Use of OpenFoam in a CFD analysis of a finger type slug catcher

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Project background

Analytical analysis of two-phase flow regimes

Computational modeling
1. Solvers and methods
2. Grid generation
3. CFD results of inlet header
4. CFD results of finger pipe

Conclusions
Upstream Oil & Gas production
Two-phase flow often results in slug generation

What is a slug?
*Large plug/amount of mostly liquid or gas travelling through a pipeline*

Slugs in a pipeline are generated thru different mechanisms:
- Terrain slugging caused by variation in elevation of a pipeline
- Hydrodynamic slugging, caused by a liquid wave induced by the gas flow rate
- Severe slugging, associated with the accumulation of liquid at bottom of riser pipes
Slugs should be avoided!

Experimental visualization of slugs

Slugs induce forces

Slugs in two-phase gas flow preferably avoided:
- Slugs cause unsteady unbalanced forces at elbows
- Slugs may cause liquid overloading of separators since the fluid flow rate during slug impact may exceed the equipment design flow rate
- And equipment downstream of separators often involves gas compressor
What is a finger-type slug catcher?
Gas process units in which slugs (large liquid quantity) at pipeline outlet are collected

- Very large installations (typical diameter 1m / pipe length 50m)
- About 50 slug catchers around the world
- To separate liquid from gas by reducing flow velocities to increase residence time sufficiently to allow settlement of fluid droplets
- Finger type used multiple finger pipes: effective, but large footprint!
Typical finger-type slug catcher layout

Performance of a finger-type slug catcher is characterized by:

**Sufficient separation of liquid to prevent liquid carry-over!**

1. Gas-Liquid header
2. Separation section
3. Gas riser
4. Liquid storage section
5. Liquid boot

Relevant data:
- Required slug catcher volume = 3000 barrels ≈ 360 m³
- Required residence time is inversely proportional to the particle size
- Proposed maximum fluid particle size that is allowed to pass the catcher: \( D_p = 150 \, \mu m \)
- Nominal pipe diameter: \( D_{fo} = 42" (= 1.067 \, m) \)
- Separation section length, \( L_{sep} = 20 \, m \)
- Storage section length, \( L_{storage} = 80 \, m \)
- Number of fingers, \( n = 12 \)
Finger-type slug catcher layout

- The inlet header distributes the gas and liquid mixture over the 12 separation fingers
- Variable pipe diameter in original design
- Gas without liquid is escaping thru the gas risers
Objectives and approach

**Objective**

Verification of the performance of a finger-type slug catcher

**Approach**

1. Analytical calculations for each process condition to justify assumptions
2. Numerical modeling and application of Computational Fluid Dynamics techniques.
Five efficiency requirements should be achieved

1. Equal distribution of mass inside the 12 fingers.
2. Stratified flow in the separation section of the finger. Sufficiently low velocities.
3. Sufficiently large residence time in separation section of the finger. Depends on separation section length and fluid velocity.
4. Liquid carry-over in the gas risers has to be minimized (prevented).
5. Flow velocities need to be lower than the erosion velocity.
Introduction and background

► **Analytical analysis of two-phase flow regimes**

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Life cycle gas production results in 9 operating cases

- Fluid gas ratio change in time (different production phases)
- The mass flow decreases during the life time cycle, similar size for gas and liquid
- The volume flow for liquid very low (< 1%). Slugs not likely to occur!
Flow regimes evaluated

Two-phase flow regimes horizontal flow in pipes

- Stratified flow is desired
- For all process conditions $\frac{V_{sg}}{V_{sl}}$ is larger than 50 $\rightarrow$ stratified flow
- The flow in the header is highly unsteady flow $\rightarrow$ stratified but ‘sloshing’ may occur
- The flow in the finger pipe is stratified
Analytical approach to model droplet forces

Drag and Buoyancy Balance

\[ \sum F = \frac{\pi}{6} D_p^3 \rho_g g + C_D A \frac{1}{2} \rho_g v_t^2 - \frac{\pi}{6} D_p^3 \rho_l g = 0 \]

Drag Modeling (Schiller-Naumann)
- Valid for Reynolds numbers < 1000
- Small droplet size justifies this assumption

\[ C_D = \frac{24}{Re_p} \cdot (1 + 0.15 Re_p^{0.687}) \]

Settling Velocity
- Settling velocity is related to the time a droplet needs to drop back to the bulk
- Larger droplets are settling faster
- Smaller droplets remain more present

\[ v_t = -\sqrt{\left( \frac{4 g D_p}{3 C_D} \cdot \frac{\rho_l - \rho_g}{\rho_g} \right)} \]
Required residence time for a droplet to settle

Residence time
Variable separation length and droplet size

Gas riser efficiency

- Residence time related to the drag and settling velocity
- For a separation length of 20 m, 100% of droplets with $D_p > 70 \mu m$ is separated
- For droplets with $D_p < 70 \mu m$, a fraction is entrained with gas stream thru the gas riser, i.e. 50% of all 40 $\mu m$ particles is not separated
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Numerical modelling of two-phase flow

Governing equations for two-phase flow
► Navier-Stokes equations defined for each phase fraction
► Averaged momentum and continuity equations per phase fraction:

$$\frac{\partial \alpha_\varphi \bar{U}_\varphi}{\partial t} + \nabla \cdot (\alpha_\varphi \bar{U}_\varphi \bar{U}_\varphi) + \nabla \cdot (\alpha_\varphi \bar{R}_{\text{eff}}) = -\frac{\alpha_\varphi}{\rho_\varphi} \nabla p + \alpha_\varphi g + \frac{\bar{M}_\varphi}{\rho_\varphi}$$

$$\frac{\partial \alpha_\varphi}{\partial t} + \nabla \cdot (\bar{U}_\varphi \alpha_\varphi) = 0$$

$$\bar{U} = \alpha_a \bar{U}_a + \alpha_b \bar{U}_b.$$  

► Inter-phase momentum transfer for drag, lift and virtual mass
► Drag modeling of a droplet (Schiller-Naumann):

$$C_d = \frac{24}{Re} \left( 1 + 0.15Re^{0.687} \right)$$
CFD methods and boundary conditions

**CFD solver and methods**
► Main OpenFOAM® calculation using twoPhaseEulerFoam

► **twoPhaseEulerFoam** modified to calculate superficial velocities and liquid percentage

► Additional OpenFOAM utilities to monitor mass flow at specified boundaries

► 2\textsuperscript{nd} order spatial and temporal discretisation

► **ANSYS CFX®** Solver used for shadow calculations (very similar results)

**Inflow boundary condition**
Dirichlet for velocity and Neumann for pressure (Header Inlet, Finger Inlet)

**Outflow boundary conditions**
Neumann for velocity and Dirichlet for pressure (Finger Outlets and Riser Outlet)
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Grids generation of header and finger

**Inlet Header model**
Gas flow to optimize flow in header

**Finger model**
Two-phase flow to study liquid carry-over

**Approach**
- Separate CFD calculations of the header and the finger
- CFD of the header to study the mass flow distribution
- CFD of the finger to study if liquid carry-over occurs

**Grid Generation**
- Gambit, SnappyHexMesh and a derived mesher
- Boundary conditions for all process conditions
Proposed and final header configuration

**Proposed configuration**

**Final configuration**

**Approach**

- Gas flow is simulated. The mass flow through the finger outlets is analyzed
- A symmetry plane is used, which is physically justified
- Different geometrical variations
Different header configurations
Based on experience with slug catchers (diameter and geometry variation)

1. Variable Pipe Diameter
2. Constant Pipe Diameter
3. Large Header Pipe
4. Varying Inlet Pipe
5. Extra Split
Agenda

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Flow distribution in inlet header
Contour plots

**Different header configurations**
Equal flow is promoted by constant pipe diameter and extra split
Flow distribution in inlet header
Mass flow at finger pipe outlets

**Mass flow at finger inlets**
Pipe diameter variations

**Mass flow at finger inlets**
Extra split position variations

- Each finger should receive a flow rate as closely as possible to the nominal average of 18 kg/s
- The original design leads to large scattered mass flow, i.e. finger 8 gets twice the nominal value
- The constant diameter and extra split improves the design considerably
- Design 9 provides the best performance in terms of mass flow distribution
Comparison between original and final designs

**Proposed design**
Velocity contours

**Final design**
Constant pipe diameter and extra split

- The peak flow velocity in the original design is too large (erosion) and fluctuations are too big.
- The increased and constant diameter of the intermediate header (42") decrease the flow velocity.
- The extra split promotes a better distributed mass flow through the fingers.
- However, the erosion velocity of about 21 m/s is reached in the first pipe.
Two-Phase flow in the inlet header

- Original design
- Final design

- Liquid accumulation
- Almost no liquid flow

- Volume fraction of the liquid fraction is shown
- The proposed design shows large fluctuations in liquid volume fraction
- Finger 7 shows a liquid flow rate of nearly zero!
- The final design shows a leveling of liquid mass flow
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  4. **CFD results of finger pipe**

Conclusions
Finger pipe to study if liquid carry over occurs

- **Hybrid mesh of the finger**
- **Zoom of the modeled vessel**

- Fully two-phase flow simulations
- Different computational meshes, up to 500k cells
- The storage section is modeled by a vessel, to contain the liquid
- The size of the storage section influence the reliable simulation time
- The inflow conditions, velocities and phase fraction, are derived for all process conditions
- The water mass fraction through the riser is analyzed
The accuracy of the solution is grid independent, and converges for the finest grid (500k).

For 150 μm particles, less than 0.01% leaves the riser. This is close to our analytical results.

Percentage liquid flow rate reaches a steady state.

All case have a separation efficiency larger than 99%, for 150 μm droplets.

The finger geometry of the proposed slug catcher is properly defined!
Two-phase flow in finger pipe
Liquid volume fraction visualized

- A contour of water volume fraction shows that the flow is stratified
- Gravity acts sufficiently as a separator for 150 µm particles for 20 m of separator length
- The flow in the finger is fully stratified, with a little bit of waviness, due to flow unsteadiness
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▶ Conclusions
Conclusions

CFD Analysis of the Inlet Header
► The original design (variable pipe diameter) results in a large offsets from the equal distribution.
► A constant header diameter with a split in the main header pipe improves the slug catcher performance significantly.

CFD Analysis of the Finger
► Two-phase simulations were successfully performed using twoPhaseEulerFoam
► No liquid carry-over of slugs occurs for all operating cases.
► A separation efficiency of 99% for all process conditions (for 150 µm droplets)
Thanks for your attention!