Solid Particle Transport in Multiphase Horizontal Pipes

Kamyar Najmi
Ph.D. Student, Research Assistant
Tulsa University Sand Management Projects
Mechanical Engineering Department
The University of Tulsa

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Outline

• Introduction

• Research Objectives

• Current Studies
  • Multi-phase Experiments
  • Single-phase Modeling

• Future Studies
Introduction

• Significant work has been performed for liquid-solid and gas-solid flows

• In oil and gas production, it is very common to have gas, liquid and solids flowing simultaneously

• Studies for sand transport in gas-liquid flows are very limited
Research Objectives

• Conduct experiments for particle transport in multiphase flow to develop a database

• Compare new data with previously obtained data for multiphase flow with particles

• Develop a mechanistic model for particle transport in multiphase flow
  – First step is to generalize model for single phase
Literature Review

Various Multiphase Studies

- Experimental Data
  - Oudeman (1992)
  - Stevenson (2002)
  - Al-Lababidi (2008)
  - Arevalo (2010)
  - Hill (2011)

- Modeling
  - Angelsen (1989)
  - Salama (2000)
  - Stevenson (2002)
  - Danielson (2007)
Existing Multiphase Models

- $D = 0.051 \text{ m} \quad d_p = 300 \mu \text{m} \quad C = 0.1\% \left( 930 \frac{\text{lb}}{1000 \text{ bbl}} \right)$

![Diagram showing the relationship between $V_{SL}$ and $V_{SG}$ with different models and regions marked: Moving Particle Region, Non-Moving Particle Region, Stevenson (2002), Angelson (1989), Danielson (2007), and Salama (2000).]
# Experimental Matrix

<table>
<thead>
<tr>
<th></th>
<th>Particle Diameter (Micron)</th>
<th>Particle Volume Concentration (%)</th>
<th>Particle Volume Concentration (lb/1000bbl)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2 inch pipe</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>0.1</td>
<td>930</td>
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<tr>
<td></td>
<td>150</td>
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<td>0.1</td>
<td>930</td>
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<td>300</td>
<td>0.01</td>
<td>93</td>
</tr>
<tr>
<td><strong>4 inch pipe</strong></td>
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<tr>
<td></td>
<td>150</td>
<td>0.1</td>
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<td></td>
<td>300</td>
<td>0.01</td>
<td>93</td>
</tr>
</tbody>
</table>
Flow Regime in 2-inch Pipe

- $V_{SL} = 0.43 \text{ m/s}$
- $V_{SG} = 2.3 \text{ m/s}$
Multiphase Flow Data

- $D = 0.051 \, m$  
- $d_p = 150 \, \mu m$  
- $C = 0.1\% \left(930 \frac{lb}{1000 \, bbl}\right)$

![Slug Flow Graph](image)

- Current Study
- Arevalo (2010)
- Al-lababidi (2008)
- Stevenson (2002)
- Angelson (1989)
- Danielson (2007)

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$V_{SL} (m/s)$ vs. $V_{SG} (m/s)$
Multiphase Flow Data

- \( D = 0.051 \, m \)  \( d_p = 150 \, \mu m \)  \( C = 0.01\% \left( \frac{lb}{1000\, bbl} \right) \)

![Graph showing Slug Flow and Low Liquid Loading Region with various data points and lines representing different studies: Current Study, Arevalo (2010), Al-lababidi (2008), Stevenson (2002), Angelson (1989), Danielson (2007).]
Multiphase Flow Data

- \( D = 0.051 \, m \), \( d_p = 300 \, \mu m \), \( C = 0.1\% \) (930 \( \frac{lb}{1000 \, bbl} \))

![Graph showing multiphase flow data with various datasets and markers for different studies.]

- Current Study
- Arevalo (2010)
- Stevenson (2002)
- Angelson (1989)
- Danielson (2007)
Multiphase Flow Data

- $D = 0.051 \, m \quad d_p = 300 \, \mu m \quad C = 0.01\% \left(\frac{93 \text{ lb}}{1000 \text{ bbl}}\right)$
Flow Regime in 4-inch Pipe

- $V_{SL} = 0.26 \text{ m/s}$
- $V_{SG} = 1.44 \text{ m/s}$
Multiphase Flow Data

- \( D = 0.1 \text{ m} \), \( d_p = 150 \mu \text{m} \), \( C = 0.1\% \) (930 lb/1000 bbl)

**Stratified Wavy Flow**

- Current Study
- Hill (2011)
- Stevenson (2002)
- Angelson (1989)
- Danielson (2007)
Multiphase Flow Data

- $D = 0.1 \text{ m}$  
- $d_p = 150 \mu\text{m}$  
- $C = 0.01\% \left( \frac{lb}{1000 \text{ bbl}} \right)$

![Stratified Wavy Flow](image)

- Current Study
- Hill (2011)
- Stevenson (2002)
- Angelson (1989)
- Danielson (2007)
Multiphase Flow Data

- $D = 0.1 \text{ m} \quad d_p = 300 \mu\text{m} \quad C = 0.1\% \left(930 \frac{lb}{1000\text{bbl}}\right)$

Multiphase Flow Data

- $D = 0.1 \ m \quad d_p = 300 \ \mu m \quad C = 0.01\% \ (93 \ \frac{lb}{1000\ bbl})$

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![Stratified Wavy Flow](image)

- Current Study
- Hill (2011)
- Stevenson (2002)
- Angelson (1989)
- Danielson (2007)

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Existing Single Phase Models

- Saks (1970)
- Davies (1987)
- Chien (1994)
- Ponagandla (2008)
- Turian (1980)
New Model

\[ V = \sqrt[3]{\frac{F_\mu}{F_S}} \left( \frac{d_p g}{f/8} \right)^{0.5} \times F_C \]

- $F_\mu$ : Wall Fluid-Friction/Roughness Function
- $F_S$ : Shape Factor
- $f$ : Friction Coefficient
- $d_p$ : Particle Diameter
- $\rho_p$ : Particle Density
- $\rho_f$ : Fluid Density
- $F_C$ : Concentration Factor
Correction Parameter

\[ F_\mu = \frac{(\frac{\mu_f V}{Kd_p})^n}{1 - \exp(-d_p^+)} \]

\[ F_C = C^{0.1536} \times (1 - C)^{0.3564} \]

\[ d_p^+ = \frac{d_p u_\tau}{v} \]

\[ u_\tau = V \sqrt{\frac{f}{8}} \]

- \( d_p^+ \): Dimensionless Particle Diameter
- \( u_\tau \): Frictional Velocity
- \( \mu_f \): Fluid Dynamic Viscosity
- \( v \): Fluid Kinematic Viscosity
- \( K,n \): Empirical Constants
Gas Data Comparison

Particle: Alumina  Gas Flow: Air  Pipe Diameter=0.052 m
Ambient Pressure and Temperature

- Exp. Cabrejos (1992-94)
- Oroskar & Turian
- Saks
- New Model

Critical Velocity (m/s) vs. Particle Diameter (Micron)

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Gas Data Comparison

Particle: Beach Sand  Gas Flow: Air  Pipe Diameter=0.052 m
Ambient Pressure and Temperature

- Exp. Halow (1972)
- Oroskar & Turian
- Saks
- New Model

Critical Velocity (m/s)

Particle Diameter (Micron)
Gas Data Comparison

Particle: Glass   Gas Flow: Air   Pipe Diameter=0.025 m
Ambient Pressure and Temperature

- Oroskar & Turian
- Saks
- New Model

Critical Velocity (m/s) vs. Particle Diameter (Micron)
Gas Data Comparison

Particle: Sand  Gas Flow: Air  Pipe Diameter=0.1 m
Ambient Pressure and Temperature

- Exp. Rabinovich (2009)
- Oroskar & Turian
- Saks
- New Model

![Graph showing critical velocity vs. particle diameter for different models and experimental data.](image-url)
Comparison of Gas Data to Model

![Graph showing comparison of critical velocity (m/s) to particle diameter (micron) between Oroskar & Turian and experiment (different sources).]
Comparison of Gas Data to Model

Critical Velocity (m/s)

Saks  Experiment (Different Sources)

Particle Diameter (Micron)
Comparison of Gas Data to Model

- New Model
- Experiment (Different Sources)

Critical Velocity (m/s)

Particle Diameter (Micron)

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Liquid Data Comparison

Particle: Sand  Particle Diameter: 450 Micron  Liquid Flow: Water  
Liquid Viscosity: 1 cP  Pipe Diameter=0.152 m  
Ambient Pressure and Temperature

- Davis
- Oroskar & Turian
- New Model

Graph showing critical velocity (m/s) against concentration (%) for different models.
Particle: Sand  Particle Diameter: 360 Micron  Liquid Flow: Water
Liquid Viscosity: 1 cP  Pipe Diameter=0.1 m
Ambient Pressure and Temperature

- Exp. Roco (1991)
- Davies
- Oroskar & Turian
- New Model
Liquid Data Comparison

Particle: Sand  Particle Diameter: 150 Micron  Liquid Flow: Water
Liquid Viscosity: 1 cP  Pipe Diameter=0.052 m
Ambient Pressure and Temperature

- Exp. Delavan (2012)
- Davies
- Oroskar & Turian
- New Model

Critical Velocity (m/s) vs. Concentration (%)

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Liquid Data Comparison

Particle: Sand  Particle Diameter: 150 Micron  Liquid Flow: Water + CMC
Liquid Viscosity: 3 cP  Pipe Diameter=0.052 m
Ambient Pressure and Temperature

• Exp. Delavan (2012)  • Davies  • Oroskar & Turian  • New Model

Critical Velocity (m/s)

Concentration (%)
Particle: Sand  Particle Diameter: 150 Micron  Liquid Flow: Water + CMC  Liquid Viscosity: 5 cP  Pipe Diameter=0.052 m  Ambient Pressure and Temperature

- Exp. Delavan (2012)
- Davies
- Oroskar & Turian
- New Model

Critical Velocity (m/s) vs Concentration (%)

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Liquid Data Comparison

Particle: Sand   Particle Diameter: 150 Micron   Liquid Flow: Water + CMC
Liquid Viscosity: 10 cP   Pipe Diameter=0.052 m
Ambient Pressure and Temperature

- Exp. Delavan (2012)
- Davies
- Oroskar & Turian
- New Model

Critical Velocity (m/s) vs. Concentration (%)

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Liquid Data Comparison

Particle: Sand  Particle Diameter: 150 Micron  Liquid Flow: Water + CMC
Liquid Viscosity: 1 & 10 cP  Pipe Diameter=0.052 m
Ambient Pressure and Temperature

- Exp. Delavan (1cP)
- Oroskar & Turian (1cP)
- New Model (1cP)
- Exp. Delavan (10cP)
- Oroskar & Turian (10cP)
- New Model (10cP)

![Graph showing critical velocity vs. concentration for different models and viscosity levels.](image-url)
Experimental Study Conclusions

- Increases in particle concentration or particle diameter increases the required flow rates of the carrier fluids for effective sand transport.
- An increase in gas or liquid flow rate improves the transport of the particle.
- When a small rate of gas is introduced into single-phase flow, the effectiveness of the transport dramatically increases.
- As the gas rate is increased, the transport effectiveness increases but not as significantly.
Modeling Study Conclusion

• New model is the first model which works both for gas and liquid flow
• New model is able to predict critical velocity well for a wide range of data
• An effective model should include the effects of viscous sub-layer and friction between particles and pipe surface even in gas flow
• Critical velocity increases by increasing particle diameter, particle concentration and fluid viscosity
Possible Areas for Future Experimental Work

• Investigation of Sand Size and Viscosity Effects in:

  ➢ Gas-Liquid-Sand (Low Liquid)

  ➢ Gas-Liquid-Sand (Slug, Stratified)

  ➢ Gas-Water-Oil-Sand
Future Experimental Facility

- Low Liquid Loading Experimental Facility
Future Modeling Work

• Expand the model for multiphase flow taking into account different flow regimes and also particle concentration