Theme 1 – Produced Fluid

Flow Assurance and Separation for the Oil & Gas Industry

Phil Stopford
ANSYS UK
Flow Assurance Overview

- Multiphase flow
  - Gas-liquid systems
    - CFD methods
    - Slugging flow
    - Gas lift
  - Fluid-solid systems
    - Sand transport
    - Hydrates
Introduction

• Oil fields produce a mixture of oil, gas and water

• Challenges
  – Harsh environments, uneven terrain, remote location

• Flow assurance
  – Produce and transport hydrocarbon fluids economically and reliably
Multiphase - What’s Happening?

- Film flow
- Erosion
- Slugging flow
- Bubbles
- Gas hydrates
- Droplets
- Gas
- Oil
- Wax
- Corrosion
- Surface scale
- Emulsions
- Suspended particles
- Slurry
- Sand
Typical Oil Production

- Reservoir
- Liquid
- Bubble point
- Liquid + gas bubbles
- Subsea manifold
- Platform


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Gas – Liquid Systems
Flow Regimes

Vertical flow
- Bubble flow
- Churn flow
- Slug flow
- Annular flow

Horizontal flow
- Bubble flow
- Plug flow
- Stratified-wavy flow
- Slug flow
- Annular flow
- Mist flow


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Further Complicated

• Flow regime not just a function of flow rates
Two Distinct Scales

• Lower resolution, large scale models (whole pipeline)
  – Model applicability is geometry and flow condition specific
  – 1D data available
  – Examples include OLGA, TACITE, PEPITE and PIPESIM

• High resolution, small(er) scale models (specific locations)
  – Empirical correlations valid over wide range of geometry and flow conditions
  – 3D data available
  – More computationally expensive
  – ANSYS CFD software
Computational Models

- Discrete Phase Model/Particle Transport Model
  - Liquid droplets, solid particles or gas bubbles
  - Maximum of 10% volume fraction
  - Can be used as a post-processing tool
  - Computationally cheap
Computational Models

- **Eulerian Model**
  - Liquid droplets/gas bubbles
  - No maximum volume fraction
  - Expensive if many dispersed particle diameters needed
  - Heterogeneous – each phase has a separate velocity field

Air volume fraction on cross section for bubbly flow regime

Volume of control cell $V_c$
Volume occupied by phase $\alpha = r_\alpha V_c$
Volume occupied by phase $\beta = r_\beta V_c$
Computational Models

• **Volume of Fluid (VOF) Model**
  
  – Applies to immiscible fluids only
  – Homogeneous
    • only one velocity field
  – Tracks fluid interface
  – No maximum volume fraction
  – Cannot be used if significant engulfment occurs
  – Not practical for droplet/bubble modelling at large scale

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Modeling of Turbulence in the Free surface

Effect of Damping (Verification Case)

Case 1
- Air: 5 m/s
- Water: 1 m/s

Wall Velocity = 1 m/s

Case 2
- Air: 5 m/s
- (Single phase case with only air flowing over moving wall)

Single phase
Multiphase + damping
Multiphase + No damping

No damping

With damping
A source term is added to the omega equation for turbulence damping.

\[ S = A \Delta n \beta \rho \left( \frac{6B \mu}{\beta \rho \Delta n^2} \right)^2 \]

where:
- \( S \): Model constant, typically 0.075
- \( \beta \): Damping factor
- \( B \): Interfacial area density
- \( \mu \): Viscosity of phase \( i \)
- \( \rho \): Density of phase \( i \)
- \( \Delta n \): Grid size at interface

Interfacial area density is calculated as

\[ A = 2.0 \times f \times |\nabla f| \]

where
- \( f \): Volume fraction of phase \( i \)
- \( |\nabla f| \): Magnitude of gradient of volume fraction

Grid size \( \Delta n \) is calculated internally using grid information.
Slug Flow

From http://www.fzd.de/FWS/FWSF/messtechnik/videometrie/slug.avi

<table>
<thead>
<tr>
<th>Cause</th>
<th>Effect</th>
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<td>Higher pressure drop for flow</td>
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Horizontal Slug Flow Validation

Experiments by Th. Lex et al, TD, TU Munich.
Terrain Induced Slugging: Results
Gas pipeline from off-shore field to land-based Hannibal terminal
Slug catcher separates residual liquid from gas at end of pipeline
Plan to increase pipeline capacity to supply new power station
*Does capacity of slug catcher also have to be increased?*

Inlet conditions for liquid-gas from Olga 1D pipeline model

Estimated cost of modifying slug catcher $25M
Can slug catcher cope with increase in capacity of pipeline?

Yes – Only small amount of liquid carry-over in the form of a fine aerosol
Transient Adaptation in Inlet Header

Initial Mesh

Adapted Mesh
Operational: Gas Lift

• **Need**
  – Enhance oil production
  – Mitigate slugging

• **Physics**
  – Bubble size
    • Drag coefficient

• **Topsides**
  – Gas removal
  – Cause of gas slugging?

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From Flow assurance, Elijah Kempton & Tommy Golczyński, MTS symposium
Gas Lift: Hold Up Profiles

- Small bubbles
  - Wall peaking at both positions

- Large bubbles
  - Wall peaking for lower position
  - Centre peaking for upper position

Bubble Size effect on the gas-lift technique PhD thesis of Sebastien Christophe Laurent Guet
Gas Lift: Hold Up Profiles

H = 5 m  Low point  H = 13 m  High point

Simulation & experiment, different positions

Bubble Size effect on the gas-lift technique PhD thesis of Sebastien Guet
Fluid - Solid Systems
Slurry Flow Regimes

- Slurry flow is classified into different regimes
- The transition between regimes depends on:
  - Solids concentration
  - Velocity
  - Particle Diameter
  - Turbulence
  - Profile

Solids Phase Models

• Similar to gas-liquid systems
  – Discrete Phase Model
    • Low solids concentration
    • Best suited for “mobile” particles
    • Erosion & accretion models available
    • Computationally quick and cheap
  – Eulerian Granular
    • High solids concentration
    • Can account for both mobile and stationary particles
    • Computationally more expensive than DPM
Sand Transport

- Analysis of the following variables:
  - Slurry velocity
  - Solids concentration
  - Solid particle diameter

- Mesh: 0.5 million cells

Heterogeneous flow

Solids Volume Fraction

Y / D

- Fluent CFD: dp = 120 um
- Matousek, 2002 (dp = 120 um)
- Fluent CFD: dp = 370 um
- Matousek, 2002 (dp = 370 um)
Modelling for hydrates

- **Hydrate prevention strategies**
  - Insulation and heating under normal operation
  - Identifying cold spots, remedies
  - Flushing and inhibition strategies
  - Water removal and dehydration

- **Hydrate management strategies**
  - Models for hydrate formation and deposition
  - Particulate transport, erosion
  - Hydrate plug transport and acceleration
Heat transfer in bundled pipelines
Experimental and CFD studies of heat transfer in an air-filled four pipe tube bundle
L. Liu, G. F. Hewitt, S. M. Richardson
Risk management

- Hydrate formation in gas rich systems
  - Real gas behaviour of natural gas
  - Nucleation, growth and deposition of particles
  - Dilute and dense multiphase flows
- CFD to determine flow field
- Model for hydrate nucleation and growth
- Track particle velocity
- Model for particle motion and deposition near walls

A new approach to investigate hydrate deposition in gas-dominated flow-lines
Jassim et al., J. Natural Gas and Engineering, 2, 163-177 (2010)
Deposition distance v experiment

Fig. 15. Deposition distance predicted by simulation and measured during a function of pipe size.

Fig. 20. Comparison of hydrate deposition distance predicted by proposed model and experimental results as a function of Reynolds number.

DD v Pipe Diameter

DD v Pipe Diameter for ice particles and liquid droplets
Multiphase Separators
Separators Overview

• Modelling methods
• Separator types
  – Gravity separators
  – Sloshing
  – Cyclones
  – Axial flow cyclone
  – Twister separator
Multi-phase modelling in separators

- **Lagrangian Particle, droplet or bubble tracking (DPM)**
  - Individual trajectories are predicted
  - Can include momentum interaction
  - Does not account for the volume occupied by the dispersed phase

- **Mixture model**
  - Simple and cost effective model accounts for volume occupied by the dispersed phase.
  - Assumes both phases have the same velocity consequently no counter current flow

- **Volume of fluid modelling**
  - Used to predict stratified flows

- **Eulerian – Eulerian and Eulerian - Granular**
  - Accounts for high volume fractions of dispersed phase
  - Can accommodate coupling between the phases
Four-phase separator

- **Objectives**
  - Compare designs for two inlet configurations
  - Investigate water and gas distribution in detail
  - Characterize destination of smaller quantities of oil and sand
- **It consists of an inlet, several baffles, a water outlet, and a spillweir**

*Courtesy of Zeta-pdm Ltd.*
Four-phase separator

- The gas-water mixture is simulated using the Eulerian multiphase model
- Trajectories of sand (for a range of sizes) are computed using DPM
- The oil concentration is small, so this component is neglected

The water-gas interface near the inlet region

Courtesy of Zeta-pdm Ltd.
Four-phase separator

• Contours of volume fraction of gas near the inlet are shown
• The highly turbulent inlet mixture is calmed by the baffles
  – Note the change in the interface
• Assessing the effectiveness of the baffle design (not shown) was one motivation for the analysis

Courtesy of Zeta-pdm Ltd.
Four-phase separator

- Two inlet designs were tested
- Both performed well for separating large bubbles and particles
- Inlet 1 performed better for small bubble/particle sizes
- Results confirmed that the baffle design was good, and helped find the most efficient inlet design
Water surface in four-phase separator
Sloshing example

- A 10 ft diameter by 40 ft long tank with internals is simulated under “stormy” conditions

- Three-dimensional, three-phase transient VOF simulation of gas/oil/water interfaces

- 30K cells full hexahedral mesh run on a dual-processor workstation. Run time is ~ 29 hours for 23 seconds of real time simulation

- Dynamic simulation is achieved by modelling all six degrees of wave motion through a set of User Defined Functions
Sloshing example

Time = 000 E-01 sec.

Courtesy: Chang-Ming Lee, Ph.D.  NATCO Group Inc., Houston, TX
Cyclone

- CFD provides a detailed understanding of flow distribution, pressure losses, heat transfer, particulate separation, collection efficiency, etc.
- Analyze the impact of changes to equipment geometry
  - Study off-design operating conditions
  - Examine scaling effects
- Reduce design time and expense
  - Faster than testing
  - Minimize expensive equipment outages
Cyclone

• Cyclone separates by generating g-forces

• G-forces required for efficient separation is determined by:
  – Density differential
  – Fluid viscosity
  – Particle diameter

• CFD analysis is used to determine the average g-force generated for specified operating conditions
Cyclone - validation

Tangential velocity

Axial velocity

+ k-epsilon, RNG, — RSM, Δ experiment [LDA]
Cyclone – flow features

- Vortex core clearly visible
- Velocity vectors showing axial flow
- Modelled using the LES turbulence model
Cyclone - multiphase

- Particle separation
  - Air core present
  - Green particles low inertia
  - Yellow particles high inertia
RSM and Eulerian simulation results
Cokljat et. al. 2003

Mondron cyclone simulated using RSM and Eulerian-Eulerian approach, 5 phases simulated on 70,000 cells took 4 days to solve on 6 parallel CPU.
Particle Erosion predictions in Krebs PL5109

- Erosion rate shown on the under and overflow sections (different scale used)
Model for gas dehydration

In Twister, the feed gas is expanded to supersonic velocity, thereby creating a homogeneous mist flow. During the expansion, a strong swirl is generated via a delta wing, causing the droplets to drift toward the circumference of the tube. Finally a co-axial flow splitter (vortex finder) skims the liquid enriched flow from the dried flow in the core. The two flows are recompressed in co-axial diffusers resulting in a final pressure being approximately 35% less than the feed pressure.

Betting, Lammers and Brost, Twister BV
www.TwisterBV.com
Typical mid Twister conditions:

Schematic representation

Saturated Gas

Liquid / Gas Separation

Dry Gas

Liquids

Typical inlet conditions:
100 bar, 25 degC

Acceleration to Mach 1 cools gas
Further cooling from acceleration to Mach > 1

Cooling causes condensation

Axial velocity

High

Low

Typical mid Twister conditions:
30 bar, -45 degC

Typical outlet conditions:
70 bar, 15 degC
Twister Supersonic Separator

- EOS including phase change model
- Condensable and non-condensable gas species
- Nucleation and growth model
- Droplet coalescence
- Slip model for separation
- Turbulence dispersion model
Summary

• The flow regimes likely to be encountered in upstream operations have been investigated
• Suitable computational approaches have been outlined, and examples given

• The appropriate use of detailed engineering simulations can increase knowledge and thereby mitigate flow assurance and separation issues
• Encouraging results obtained for gas-lift, slug flow and sand transport

• New simulation technologies and models will increasingly play a crucial role in flow assurance and separator modelling
  – CFD for complex sections of equipment
  – In combination with 1-D models (e.g. OLGA 2000) for full pipeline models