length is achieved. At higher gas flow rates, these Taylor bubbles get disrupted and we get churn flow. In churn flow or froth flow, there is chaotic motion of irregular shaped gas pockets and there is no discernible interfacial shape and it keeps on changing with time. Then at still higher gas flow rates, we get annual dispersed flow or annular mist flow rates; we get annular dispersed flow or annular mist flow. In this there is a thin liquid film and it is often wavy and it sticks to the wall and at the core there is gas which often contains entrained droplets. The common droplet diameter is in the range of

10 to 100 microns, there is continuous impingement of droplets on to liquid film and also there is entrainment of liquid droplets from the liquid film surface.

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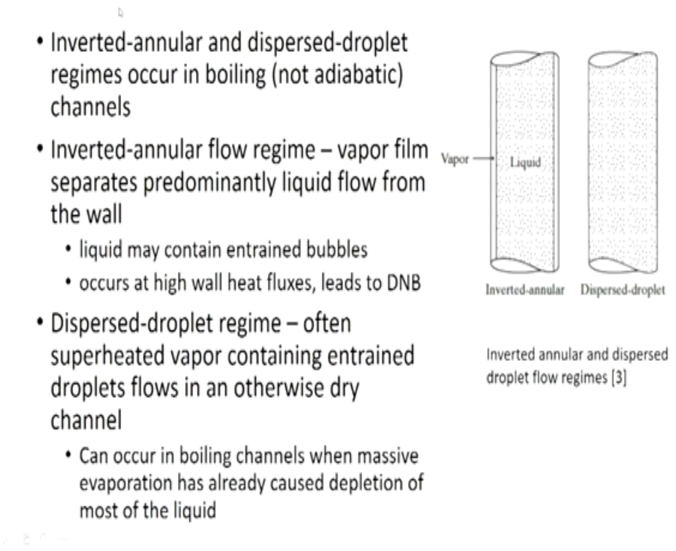
- Inverted-annular and dispersed-droplet regimes occur in boiling (not adiabatic) channels
- Inverted-annular flow regime – vapor film separates predominantly liquid flow from the wall
  - liquid may contain entrained bubbles
  - occurs at high wall heat fluxes, leads to DNB
- Dispersed-droplet regime – often superheated vapor containing entrained droplets flows in an otherwise dry channel
  - Can occur in boiling channels when massive evaporation has already caused depletion of most of the liquid

Inverted annular and dispersed droplet flow regimes [3]

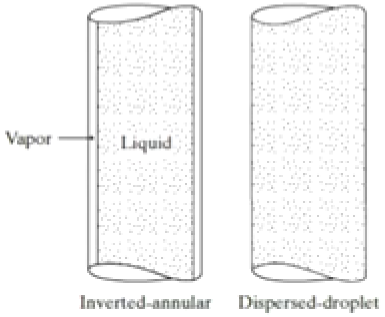

Figure 3: Inverted annular and dispersed droplet flow regime (image source: internet)

And there is inverted annular and dispersed droplet regimes (figure 3), these occur only in boiling channels, but not in adiabetic channels. In the inverted annular flow regime, there is vapor film at the wall not liquid film and at the center there is liquid core. The liquid may contain entrained bubbles. This occurs at high wall heat fluxes and it leads to what is called departure from nucleate boiling. Then there is a dispersed droplet flow regime in this usually there is superheated vapor and it contains entrained droplets and this can occur in boiling channels. When massive evaporation has already caused depletion of most of the liquid so, there is very little liquid in this type of flow regime.

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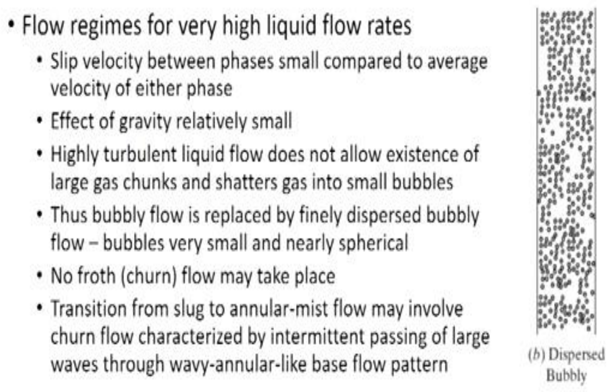

- Flow regimes for very high liquid flow rates
  - Slip velocity between phases small compared to average velocity of either phase
  - Effect of gravity relatively small
  - Highly turbulent liquid flow does not allow existence of large gas chunks and shatters gas into small bubbles
  - Thus bubbly flow is replaced by finely dispersed bubbly flow – bubbles very small and nearly spherical
  - No froth (churn) flow may take place
  - Transition from slug to annular-mist flow may involve churn flow characterized by intermittent passing of large waves through wavy-annular-like base flow pattern

(*b*) Dispersed Bubbly

For very high liquid flow rates, what happens is that the slip velocity with between the phases is small compared to the average velocity of either of the two phases (figure 4). The effect of gravity is relatively small. So, highly turbulent liquid flow does not allow existence of large gas chunks and shatters the gas into small bubbles. Thus bubbly flow is replaced by finely dispersed bubbly flow, bubbles very small and nearly spherical. And under these conditions froth flow or churn flow may not occur. The transition from slug to annular mist flow may involve churn flow characterized by intermittent passing of large waves through wavy annular like base flow pattern.

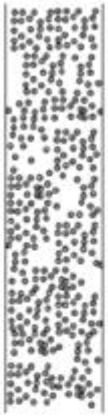

Figure 4: Dispersed bubbly regime for high liquid flow rate (image source: internet)

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- Flow regimes discussed are major distinguishable flow patterns
  - In actual experiments, transition from one major flow regime to another is never sudden
  - Each pair of major flow regimes are separated from one another by a relatively wide transition zone

These flow regimes which we have discussed, these are major distinguishable flow patterns. In the actual experiments transition from one regime to another is gradual. It does not happen suddenly. Similar to transition from laminar to turbulent flow and single phase flow in between there is a transition regime; similarly here also in two phase flow between any two major flow regimes, there is a transition regime. Each flow major flow regimes are separated from another by a relatively wide transition zone.

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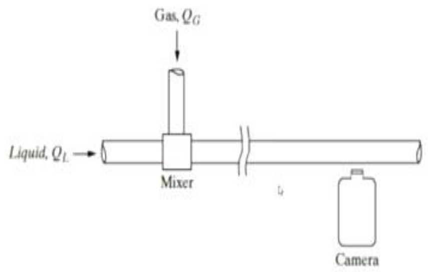

A simple flow regime observation experimental system for horizontal pipes [3]

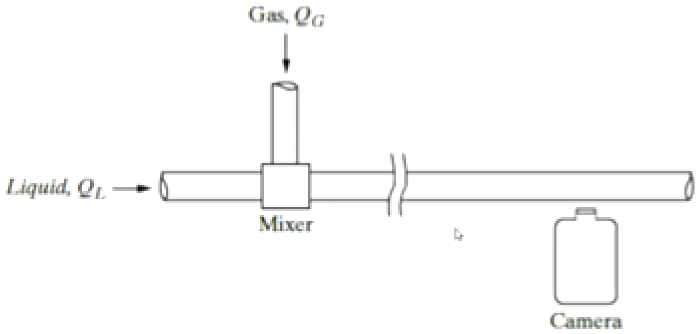

Figure 5: A simple flow regime observation experimental system for horizontal pipes (image source: internet)

In figure 5, we see a flow regime observation experimental system for horizontal pipe. It is similar to that for vertical pipe except that the pipe is horizontal in this case. Figures 6 and 7 show the flow patterns at low and high liquid flow rates respectively.

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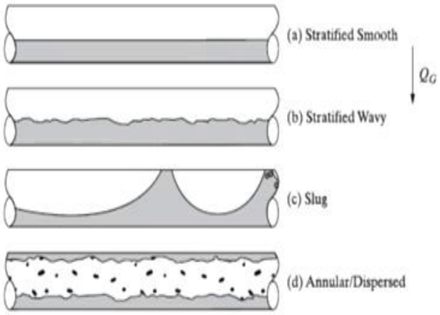

Major flow regimes in a horizontal pipe with low liquid flow rates [3]

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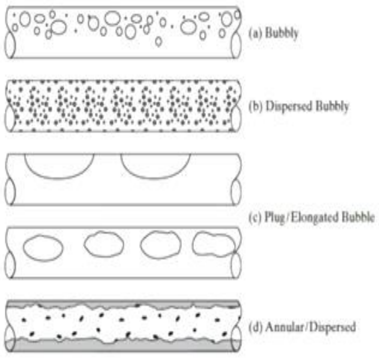

Major flow regimes in a horizontal pipe with high liquid flow rates [3]

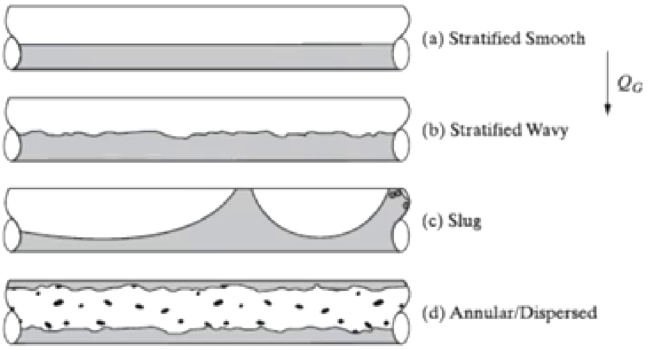

Figure 6: Major flow regimes in horizontal pipe flow for low flow rates (image source: internet)

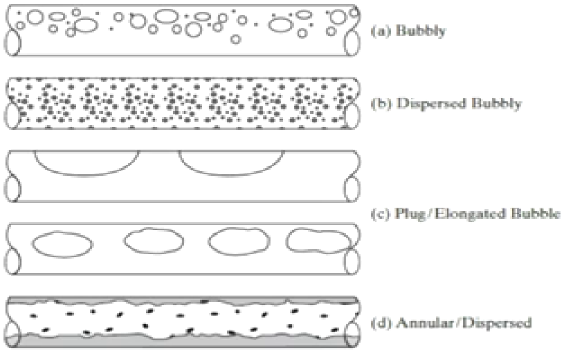

Figure 7: Major flow regimes in horizontal pipe flow for low flow rates (image source: internet)

From top to bottom, the gas volumetric flow rate is increasing. So, for low liquid flow rates when the gas flow rate is low the liquid stays at the lower part of the channel and the gas stays at the upper part of the channel and what we get is stratified smooth flow. The interphase is smooth. When the gas flow rate increases, the interphase becomes wavy and we get stratified wavy flow. And when gas flow increases further, we get slug flow. In this there are liquid slugs and large vapor bubbles and at still higher gas flow rates, we get annular or dispersed annular flow. At high liquid flow rates, we get the following flow patterns; at low gas flow rates, we get bubbly flow and dispersed bubbly flow which are similar to bubbly flow and dispersed bubbly flow in the vertical flow, then at higher gas flow rates we get plug flow or elongated bubble flow and at still higher gas flow rates we get annular flow or annular dispersed flow.

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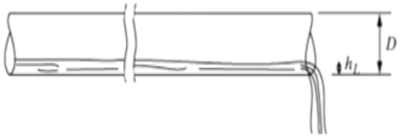

Drainage of liquid out of a horizontal pipe [3]

We will now define what is meant by low liquid flow rate and high liquid flow rate. Refer figure 8, suppose liquid is being drained out of a horizontal channel and the diameter of the channel is D and the height of the liquid is h L.

$$h_L > D/2 \rightarrow \text{liquid flow rate: low}$$

$$h_L < D/2 \rightarrow \text{liquid flow rate: high}$$

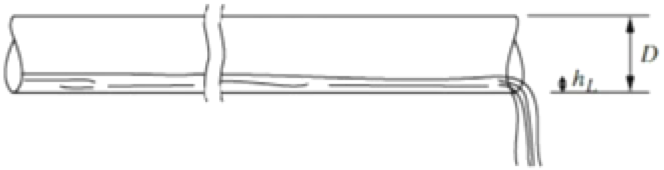

Figure 8: Drainage of liquid out of a horizontal pipe (image source: internet)

Flow regimes at low flow rates (refer figure 6): Stratified smooth flow which occurs at low liquid flow rate and low gas flow rate. The smooth there is smooth gas liquid interphase and when gas flow rate increases we get stratified wavy flow and this there are large amplitude waves at the interphase. Then as the gas flow rates increases, the waves which are generated at the liquid surface, they appear to grow large enough to bridge the entire channel cross section. And then, we get large vapor bubbles which are separated by liquid slugs. But this is different from the slug flow in vertical channels. Gas flow is not continuous, but the liquid phase is continuous. The liquid may contain entrained small gas bubbles and the gas may contain entrained liquid droplets. Then at even higher gas flow rates the waves which are generated at the liquid surface, they appear to grow large enough to bridge the entire channel cross section. And then the vapor bubbles, we get large vapor bubbles which are separated by liquid slugs. But this is different from the slug flow in vertical channels gas flow is not contiguous, but the liquid phase is contiguous. The liquid may contain entrained small gas bubbles and the gas may contain entrained liquid droplets. This is followed by annular dispersed flow or annular mist flow. This is similar to annular mist flow in vertical channels except that the liquid film is thicker near the bottom.

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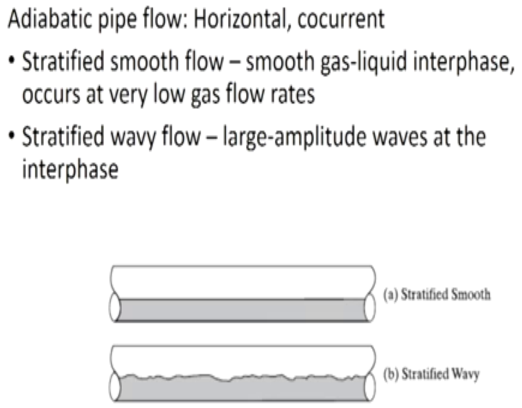

Adiabatic pipe flow: Horizontal, cocurrent

- Stratified smooth flow – smooth gas-liquid interphase, occurs at very low gas flow rates
- Stratified wavy flow – large-amplitude waves at the interphase

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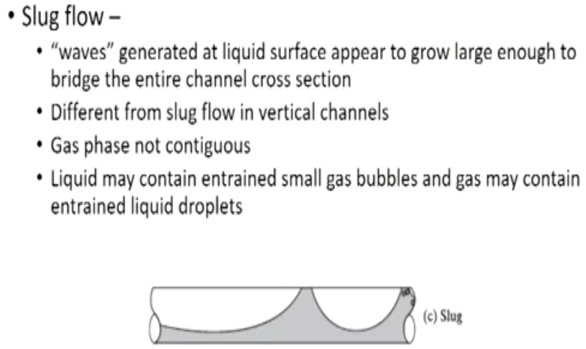

- Slug flow –
  - "waves" generated at liquid surface appear to grow large enough to bridge the entire channel cross section
  - Different from slug flow in vertical channels
  - Gas phase not contiguous
  - Liquid may contain entrained small gas bubbles and gas may contain entrained liquid droplets

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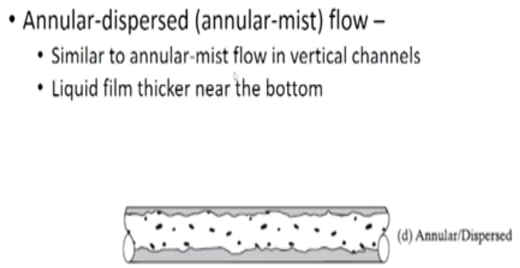

- Annular-dispersed (annular-mist) flow –
  - Similar to annular-mist flow in vertical channels
  - Liquid film thicker near the bottom

(d) Annular/Dispersed

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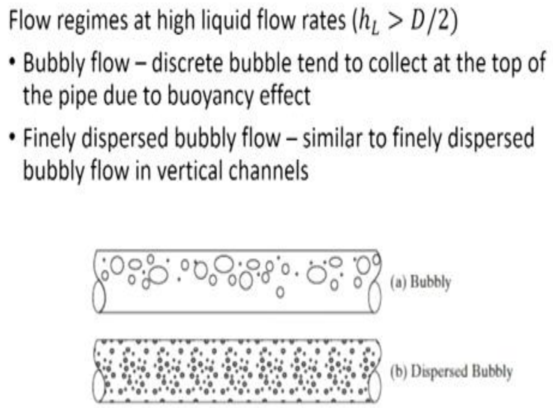

Flow regimes at high liquid flow rates ($h_L > D/2$)

- Bubbly flow – discrete bubble tend to collect at the top of the pipe due to buoyancy effect
- Finely dispersed bubbly flow – similar to finely dispersed bubbly flow in vertical channels

(a) Bubbly

(b) Dispersed Bubbly

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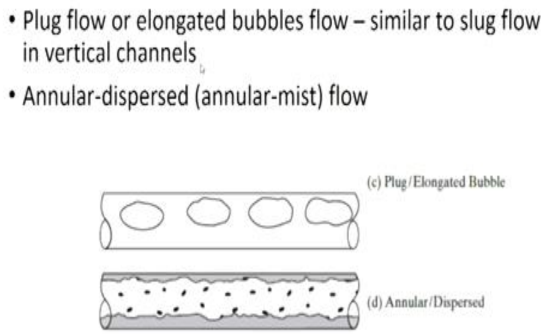

- Plug flow or elongated bubbles flow – similar to slug flow in vertical channels
- Annular-dispersed (annular-mist) flow

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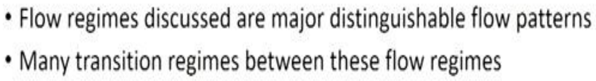

- Flow regimes discussed are major distinguishable flow patterns
- Many transition regimes between these flow regimes

Flow regimes at high flow rates (refer figure 7): Here, we get the following flow patterns. There is bubbly flow and this discrete bubbles tend to collect at the top of the pipe due to buoyancy effect; otherwise, it is similar to bubbly flow in vertical channels. Finely dispersed bubbly flow in this there are small spherical bubbles. This is similar to finely dispersed bubbly flow in vertical channels. Then we have plug flow or elongated bubbles flow; in this we have long bubbles separated by liquid slugs and this is similar to slug flow in vertical channels. Then there is annular dispersed flow or annular mist flow at higher gas flow rates. Similar to vertical flow, here also the flow regimes which we have discussed are major distinguishable flow patterns and between any two flow regimes, there are transition regimes.

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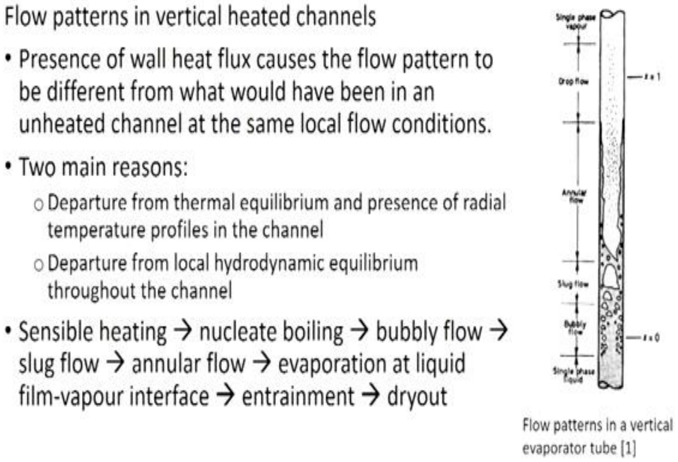

Flow patterns in vertical heated channels

- Presence of wall heat flux causes the flow pattern to be different from what would have been in an unheated channel at the same local flow conditions.
- Two main reasons:
    - Departure from thermal equilibrium and presence of radial temperature profiles in the channel
    - Departure from local hydrodynamic equilibrium throughout the channel
- Sensible heating → nucleate boiling → bubbly flow → slug flow → annular flow → evaporation at liquid film-vapour interface → entrainment → dryout

Flow patterns in a vertical evaporator tube [1]

Flow patterns in vertical heated channels flow patterns in heated channels can be different from those is in adiabatic channels (figure 9). The presence of wall heat flux causes the flow pattern to be different from what would have been in an unheated channel at the same local flow conditions. There are two main reasons for this, there is departure from thermal equilibrium and because of that there is presence of radial temperature profiles in the channel. The second region is departure from the local hydrodynamic equilibrium throughout the channel. Here flow patterns in an evaporator tube are shown vertical evaporator tube. At the inlet it is a pooled liquid and for some distance it remains single phase liquid, there is sensible heating. Then at a certain point nucleate boiling starts bubbles are generated at nucleation sites, then we get bubbly flow and then when

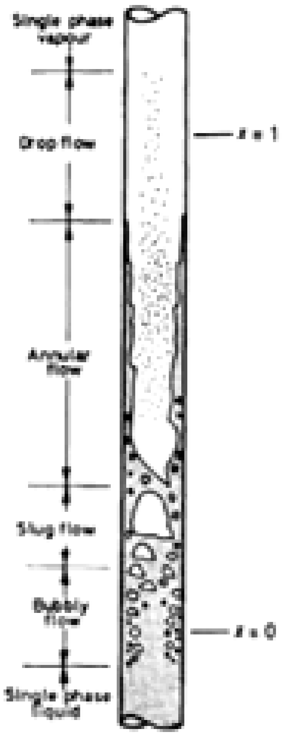

Figure 9: Flow pattern in a vertical evaporator tube (image source: internet)

there are large number of bubbles, they coalesce and form large bubbles and we get slug flow.

When further evaporation takes place, the amount of vapor is large enough to form a vapor core and we get annual flow. And after annular flow after a certain difference the nucleate boiling becomes very low and evaporation mainly vapor generation occurs because of evaporation at the liquid vapor interphase. There is also entrainment of liquid droplets in the vapor core in this flow pattern and finally, the liquid film becomes thinner and thinner and finally, liquid film completely evaporates and we get a dryout. After dryout there is drop flow in which there are drops there is a it is mostly superheated vapor and contains liquid drops. Finally at a certain point all the drops evaporate and we get completely single phase vapor.

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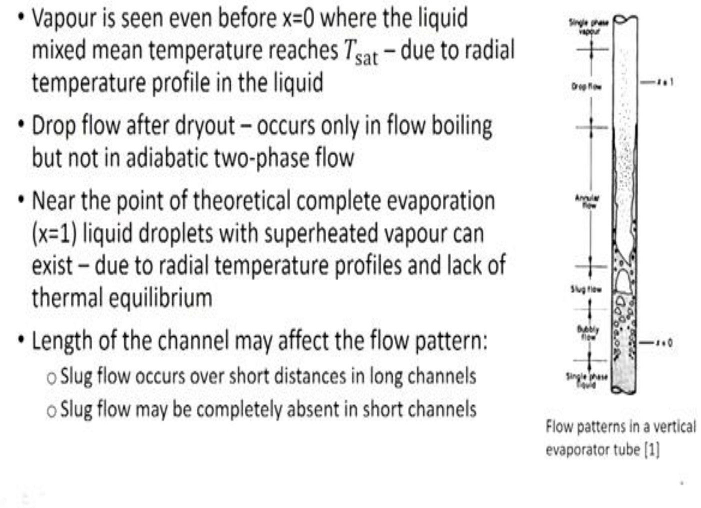

- Vapour is seen even before x=0 where the liquid mixed mean temperature reaches T_{sat} – due to radial temperature profile in the liquid
- Drop flow after dryout – occurs only in flow boiling but not in adiabatic two-phase flow
- Near the point of theoretical complete evaporation (x=1) liquid droplets with superheated vapour can exist – due to radial temperature profiles and lack of thermal equilibrium
- Length of the channel may affect the flow pattern:
    - Slug flow occurs over short distances in long channels
    - Slug flow may be completely absent in short channels

Flow patterns in a vertical evaporator tube [1]

Certain points here can be noted here we see that x =0. This is the point where the thermodynamic vapor quality is 0; that means, the mean temperature at this cross section is equal to the saturation temperature. The mean enthalpy is equal to the saturated liquid enthalpy, but because of the radial temperature profile the temperature near the walls is higher and the temperature at the core is lower. So, evaporation takes place, bubbles are generated near the walls and but at the center there is a pooled liquid.

Near the point of theoretical complete evaporation that is x equal to 1, liquid droplets with superheated vapor can exist. This is due to radial temperature profiles and lack of thermal equilibrium.

The length of the channel may also affect the flow pattern. Under the same local conditions if the length is small or large, different flow patterns can occur. If it is a long channel, then slug flow usually occurs over short distances. But if the channel is short, slug flow may be completely absent this happens because it takes some time for bubbles to coalesce and slug flow to occur. And if the channel is very short, then the fluid does not get enough time for bubble coalesces and therefore, slug flow may not occur.

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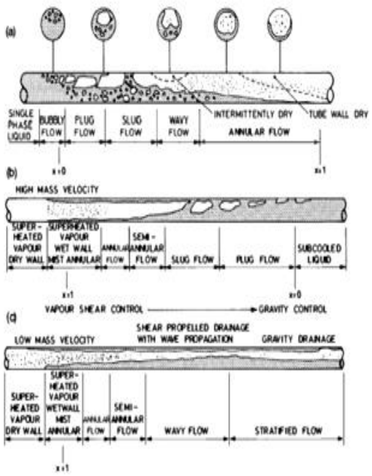

Two-phase flow patterns in horizontal tubes (a) evaporation; (b) condensation with low liquid loading; (c) condensation with high liquid loading [1]

Figure 10 shows two phase flow patterns in horizontal tubes for evaporation and condensation. Here evaporation is shown and this is for low flow rate. At the inlet, it is sub cooled liquid and for some distance there is sensible heating and here x=0. And we see that even before x equal to 0, bubble generation has occurred this is similar to what occurs in vertical evaporator tube which we have already discussed. Then when large number of bubbles are generated, they coalesce to form large bubbles and we get plug flow. After that we get slug flow for some distance and when the amount of vapor is very large, we get wavy flow and here the wall can be intermittently wet and dry. Then after that we get annular flow and after a certain distance, the wall the upper part of the wall can become dry.

For flow pattern during condensation: At the inlet, it is superheated vapor and the wall is dry. Then after that some condensation has occurred so, we get annular flow annular flow and superheated vapor is also

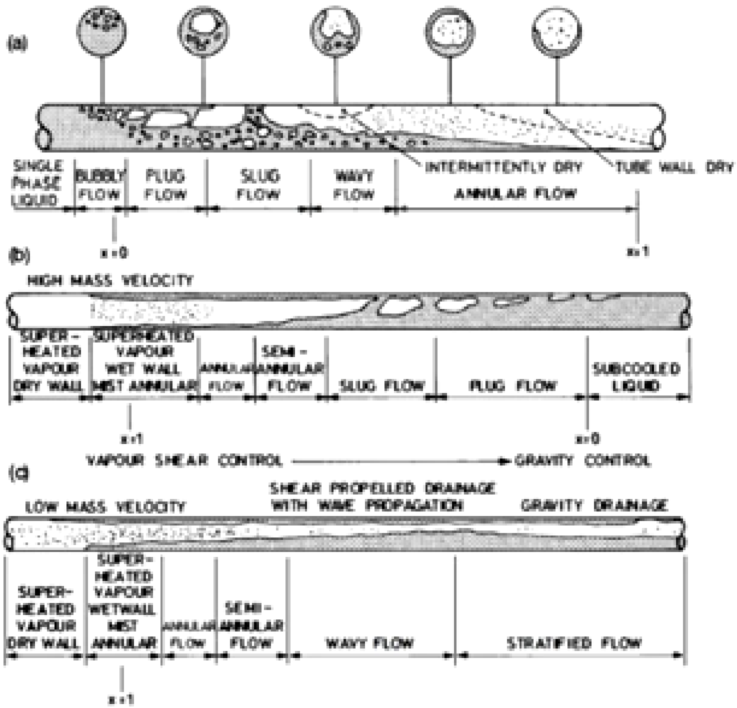

Figure 10: Two phase flow patterns in horizontal tubes (a) evaporation, (b) condensation with low liquid loading, (c) condensation with high liquid loading (image source: internet)

there. Then there is annular flow and semi annular flow, then after that we get slug flow and then plug flow and then well all the vapor has condensed, then we get subcooled liquid. When the less condensation has occurred the vapor velocity is large and the flow regime is controlled by vapor shear, but after large amount of condensation has taken place the vapor flow rate becomes low and therefore, the vapor velocity also become low and then the flow patterns are controlled by gravity. So, the flow moves from vapor shear control to gravity control. Here flow regimes for condensation are shown for high liquid flow rate. At the inlet it is superheated vapor, then after that there is annular flow, then semi annular flow and after that there is wavy flow and then after that stratified flow.

Now how to predict flow regimes? Under given conditions how do we predict which flow regime will occur so, for that there are flow regime maps. Many researchers have done experiments and they have developed flow regime maps as we have discussed before there are many parameters which determined flow regimes. But if we have to draw a map on a paper, then only two parameters can be chosen. So, different researchers have chosen different parameters which they consider to be important. For vertical flow, there is a very popular flow pattern map of Hewitt and Roberts (figure 11) as shown by equation (1).

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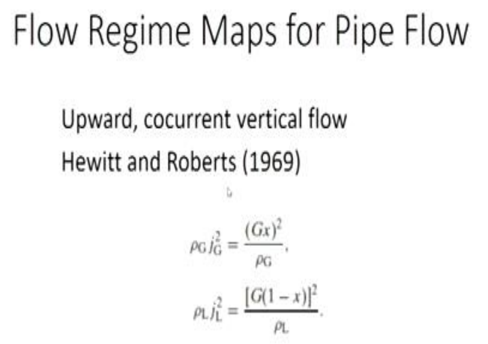

Flow Regime Maps for Pipe Flow

Upward, cocurrent vertical flow

Hewitt and Roberts (1969)

$$\rho_G j_G^2 = \frac{(Gx)^2}{\rho_G},$$

$$\rho_L j_L^2 = \frac{[G(1-x)]^2}{\rho_L}.$$

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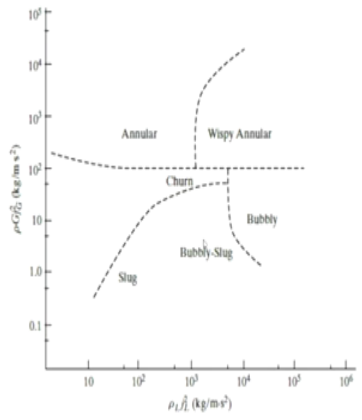

Flow regime map of Hewitt and Roberts (1969) for upward, cocurrent vertical flow

$$\rho_G j_G^2 = \frac{(Gx)^2}{\rho_g}; \quad \rho_L j_L^2 = \frac{\left[\left(G(1-x)\right)\right]^2}{\rho_L} \ldots\ldots (1)$$

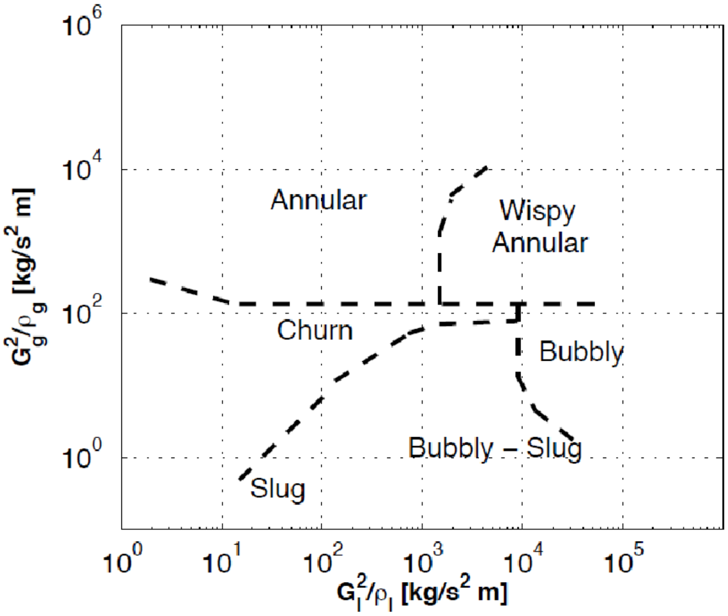

Figure 11: Flow pattern map of Hewitt and Roberts (1969) for upward, concurrent vertical flow (image source: internet)

So, in figure 11, $\rho_L j_L^2$ is on the horizontal axis and $\rho_G j_G^2$ is on the vertical axis and we locate the point and then based on that we can predict which flow pattern will occur depending on the location of the point. Note that both scales are logarithmic, the horizontal scale and vertical scale both are logarithmic.

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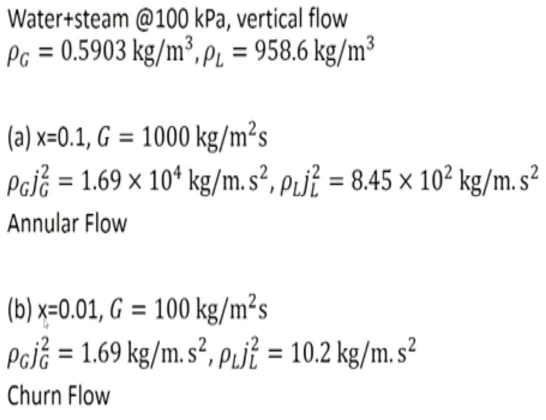

Water+steam @100 kPa, vertical flow
$\rho_G = 0.5903$ kg/m^3, $\rho_L = 958.6$ kg/m^3

(a) x=0.1, $G = 1000$ kg/m^{2}s
$\rho_G j_G^2 = 1.69 \times 10^4$ kg/m.s^2, $\rho_L j_L^2 = 8.45 \times 10^2$ kg/m.s^2
Annular Flow

(b) x=0.01, $G = 100$ kg/m^{2}s
$\rho_G j_G^2 = 1.69$ kg/m.s^2, $\rho_L j_L^2 = 10.2$ kg/m.s^2
Churn Flow

Numerical problem 1: Water+steam at 100 kPa, vertical flow: $\rho_G = 0.5903$ kg/m^3, $\rho_L = 958.6$ kg/m^3 (a) x=0.1, G=1000 kg/m^{2}s (b) x=0.01, G=100 kg/m^{2}s. Find the flow pattern using Hewitt and Roberts (1969) pattern map.

Solution: Using equation (1):

(a) $\rho_G j_G^2 = 1.69 \times 10^4 kg/ms^2$; $\rho_L j_L^2 = 8.45 \times 10^2 kg/ms^2$
Annular flow

(b) $\rho_G j_G^2 = 1.69\ kg/ms^2$; $\rho_L j_L^2 = 10.2\ kg/ms^2$
Churn flow

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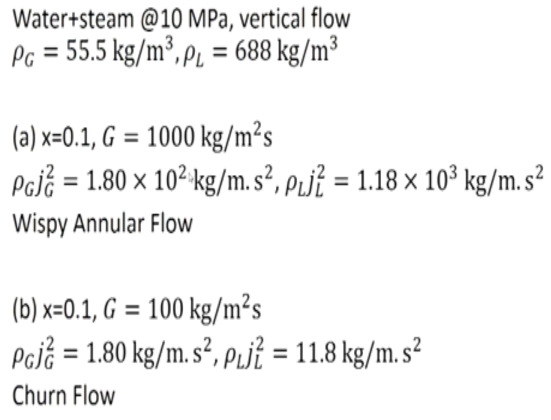

Water+steam @10 MPa, vertical flow

$\rho_G = 55.5 \text{ kg/m}^3, \rho_L = 688 \text{ kg/m}^3$

(a) x=0.1, $G = 1000 \text{ kg/m}^2\text{s}$

$\rho_G j_G^2 = 1.80 \times 10^2 \text{ kg/m.s}^2, \rho_L j_L^2 = 1.18 \times 10^3 \text{ kg/m.s}^2$

Wispy Annular Flow

(b) x=0.1, $G = 100 \text{ kg/m}^2\text{s}$

$\rho_G j_G^2 = 1.80 \text{ kg/m.s}^2, \rho_L j_L^2 = 11.8 \text{ kg/m.s}^2$

Churn Flow

Numerical problem 2 (High pressure problem): Water+steam at 10 MPa, vertical flow: $\rho_G = 55.5$ kg/m^3, $\rho_L = 688$ kg/m^3 (a) x=0.1, G=1000 kg/m^{2}s (b) x=0.01, G=100 kg/m^{2}s. Find the flow pattern using Hewitt and Roberts (1969) pattern map.

Solution: Using equation (1):

(a) $\rho_G j_G^2 = 1.8 \times 10^2 kg/ms^2$; $\rho_L j_L^2 = 1.18 \times 10^3 kg/ms^2$

Wispy annular flow

(b) $\rho_G j_G^2 = 1.8\ kg/ms^2$; $\rho_L j_L^2 = 11.8\ kg/ms^2$

Churn flow

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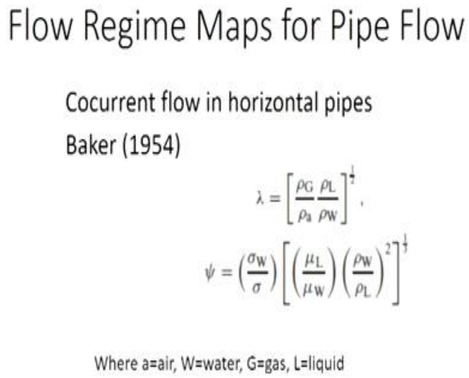

Flow Regime Maps for Pipe Flow

Cocurrent flow in horizontal pipes

Baker (1954)

$$\lambda = \left[\frac{\rho_G}{\rho_a}\frac{\rho_L}{\rho_W}\right]^{\frac{1}{2}},$$

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

Where a=air, W=water, G=gas, L=liquid

For horizontal pipes, there is a flow regime map by baker which is very popular (figure 12). Its parameters are defined by equation 2.

$$\lambda = \left[\frac{\rho_G}{\rho_a}\frac{\rho_L}{\rho_w}\right]^{1/2}; \quad \psi = \left(\frac{\sigma_w}{\sigma}\right)\left[\left(\frac{\mu_L}{\mu_W}\right)\left(\frac{\rho_w}{\rho_L}\right)^2\right]^{1/2} \quad (2)$$

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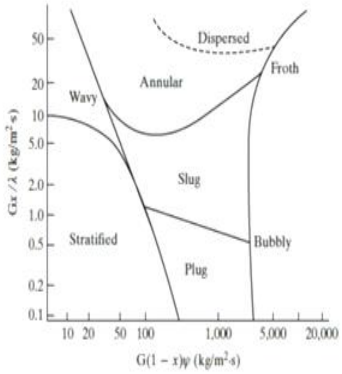

Flow regime map of Baker (1954) for cocurrent flow in horizontal pipes

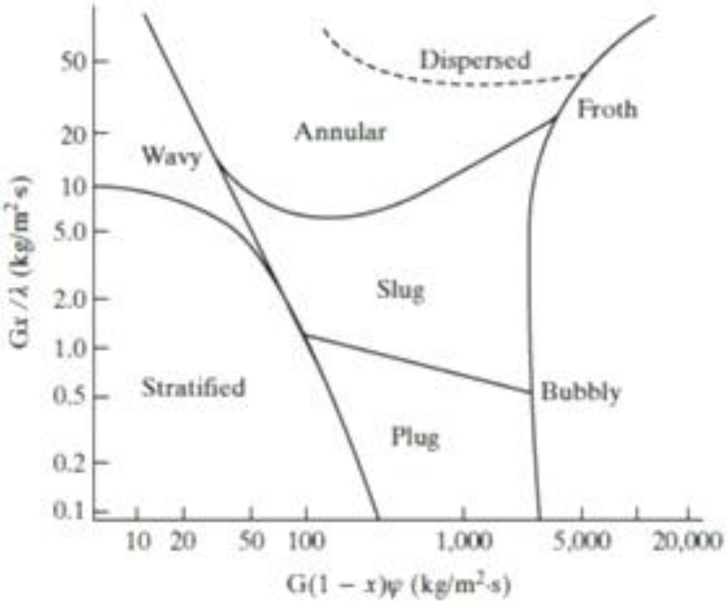

Figure 12: Flow pattern map of Baker(1954) for concurrent horizontal flow in pipes (image source: internet)

Here, subscript a and w means property of air and water at atmospheric condition. Here also both scales are logarithmic, the horizontal and vertical both scales.

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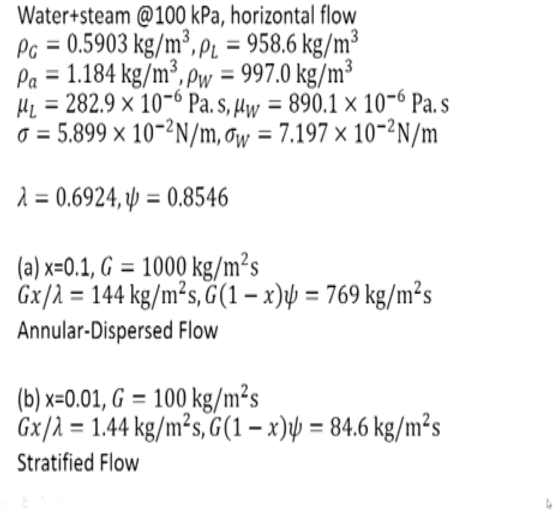

Water+steam @100 kPa, horizontal flow

$\rho_G = 0.5903$ kg/m^3, $\rho_L = 958.6$ kg/m^3

$\rho_a = 1.184$ kg/m^3, $\rho_W = 997.0$ kg/m^3

$\mu_L = 282.9 \times 10^{-6}$ Pa.s, $\mu_W = 890.1 \times 10^{-6}$ Pa.s

$\sigma = 5.899 \times 10^{-2}$N/m, $\sigma_W = 7.197 \times 10^{-2}$N/m

$\lambda = 0.6924, \psi = 0.8546$

(a) x=0.1, $G = 1000$ kg/m^{2}s

$Gx/\lambda = 144$ kg/m^{2}s, $G(1-x)\psi = 769$ kg/m^{2}s

Annular-Dispersed Flow

(b) x=0.01, $G = 100$ kg/m^{2}s

$Gx/\lambda = 1.44$ kg/m^{2}s, $G(1-x)\psi = 84.6$ kg/m^{2}s

Stratified Flow

Numerical problem 3: Water+steam at 100 kPa, horizontal flow: $\rho_G = 0.5903$ kg/m^3, $\rho_L = 958.6$ kg/m^3, $\rho_a = 1.184$ kg/m^3, $\rho_W = 997.0$ kg/m^3, $\mu_L = 282.9 \times 10^{-6}$ Pa.s, $\mu_W = 890.1 \times 10^{-6}$ Pa.s, $\sigma = 5.899 \times 10^{-2}$ N/m, , $\sigma_W = 7.197 \times 10^{-2}$ N/m. (a) x=0.1, G=1000 kg/m^{2}s (b) x=0.01, G=100 kg/m^{2}s. Find the flow pattern using Baker (1954) pattern map.

Solution: Using equation (2):

$\lambda = 0.6924$; $\psi = 0.8546$

(a) $Gx/\lambda = 144 kg/\mathrm{m}^2 s$; $G(1-x)\psi = 769 kg/\mathrm{m}^2 s$

Annular-dispersed flow

(b) $Gx/\lambda = 1.44 kg/\mathrm{m}^2 s$; $G(1-x)\psi = 84.6 kg/\mathrm{m}^2 s$

Stratified flow

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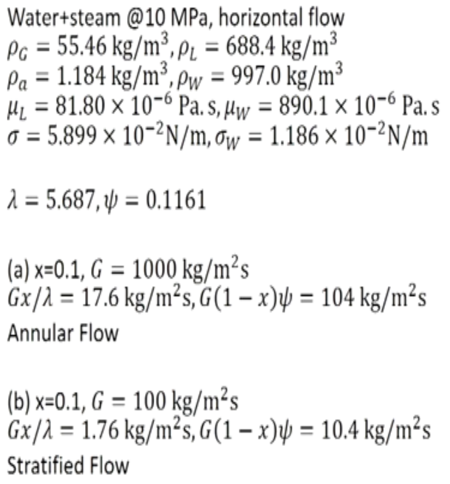

Water+steam @10 MPa, horizontal flow
$\rho_G = 55.46$ kg/m^3, $\rho_L = 688.4$ kg/m^3
$\rho_a = 1.184$ kg/m^3, $\rho_W = 997.0$ kg/m^3
$\mu_L = 81.80 \times 10^{-6}$ Pa. s, $\mu_W = 890.1 \times 10^{-6}$ Pa. s
$\sigma = 5.899 \times 10^{-2}$N/m, $\sigma_W = 1.186 \times 10^{-2}$N/m

$\lambda = 5.687, \psi = 0.1161$

(a) x=0.1, $G = 1000$ kg/m^{2}s
$Gx/\lambda = 17.6$ kg/m^{2}s, $G(1-x)\psi = 104$ kg/m^{2}s
Annular Flow

(b) x=0.1, $G = 100$ kg/m^{2}s
$Gx/\lambda = 1.76$ kg/m^{2}s, $G(1-x)\psi = 10.4$ kg/m^{2}s
Stratified Flow

Numerical problem 4 (high pressure): Water+steam at 10 MPa, horizontal flow: $\rho_G = 55.46$ kg/m^3, $\rho_L = 688.4$ kg/m^3, $\rho_a = 1.184$ kg/m^3, $\rho_W = 997.0$ kg/m^3, $\mu_L = 81.8 \times 10^{-6}$ Pa.s, $\mu_W = 890.1 \times 10^{-6}$ Pa.s, $\sigma = 5.899 \times 10^{-2}$ N/m, , $\sigma_W = 1.186 \times 10^{-2}$ N/m. (a) x=0.1, G=1000 kg/m^{2}s (b) x=0.01, G=100 kg/m^{2}s. Find the flow pattern using Baker (1954) pattern map.

Solution: Using equation (2):

$\lambda = 5.687; \quad \psi = 0.1161$

(a) $Gx/\lambda = 17.6 kg/\mathrm{m}^2 s; \quad G(1-x)\psi = 104 kg/\mathrm{m}^2 s$
Annular flow
(b) $Gx/\lambda = 1.76 kg/\mathrm{m}^2 s; \quad G(1-x)\psi = 10.4\, kg/\mathrm{m}^2 s$
Stratified flow