New Perspectives on Gas Well Liquid Loading & Unloading

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Outline of Presentation

• Compare droplet size postulated by Turner against droplet size observed in nature and flow loop testing

• Recognise role of film reversal observed in flow loop experiments and transient multiphase flow modelling

• Explore consequences for gas well deliquification
  – Reduce droplet size
  – Generate swirl
  – Create foam
  – Modify tubing wall

• Summary
Droplet Size in Turner – *Big Rain*

- Turner criterion equates liquid loading to droplet reversal i.e. gas rate where friction drag force on droplet becomes less than gravity force on droplet

\[
\text{Force balance: } \pi D_p^3 \Delta \rho g / 6 = C_d \rho_g v_g^2 \pi D_p^2 / 8
\]

- Friction drag force depends on droplet size and shape

\[
\text{Drag force coefficient: } C_d = f(\text{Re,shape})
\]

- Turner assumes a droplet size based on a large critical Weber number \( \text{We} = 30 \)

\[
\text{Shear force Vs surface tension: } \text{We} = \rho_g v_g^2 / \sigma
\]

- Turner droplet size and \( \text{We} \) is much larger than typically observed in nature e.g. rain has \( \text{We} = 8 \)
Droplet Size in Flow Loop Tests

- Droplet size distribution has been measured in air-water flow loop testing using PDA (Particle Doppler Anemometry)

- 50% of water mass flow carried in droplet phase is smaller than 4 mm

- Maximum droplet size 10x P50 droplet size
Empirical Droplet Size

- Entrainment relation derived from lab data supports smaller critical We i.e. smaller droplets
**Droplet Reversal?**

- At Turner gas velocity realistic size droplets are not expected to cause liquid loading.
- Droplet reversal should only occur at $\frac{1}{2}$ of Turner gas rate.
- What is then causing liquid loading?

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**Diagram:**
- **Turner assumes unrealistic droplet size**
- **Realistic droplets require lower velocity**

**Equations:**
- $F_{\text{Drag}} = F_{\text{Gravity}}$ (Downhole)
- $F_{\text{Drag}} = F_{\text{Gravity}}$ (Wellhead)
- Turner criterion (Downhole)
- Turner criterion (Wellhead)
Droplet Reversal?

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**Busted**

**Droplet Reversal**

- Turner assumes unrealistic droplet size
- Realistic droplets require lower velocity
Droplet and Film Movement

- Flow loop tests show that liquid is transported both by droplets up core and annular film up tubing wall

- Same air-water flow loop tests show that liquid loading is caused by film reversal
Film Reversal

- Film reversal model developed by Jos Van ‘t Westende (PhD Thesis TU Delft, 2008)

Air-water experimental*

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<table>
<thead>
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<tr>
<td>Experimental</td>
<td>13 m/s</td>
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<td>Turner</td>
<td>15 m/s</td>
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<td>Film model</td>
<td>18 m/s</td>
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<td>OLGA</td>
<td>17 m/s</td>
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Use of Turner Criterion

- Turner criterion remains extremely useful engineering tool: film and droplet reversal depend on the same well and fluid parameters in a similar manner.

- SPE 123657 introduces Modified Turner criterion, based on field data and in line with multiphase flow modelling results.
Film Reversal in OLGA

- Movement of and exchange between droplet and film included in OLGA multiphase flow modelling software
- OLGA specifies liquid transport in film and droplet phase

0 degrees deviation (75 bara, 0.1 m ID)
Vertical Well - 0.1 m ID - 50 bar FTHP

- **Q_{\text{min}}** = 130e3 m^3/d
  - at \( P_{\text{res}} = 67.25 \) bar

\( P_{\text{res}} \) decreases from 70 to 65 bar in 100 days.
Annular flow: droplet flow and film flow both important

\[ P_{\text{res}} = 69.80 \text{ bar} \]

Gas \( = 0.184 \times 10^6 \text{ m}^3/\text{d} \)

Total water \( = 3.2 \text{ m}^3/\text{d} \)

Water film \( = 1.7 \text{ m}^3/\text{d} \)

Flow regime = Annular

Holdup = 0.007
Liquid loading starts when film flow “flips” i.e. changes from upward to downward, generally starts at

\[ P_{res} = 67.40 \text{ bar} \]

- Holdup = 0.015
- Water film = 0.0 \( \text{m}^3/\text{d} \)
- Total water = 2.4 \( \text{m}^3/\text{d} \)
- Gas = 0.129e6 \( \text{m}^3/\text{d} \)
- Flow regime = Annular

Flow regime: 

- HOL [-] (WELL) "HOLDUP (LIQUID VOLUME FRACTION)"
- ID [] (WELL) "FLOW REGIME INDICATOR"
- QGST [MSm³/d] (WELL) "GAS VOLUME FLOW AT STANDARD CONDITIONS"
- QLTWT [m³/d] (WELL) "VOLUMETRIC FLOW RATE WATER"
- QLWVT [m³/d] (WELL) "VOLUMETRIC FLOW RATE WATER FILM"
Downward film flow increases holdup and shifts holdup downward, increase of droplet flow upward partly compensates for film flow.

\[ P_{\text{res}} = 67.25 \text{ bar} \]

- Gas = \(0.117 \times 10^6\) m\(^3\)/d
- Total water = 1.5 m\(^3\)/d
- Water film = -0.2 m\(^3\)/d
- Flow regime = Annular
- Holdup = 0.013
\( P_{\text{res}} = 67.25 \text{ bar} \)

At some point total water flow becomes downward.

- Holdup = 0.019
- Water film = 0.0 m\(^3\)/d
- Total water = 0.7 m\(^3\)/d
- Gas = 0.104e6 m\(^3\)/d
- Flow regime = Annular
- Holdup = 0.019

\( Q_{\text{GST}} [\text{m}^3/\text{d}] \) (WELL) "GAS VOLUME FLOW AT STANDARD CONDITIONS"

\( Q_{\text{LTWT}} [\text{m}^3/\text{d}] \) (WELL) "VOLUMETRIC FLOW RATE WATER"

\( Q_{\text{LWT}} [\text{m}^3/\text{d}] \) (WELL) "VOLUMETRIC FLOW RATE WATER FILM"
Reduce Droplet Size – *Into Thin Air*

- At small enough droplet size relaxation length will equal well depth.
- Small enough droplets could be generated by large shear forces i.e. very high gas velocities.
- Necessary choke size would result in excessive pressure loss defeating the purpose.

![Graph showing droplet diameter vs. gas velocity]
Droplet and Film Exchange

- Flow loop tests highlight the continuous exchange of liquid between film phase and droplet phase through deposition and entrainment.

- Droplet relaxation length is typically short for larger size droplets.
Droplet Relaxation Length

- Relaxation length Vs droplet diameter for ID = 0.1 m

\[ n(x) = e^{-x/L_{rel}} \]

\( L_{rel} = \frac{\mu m}{100 m} \)
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Generate Swirl – *Let* *s* *Twist*

- **Spiral Flow = Helical Flow = Vortex Flow**
  - Norm Hein (2007 GWD Workshop, Denver)

- **Vortices have “memory” i.e. persist over extended time and distance (100-1000 D)**
  - Benefit observed both in lab testing and field applications
  - Improves film flow rather than droplet flow
  - Promising as temporary measure e.g. while waiting for compression
  - May require multiple tools to cover tubing length depending on relaxation length

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Create Foam – *Tall Tale*

- Stable foam requires liquid content between 10% and 40%, foam breaks up and turns into mist @ liquid fraction less than 4% (SPE 86927)
- Liquid fraction in wellbore rarely exceeds 1%, hence stable foam columns do not exist in wells
- Lower surface tension (2x-3x) reduces droplet size, increases entrainment and increases velocity of film roll waves
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Modify Tubing – *Die Zauberflöte*

- Apply hydrophilic of hydrophobic coating
  - Small scale lab tests show promising effects

Fig. 7. Typical churn flow images in test pipes ($\langle j_g \rangle = 3.3 \text{ m/s}$, $\langle j_f \rangle = 0.3 \text{ m/s}$).
Modify Tubing – *Die Zauberflöte*

- Apply ID profile
  - Small scale lab tests show promising effects

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Fig. 8. Typical annular flow images in test pipes ($\bar{j}_g = 10 \text{ m/s}$, $\bar{j}_l = 0.10 \text{ m/s}$).
Modify Tubing – *Die Zauberflöte*

- Modify tubing wall to delay film reversal
  - Small scale lab tests show promising effects
- Apply hydrophilic of hydrophobic coating
  - Small scale lab tests show promising effects
- Apply ID profile (small scale – large scale)
  - Small scale lab tests show promising effects

Promising

*Fig. 7. Typical churn flow images in test pipes \((\dot{V}_L = 3.3 \text{ m/s}, \dot{V}_H = 0.3 \text{ m/s})\).*

*Fig. 8. Typical annular flow images in test pipes \((\dot{V}_L = 10 \text{ m/s}, \dot{V}_H = 0.10 \text{ m/s})\).*
Summary

- Droplet size assumed by Turner is much larger than observed in flow loop tests.
- Flow loop tests and multiphase modelling indicate that liquid loading is caused by flow reversal rather than droplet reversal.
- Therefore deliquification must delay film reversal rather than droplet reversal.
- Droplet size reduction could help, but is impractical due to associated pressure loss.
- Swirl generation could help, may require installation at multiple depths.
- Surfactant injection helps, but mechanism may be different than assumed.
- Tubing wall modification could help, under investigation.
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