Numerical Simulation of Slug Generation at a V-Shaped Elbow Between Inclined Pipes

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Slug generation at a V-shaped elbow
Background

Oil and Gas Transport Pipeline

Overland pipeline

(Image: Marc Shandro via flickr.com, http://gasline.alaska.gov/)

Offshore pipeline

Background

In such hilly-terrain pipelines, there are V-shaped elbows between descending and ascending pipes.

- Flow pattern and flow characteristics of oil and gas two-phase flow varies at V-shaped elbow
- Liquid slugs are often generated at V-shaped elbows
Background

Liquid Slugs at a V-shaped Elbow

- Significant pressure fluctuation
- Overflow in separator
- Reduction of transport performance

- Slug flow in horizontal, vertical and inclined piping have been received much attention.
- Knowledge on the slugging at a V-shaped elbow is scarce.

For the piping design and execution of appropriate operation procedure, predicting slug generation and their characteristics is important.
To give reasonable predictions for this phenomena, three-dimensional simulation is required.
Objectives

Three-dimensional numerical simulation was carried out to examine its applicability to prediction of slug generation at a V-shaped elbow and slug characteristics.

[Numerical Method]
• Two-fluid model
• The free-surface model for the interfacial area density
Previous Work (Hosokawa and Tomiyama, 2003)

Test Fluids: Water and Air
- \(D = 20\) mm
- \(\theta = 3^\circ, 5^\circ, 7^\circ\)
- \(J_G = 0.095 - 1.041\) m/s
- \(J_L = 0.087 - 1.034\) m/s
Previous Work (Hosokawa and Tomiyama, 2003)

Flow Pattern in the Ascending Pipe

Flow Pattern Map

$D = 20\text{mm}$

$\theta = 5^\circ$
Previous Work (Hosokawa and Tomiyama, 2003)

- **Parameters:**
  - Diameter ($D$): 20 mm
  - Inclination angle ($\theta$): 5°
  - Gas flow rate ($J_G$): 0.61 m/s
  - Liquid flow rate ($J_L$): 0.22 m/s
  - Lengths: $l = 800 \pm 25$ mm

- **Measured Liquid Profile:**

![Graph showing liquid level over time for different conditions](image)
Previous Work (Hosokawa and Tomiyama, 2003)

Correlation for Slug Characteristics

 Slug Velocity $V_S$:
\[
V_S = 1.07 \langle J_G + J_L \rangle + \sqrt{\frac{\Delta \rho g D}{\rho_L}} \{0.35 \sin \theta + (0.135 \log_{10} E_o + 0.056) \cos \theta\}
\]

 Slug Frequency $f_S$:
\[
f_S = \frac{V_S}{L_U D} = \exp \left( -3.2 \frac{\langle J_L \rangle}{\langle J_G + J_L \rangle} + 3.94 \right)
\]

 Slug Length $L_S$:
\[
1 - \frac{L_S}{L_U} = \frac{1}{\alpha_G} \frac{\langle J_G \rangle}{V_S}
\]

(Gas Volume Fraction $\alpha_G$)
\[
\alpha_G = 0.625 \frac{\langle J_G \rangle}{\langle J_G + J_L \rangle} + 0.227
\]

$D = 20, 30, 40$ mm  
$\theta = 3^\circ, 5^\circ, 7^\circ$  
$J_G = 0.087 - 1.034$ m/s  
$J_L = 0.095 - 1.041$ m/s
Numerical Method

Governing Equations

Mass: \( \frac{\partial \alpha_k}{\partial t} + \nabla \cdot \alpha_k \mathbf{V}_k = 0 \)

Momentum: \( \frac{\partial \mathbf{V}_k}{\partial t} + (\mathbf{V}_k \cdot \nabla) \mathbf{V}_k = -\frac{1}{\rho_k} \nabla P + \frac{1}{\alpha_k} \nabla \cdot \alpha_k [\mathbf{v}_k \{\nabla \mathbf{V}_k + (\nabla \mathbf{V}_k)^T\} + \tau_{tk}] + \mathbf{g} + \frac{F_{ik}}{\rho_k \alpha_k} + \frac{F_s}{\rho_k \alpha_k} \)

Closure Models

Interfacial force: \( \mathbf{F}_{ig} = -\mathbf{F}_{IL} = \frac{1}{8} C_f A_i \rho_{GL} |\mathbf{V}_G - \mathbf{V}_L| (\mathbf{V}_G - \mathbf{V}_L) \)

Area density: \( A_i = |\nabla \alpha_L| \)

Density: \( \rho_{GL} = 0.5 \rho_G + 0.5 \rho_L \)

Friction coeff.: \( C_f = 3.5 \)

Turbulent stress: \( \tau_{tk} = \mathbf{v}_t [\nabla \mathbf{V}_k + (\nabla \mathbf{V}_k)^T] \)

Surface tension: \( \mathbf{F}_s = \sigma_s \kappa \mathbf{n} \mathbf{d} \)

Commercial Software CFX13 was used.

Free-surface treatment

(Egorov, 2004; Vallée et al., 2005; Höhne et al., 2011)

The \( k-\varepsilon \) model for the two-phase mixture was used for turbulent viscosity \( \mathbf{v}_t \).

The Continuum Surface Force Model (Brackbill, 1992) was used for the surface tension.
Simulation Model

Calculation Model

Number of cell : 54,000  
Time step : 0.005 s  
Time duration : 30 - 60 s  
Calculation time : 4 – 6 d / run  
CPU : Intel Xeon(2.9GHz, 4GB-RAM)  
Parallel Core : 4 cores
Result

Computed Liquid Distribution

$D = 20\,\text{mm}$
$\theta = 5^\circ$
$J_G = 0.60\,\text{m/s}$
$J_L = 0.22\,\text{m/s}$

Stratified-Slug

Descending pipe

Ascending pipe

Flow direction

Time (s)

$L/D$
Result

Computed Liquid Profile @ $l/D = 40$

Measured

Predicted

\[ D = 20 \text{ mm} \]
\[ \theta = 5^\circ \]
\[ J_G = 0.61 \text{ m/s} \]
\[ J_L = 0.22 \text{ m/s} \]
\[ l = 800-25 \text{ mm} \]
\[ l = 800+25 \text{ mm} \]
Result

Computed Liquid Distribution

\[ D = 20 \text{ mm} \]
\[ \theta = 5^\circ \]
\[ J_G = 0.2 \text{ m/s} \]
\[ J_L = 0.4 \text{ m/s} \]

Stratified-Plug

Descending pipe

Ascending pipe

Flow direction

\( \alpha_L \)

\( \frac{l}{D} \)

Time (s)

\( <J_G> \) (m/s)

\( <J_L> \) (m/s)
**Result**

**Computed Liquid Distribution**

\[ D = 20 \text{ mm} \]
\[ \theta = 5^\circ \]
\[ J_G = 1.0 \text{ m/s} \]
\[ J_L = 0.2 \text{ m/s} \]

- Stratified-Semislug
- Descending pipe
- Ascending pipe

Flow direction

\[ \alpha_L \]

\[ \frac{l}{D} \]

\[ \text{Time (s)} \]
Flow Pattern Map

\[ D = 20 \text{ mm} \]
\[ \theta = 5^\circ \]
 Slug Characteristics

Dependence on $J_G$ and $J_L$

$D = 20$ mm
$\theta = 5^\circ$

Slug Velocity

Slug Frequency

Slug Length (non-dimensional)
Slug Characteristics

Comparison between measured and predicted results

 Slug Velocity

Measured and predicted $V_S$ (m/s)

 Slug Frequency

Measured and predicted $f_S$ (1/s)

 Slug Length (non-dimensional)

Measured and predicted $L_S/L_U$

$D = 20$ mm

$\theta = 3^\circ, 5^\circ, 7^\circ$
Summary

Three-dimensional numerical simulation of slugs generated at a V-shaped elbow was carried out. The results are summarized as follows:

- The two-fluid model with free surface treatment was able to predict the slug generation at the V-shaped elbow and slug growth and collapse in the ascending pipe.

- The model gave reasonable predictions for the effects of the gas and liquid volume fluxes on slug characteristics.

Since the pipe diameters studied here are relatively small compared with those in practical systems, validation of the method for slug flow in large-size pipes is required in the future.
END
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Sep. 18th, 2014
Effect of Mesh

Slug Velocity

Predicted $V_S$ (m/s) vs. Correlation

Slug Frequency

Predicted $f_S$ (1/s) vs. Correlation

Slug Length

Predicted $L_S/L_U$ vs. Correlation

$D = 20\, mm$

$\theta = 5^\circ$
Effect of friction coefficient $C_f$

$D = 20\text{ mm}$
$\theta = 5^\circ$

 Slug Velocity

 Slug Frequency

 Slug Length (non-dimensional)
Previous Work (Hosokawa and Tomiyama, 2003)

Correlation for Slug Characteristics

Slug Velocity $V_S$:

$$V_S = 1.07 \langle J_G + J_L \rangle + \sqrt{\frac{\Delta \rho g D}{\rho_L}} \left\{ 0.35 \sin \theta + \left( 0.135 \log_{10} E_o + 0.056 \right) \cos \theta \right\}$$

Based on the drift flux model:

$$V_S = C_o \langle J_G + J_L \rangle + \sqrt{\frac{\Delta \rho g D}{\rho_L}} \left\{ F_r \sin \theta + F_r \cos \theta \right\}$$

Slip Velocity (Bendiksen, 1984)

Slug Frequency $f_S$:

$$f_S = \frac{V_S}{L_U}, \quad \frac{L_U}{D} = \exp \left( -3.2 \frac{\langle J_L \rangle}{\langle J_G + J_L \rangle} + 3.94 \right)$$

Dimensionless slug unit length $L_U/D$ was assumed to relates to the dimensionless liquid volume flux $J_L/(J_G+J_L)$

Slug Length $L_S$:

$$1 - \frac{L_S}{L_U} = \frac{1}{\alpha_G} \frac{\langle J_G \rangle}{V_S}$$

Based on mass conservation of slug unit

($\text{Gas Volume Fraction } \alpha_G$)

$$\alpha_G = 0.625 \frac{\langle J_G \rangle}{\langle J_G + J_L \rangle} + 0.227$$

Measured $\alpha_G$ was proportional to the dimensionless gas volume flux $J_L/(J_L+J_G)$

$D = 20, 30, 40 \text{ mm}$

$\theta = 3^\circ, 5^\circ, 7^\circ$

$J_G = 0.087 - 1.034 \text{ m/s}$

$J_L = 0.095 - 1.041 \text{ m/s}$
Numerical Method

Governing Equations

Mass: \[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0 \]

Momentum: \[ \frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \nabla) \mathbf{V} = -\frac{1}{\rho} \nabla P + \frac{1}{\rho \alpha_k} \nabla \cdot \alpha_k \left( \mathbf{V} \nabla \mathbf{V} + (\nabla \mathbf{V})^T \right) + \mathbf{t} \mathbf{k} + g + \frac{F_{iG}}{\rho_k \alpha_k} + \frac{F_s}{\rho_k \alpha_k} \]

Closure Models

Interfacial Force: \[ F_{iG} = -F_{iL} = \frac{1}{8} C_f A \rho_{GL} |\mathbf{V}_G - \mathbf{V}_L| (\mathbf{V}_G - \mathbf{V}_L) \]

Area Density: \[ A_i = |\nabla \alpha_L| \]

Density: \[ \rho_{GL} = 0.5 \rho_G + 0.5 \rho_L \]

Friction Coeff.: \[ C_f = 3.5 \]

Turbulent Stress: \[ \mathbf{t}_{ik} = \nu_t \left[ \nabla \mathbf{V}_k + (\nabla \mathbf{V}_k)^T \right] \]

Surface Tension: \[ F_s = \sigma_{s \kappa n \delta} \]

Commercial Software CFX13 was used.

Free-surface treatment

(Egorov, 2004; Vallée et al., 2005; Höhne et al., 2011)

The k-ε model for the two-phase mixture (ANSYS, 2010) was used for turbulent viscosity \( \nu_t \).

The Continuum Surface Force Model (Brackbill, 1992) was used for the surface tension.
Numerical Method

Turbulence Model: $k$-$\varepsilon$ Model for Two-Phase Mixture (ANSYS, 2010)

Turbulent Kinematic Viscosity $\nu_t$: $\nu_t = C_{\mu} \frac{k^2}{\varepsilon}$

Turbulent Kinetic Energy $k$: $\frac{\partial k}{\partial t} + \mathbf{V}_m \cdot \nabla k = P_k - \varepsilon + \nabla \cdot [(\nu_m + \frac{\nu_t}{\sigma_k})\nabla k]$

Turbulent Dissipation Rate $\varepsilon$: $\frac{\partial \varepsilon}{\partial t} + \mathbf{V}_m \cdot \nabla \varepsilon = C_{\varepsilon 1} \frac{\varepsilon}{k} P_k - C_{\varepsilon 2} \frac{\varepsilon^2}{k} + \nabla \cdot [(\nu_m + \frac{\nu_t}{\sigma_k})\nabla \varepsilon]$

where

Production Rate of Shear-induced Turbulence $P_k$: $P_k = \nu_t [\nabla \mathbf{V}_m + (\nabla \mathbf{V}_m)^T] \cdot \nabla \mathbf{V}_m$

Mixture Kinematic Viscosity $\nu_m$: $\nu_m = \frac{\alpha_G \rho_G \mathbf{V}_G + \alpha_L \rho_L \mathbf{V}_L}{\rho_m}$

Mixture Velocity $\mathbf{V}_m$: $\mathbf{V}_m = \frac{\alpha_G \rho_G \mathbf{V}_G + \alpha_L \rho_L \mathbf{V}_G}{\rho_m}$
Numerical Method

Surface Tension Model: Continuum Surface Force Model (Brackbill et al., 1992)

Surface Tension $F_s: \quad F_s = \sigma_s \kappa n \delta$

where

Unit vector normal to the interface $n: \quad n = \frac{\nabla \alpha_L}{|\nabla \alpha_L|}$

Curvature of the interface $\kappa: \quad \kappa = -\nabla \cdot n = -\nabla \cdot \left( \frac{\nabla \alpha_L}{|\nabla \alpha_L|} \right) = -\frac{1}{|\nabla \alpha_L|} \left( \frac{\nabla \alpha_L}{|\nabla \alpha_L|} \cdot \nabla |\nabla \alpha_L| - \nabla \cdot \nabla \alpha_L \right)$

Delta function $\delta: \quad \delta = |\nabla \alpha_L| \quad \text{(The liquid volume fraction } \alpha_L \text{ was used as a phase indicator function.)}$

Contact Angle $n_w: \quad 70^\circ \quad n = n_w \cos \theta_w + t_w \sin \theta_w \quad @\text{Cells adjacent to wall}$
Past research in onset of slugging

- In a straight pipe
  - Kordyban and Ranov, 1970
  - Wallis and Dobson, 1973
  - Mishima and Ishii, 1980, etc.

- In a hilly-terrain pipeline
  - Mishima and Ishii, 1993
  - Zheng, Brill and Shoham, 1993
  - Hosokawa and Tomiyama, 2003
  - Masella et al., 1998
  - Issa et al., 2003
  - Bonizzi et al., 2003

- In a V-shaped elbow
  - Fitremann, 1975

For such hilly-terrain pipeline, knowledge on onset of slugging is still rudimentary. In particular, there are few studies on a slug flow in a V-shaped elbow.
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Sep. 18th, 2014