Multiphase Flow Technology

Agenda 22\textsuperscript{nd} of October 2013

• Introduction to multiphase flow
• Terms & regimes
• Conservation equations
• Stratified flow
• Applications
• Slug flow
MEK 4450
Terms & Notation
Multiphase flow – Applications
Conservation equations

Lecture notes
IFE, 2013.10.22

Jan Nossen & Karin Hald
Multiphase flow terms, notation

Void fraction: \[ \alpha = \frac{A_g}{A} \]

Oil holdup: \[ \beta_o = \frac{A_o}{A} \]

Water holdup: \[ \beta_w = \frac{A_w}{A} \]

Total holdup: \[ \beta = \beta_o + \beta_w \]
# Multiphase flow terms, notation

<table>
<thead>
<tr>
<th>Name</th>
<th>Dimension</th>
<th>Legend</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$</td>
<td>J/kg</td>
<td>Specific internal energy</td>
</tr>
<tr>
<td>$h$</td>
<td>J/kg</td>
<td>Specific enthalpy</td>
</tr>
<tr>
<td>$p$</td>
<td>Pa</td>
<td>Pressure</td>
</tr>
<tr>
<td>$S$</td>
<td>m</td>
<td>Wetted length</td>
</tr>
<tr>
<td>$\rho$</td>
<td>kg/m³</td>
<td>Density</td>
</tr>
<tr>
<td>$\alpha, \beta, \gamma$</td>
<td>-</td>
<td>Gas, liquid bulk, droplet fractions</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Pa</td>
<td>Shear stress</td>
</tr>
<tr>
<td>$\psi_E$</td>
<td>kg/(sm³)</td>
<td>Droplet entrainment rate</td>
</tr>
<tr>
<td>$\psi_D$</td>
<td>kg/(sm³)</td>
<td>Droplet deposition rate</td>
</tr>
</tbody>
</table>
Real stratified flow

\[\alpha_g\ \text{Continuous gas}\]
\[\alpha_o\ \text{Gas bubbles in oil}\]
\[\alpha_w\ \text{Gas bubbles in water}\]
\[\beta_{oc}\ \text{Continuous oil}\]
\[\gamma_o\ \text{Oil drops in gas}\]
\[\beta_{od}\ \text{Oil drops in water}\]
\[\beta_{wc}\ \text{Continuous water}\]
\[\gamma_w\ \text{Water drops in gas}\]
\[\beta_{wd}\ \text{Water drops in oil}\]
Thin liquid film on upper wall
Flow regimes

Depend on
• phase velocities
• phase quantity
• pipeline orientation
• flow system
  • gas/liquid
  • liquid/liquid

IFE Lab data
Flow regimes: Near horizontal

Gas/liquid regimes:
- Stratified
- Annular
- Slug
- Bubble

Liquid/liquid regimes:
- Stratified (separated)
- Partly separated/dispersed
- Dispersed oil/water flow
Flow regimes: Near vertical

Gas/liquid regimes:
• (a-b) bubble flow
• (c-d) slug/churn flow
• (e) annular flow

Liquid/liquid regimes:
Dispersed
Transition criteria

Liquid velocity vs. Gas velocity diagram showing regions for Stratified, Slug, Bubble, and Large Wave flow regimes.
Flow regime transitions

- The most important **flow regime transition** in pipelines is from stratified flow to slug flow.
- Two conditions must be fulfilled for slug flow to exist:
  - Stratified flow must be unstable (*Kelvin-Helmholtz instability*).
  - Slugs that are formed must be able to grow (*Minimum slip*).
- The Kelvin-Helmholtz criterion tells that the stratified flow region gets smaller with increasing pressure.
- Experimental data show that the slug flow region also gets smaller with increasing pressure.
- For high pressure we get a region of large wave flow in between stratified and slug.
In between

\[ U_{SL} \]

- slugs are stable
- stratified flow is stable
- neither is stable
Multiphase flow – Applications

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  • SINTEF Petroleum
  • IFE
Multiphase Flow Main Challenges

• Pressure loss
• Liquid management
  • Pipeline diameter selection
  • Liquid inventory control
    • Normal operation
    • Water accumulation
  • Rate changes, shut-down and Restart
  • Pigging
  • Sizing of process equipment, e.g. separators/slug catchers
• Prediction and control of slugging
Stratified flow in horizontal gas condensate pipe

- A small stream of condensate on top of a small stream of water
- The pressure gradient drives the gas which drives the condensate which drives the water
- Typical values: Gas velocity $U_g = 3$ m/s, liquid velocity $U_l = 1$ m/s
  Liquid holdup $h = 0.01$
  Superficial velocities:
  $U_{sg} = 3$ m/s  $U_{sl} = hU_l = 1$ cm/s
- Liquid transport modified by droplets in gas and water droplets in condensate/condensate droplets in water
• Below a certain production rate, pressure gradient and holdup start building up in the uphill sections
Pipe diameter selection

- Too small diameter:
  - Large pressure drop due to friction at high production rates

- Too large diameter:
  - Too low velocity
    - High holdup and flow instabilities at low production rates
    - Large liquid surges during production start-up or ramp-up
    - Possibly even severe slugging
  - More expensive pipelines

- In 1-phase flow you can just make the pipe big enough
- In multiphase flow you have to *balance* capacity needs with need to avoid liquid accumulation and instabilities
Liquid surge during ramp-up

Liquid flowing from pipeline into slug catcher when increasing rate from $Q_1$ to $Q_2$
Potential problems in multiphase flow

- WATER

Liquid accumulation and water separation in low points

- Increased liquid accumulation and pressure drop
- Large water slugs disturb process
- Corrosion
Potential problems in multiphase flow

- **SHUT-IN/RESTART and RATE CHANGES**
  - Liquid redistributes due to gravity during shut-in
  - On startup, liquid in dips can exit the pipeline as large slugs as flow is ramped up
Potential problems in multiphase flow

- **PIGGING**
  - Push a “pig” device through the pipe to
    - Push out excess liquid and/or wax on the pipe wall
    - Inspect the pipe for corrosion and wax using an instrumented pig
  - Pigging the line can create a large liquid slug ahead of the pig
  - The pigging operation can be optimized using simulations

![Diagram showing stages of pigging](image)
Potential problems in multiphase flow

• SEVERE SLUGGING
  • A: Low spots fills with liquid and flow is blocked
  • B: Pressure builds up behind the blockage
  • C&D: When pressure becomes high enough, gas blows liquid out of the low spot as a slug

– Severe slugs can cause large pressure swings and liquid surges out of pipeline.
– Severe slugging requires a dynamic model to predict and control
Potential problems in multiphase flow

- LONG SLUGS
- In *hydrodynamic* slug flow we have a random distribution of slug lengths
- Some slugs can be very long, creating problems (filling slug catcher)
- Long slugs difficult to predict

 Slug duration distribution
From Xu et al (1997)
Troll gas: Onshore slug-catcher
One-dimensional multiphase pipe flow simulators

- One dimensional models for multiphase flow of gas, oil and water in wells, pipelines and networks
- Steady state and dynamic models
- 1-D conservation equations for mass, momentum and energy
- Experimental experience used in developing closure relations
  - Wall and interfacial friction factors
  - Transport of drops and bubbles
- Testing against field data important for validation
Description of a case to be simulated

<table>
<thead>
<tr>
<th>Pipe geometry</th>
<th>Fluid properties</th>
<th>Boundary conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe elevation profile</td>
<td>Mass fractions</td>
<td>Boundary conditions at pipe ends (Flow, pressure, temperature)</td>
</tr>
<tr>
<td>Pipe inner diameter</td>
<td>Densities</td>
<td>External temperature</td>
</tr>
<tr>
<td>Internal wall roughness</td>
<td>Viscosities</td>
<td>Thermal properties of surroundings (water, air, soil)</td>
</tr>
<tr>
<td>Wall thickness</td>
<td>Surface and interfacial tensions</td>
<td></td>
</tr>
<tr>
<td>Wall material properties</td>
<td>Heat conductivities</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Specific enthalpies</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Specific heat capacities</td>
<td></td>
</tr>
</tbody>
</table>
CFD models for multiphase flow

- Standard CFD commercial codes are widely used for simulating laminar and turbulent single phase flow
- Multiphase flow give us several new challenges
  - Where is the interface?
  - Large scale interfaces (stratified flow), small scale interfaces (bubbly flow) or both at the same time
  - Continuous phases typically described by Euler methods (i.e. Reynolds averaged Navier-Stokes equations)
  - Dispersed phases typically described by either Lagrange methods (tracking each bubble/drop/particle) or Euler methods
  - More difficult when a phase is both continuous and dispersed
Eulerian CFD methods for multiphase flow

- Diffuse interface methods
  - Volume of Fluid (VOF) method
    - Computes volume fraction of each phase in each control volume
  - Level Set method
    - Interface given as zero level of an auxiliary function
  - Phase Field method
    - Extra conservation equation for «phase field» across interface

- Sharp interface methods
  - Front tracking – explicit interface tracking
1D versus CFD multiphase flow models

**1D models**
- Low resolution
- Many closure relations
  - Friction factors
  - Entrainment/deposition
  - Drop/bubble properties
- Fast
- Only tool today for long pipelines

**CFD models**
- High resolution
- Fewer closure relations
  - Depending on resolution
  - Scales not resolved must be modelled
- Slow or VERY slow
- Impractical for pipelines
- Can be good for equipment
Why are CFD models impractical for pipelines?

- Long high pressure gas condensate pipeline
  - 1m = $10^2$ cm diameter, 100 km = $10^7$ cm long
- Stratified wavy flow
  - Bulk flow varies over O(1 cm) length
- 1 cm grid resolution => $N \sim 10^2 \times 10^2 \times 10^7 = 10^{11}$ grid cells
- Bubbles, drops and other features will have sub-grid scale and need to be modelled
- Huge computing times – but uncertain accuracy
Conservation equations in multiphase pipe flow
Introduction

- Basic conservation equations: Mass, momentum, energy
- The conservation equations are formally similar for all flow regimes (flow patterns)
- The differences between the flow regimes manifest themselves in different terms (*closure relations*) for
  - Wall and interfacial friction factors
  - Dispersion of other phases as droplets and bubbles
  - Momentum transfer between phases due to mass exchange
- Thermodynamics enter conservation equations through
  - Boundary conditions
  - Source terms
  - Mass transfer
Conservation equations for 3-phase stratified flow

• 3 momentum equations
  • Gas layer with oil and water droplets
  • Oil layer with gas bubbles and water droplets
  • Water layer with gas bubbles and oil droplets

• 9 mass equations
  • 3 continuous phases
  • 6 dispersed phases

• 9 energy equations
  • Alternatively, 1 mixture energy equation