Two phase flow – flow regimes

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Classification into regimes

- Flow regimes determine the macroscopic behavior of two phase flow.

- Different regimes are classified by visual observation.

- It can be difficult to specify with certainty, which regime a particular flow belongs to.

- Many different classifications exist in the literature. Scientists don’t agree on a unique set of flow regimes.

- Classification can be useful, since different flow regimes affect parameters in different manner, such as pressure drop.
Geometrical difference

The flow regimes can be divided into three main classes:

1. Regimes for horizontal flow in pipes, where the heavier phase (water) tends to be located close to the bottom, because of gravity. In most cases the gas phase pushes the liquid phase along the flow direction.

2. Regimes for vertical flow in pipes. The liquid phase tends to be on the pipe walls, forming a stable or an unstable film. Flow velocity can be different and flow regimes form differently for upward and downward flows.

3. Regimes for sloped pipes, which are not as well known. Here the slope angle is important as well as the direction of the flow (upwards or downwards).
Horizontal – bubble flow

- Small bubbles are present in the flow, and are dispersed everywhere in the cross section.
- Bubbles gather in the top of the pipe for low velocities.
- Bubbles become foam like at high velocities.
Horizontal – plug flow

- Bubbles join and form larger gas plugs.
- The plugs flow in the upper part of the pipe because of gravity effects.
Horizontal – stratified flow

- The phases are completely separated with gas in the upper part and liquid in the lower part of the pipe.
- Surface is relatively smooth and variations are small.
- This type of flow can only occur at low velocity.
Horizontal – wavy flow

- Appears at higher velocities, compared to the stratified flow.
- Waves form on the phase boundaries, resulting in more friction between the two phases.
- Waves travel in the direction of flow, especially if gas velocity is considerably higher than liquid velocity.
Horizontal – slug flow

- Waves in the flow reach the top of the pipe, closing the gas path in the top.
- Different momentum of the phases (because of velocity difference) results in sudden pressure changes when the path closes.
- Shocks and vibrations are experienced in the flow, which should be avoided if possible.
Horizontal – annular flow

- The liquid forms a coat all around the pipe walls.
- Gas flows in the middle, possibly with liquid droplets traveling along it.
- Coat tends to be thicker at the bottom than at the top, because of gravity effects.
Horizontal – spray flow

- Liquid droplets are dispersed in the flow of gas in the pipe.
- The amount of liquid is much less in this case.
- Liquid velocity is very similar to the gas velocity, or $S \approx 1$. 
Gas bubbles are present in a liquid dominated flow.

Bubbles are mostly evenly distributed, but tend to gather near the pipe center with increased speed.

Velocity is similar for both phases, $S \approx 1$. 
Gas bubbles gather and form bullet shaped voids in the pipe center.

The flow is unstable, resulting in pressure shocks and vibrations in the pipe.
Gas bubbles gather and form a gas path in the center of the pipe.

The flow is foam like and very unstable, resulting in high pressure variations.

The gas velocity is high, pushing the liquid upwards.
Vertical – annular flow

- The liquid forms an uniform layer on the pipe walls.
- The layer can be unstable, with a wavy surface, but is much more stable than in the churn flow.
Vertical – spray flow

- The liquid is in much smaller quantity than the gas.
- The liquid is distributed in the flow as droplets or spray.
Flow regimes and phase equilibrium

- Phase equilibrium is obtainable at a constant pressure.
- Pressure variations are inevitable in most two phase flow regimes.
- Average pressure changes slowly along the pipe.
- Fast fluctuations occur in small sections in the flow.

Conclusion:
- Phase changes take place everywhere in the flow, both from steam to water and from water to steam.
- In practical cases, fast variation in phase change are neglected, and the slow pressure variations are only considered.
Flow maps for regimes

Question: Is it possible to determine the type of flow regime from available flow data?

Flow maps are attempts to answer this question and determine the flow regime type with certain accuracy. Such maps involve:

- Maps for very narrow flow conditions. Typically, specific fluids at specific pressures and temperatures.
- General flow maps for various flows and fluids, based on dimensionless parameters.
- Most maps are generated for horizontal flow.
- Few maps are available for vertical flow, upwards or downwards.
Flow regime dependencies

- Transport properties of gas and liquid:
  - Density difference.
  - Viscosity, related to the Reynolds number.
  - Surface tension, related to the Weber number.
- Geometry scales and pipe roughness.
- Mass and volume fractions in pipes.
- Velocity ratio between phases.

The flow map will indicate the most likely flow regime for the given parameters above.
Flow maps for horizontal flow

Commonly used flow maps are:

- Baker map, which is old and widely used.
- Hoogendoorn map, which is considered to be more accurate than the Baker map.
- Mandhane, Gregory, Aziz map, another old map which is considered better than the two above.
- An universal flow regime map, which is relatively new (2003), published by Spedding and others.
The Baker map

\[ \lambda = \sqrt{\frac{\rho_g}{1.2}} \frac{\rho L}{1000} \]

\[ \psi = \frac{0.0724}{\sigma_L} \left( \frac{\mu L}{0.0009} \left( \frac{1000}{\rho L} \right)^2 \right)^{\frac{1}{3}} \]
The Mukherjee and Brill map

\begin{align*}
LVN &= V_{SL} \left( \frac{\rho L}{g\sigma} \right)^{\frac{1}{4}} \\
V_{SL} &= \frac{QL}{A}
\end{align*}

Mukherjee and Brill map

Liquid velocity number

Vapor velocity number

Annular

Slug

Bubble

Nesjavellir

Krafla

Svartsengi

Bjarnarflag

Stratified

Two phase flow – flow regimes – p. 21
The Spedding and Nguyen map

The Spedding and Nguyen map shows the flow regimes for two-phase flow. The map is plotted on a logarithmic scale, with $F_r = (V_T^2/(gD)^{1/2})^{1/2}$ on the y-axis and $Q_l/Q_g$ on the x-axis. The different flow regimes are indicated by different lines and symbols:

- **Droplet**
- **Annular+Droplet**
- **Film+Droplet**
- **Annular+RW**
- **Annular+BTS**
- **Stratified+RW/BTS**
- **Stratified**
- **Slug**

Data points from different sites, such as Nesjavellir, Krafla, Svartsengi, and Bjarnarflag, are plotted on the map. The map is useful for identifying the flow regime based on the parameters and for analyzing the behavior of two-phase flow in various conditions.
Flow map for vertical flow

A popular map for vertical flow in the upward direction is the Hewitt and Roberts map. Two parameters define the axis

\[
\frac{x^2G}{\rho_g} = \frac{\dot{m}_g v_{sg}}{A}
\]

\[
\frac{(1 - x)^2G}{\rho_l} = \frac{\dot{m}_l v_{sl}}{A}
\]

which are the momentums of the two phases per pipe section. The map is based on data for steam and water in pipes up to 30 mm in diameter.
Annular flow
whispy annular
Churn flow
Bubble flow
Bubbly slug flow

Hewitt and Roberts map

Two phase flow – flow regimes – p. 24
Flow regimes – concluding remarks

- Over one hundred flow regime maps exist, based on different classification into regimes.
- Most of the existing models are verified and adjusted by using measurements in small diameter pipes (10 – 100 mm).
- Researches in the field do not agree on any universal models that can be accepted for general flow situations.
- Most likely horizontal flow regime in Icelandic geothermal power plants is a wavy stratified flow.