Welcome
Safety Moment

- Emergency Exits
- Assembly Point
- Tornado Shelter
- Campus Emergency
  - Call 9-911
  - Campus Security, ext. 5555 or 918-631-5555
- Rest Rooms
Introductory Remarks

- 77\textsuperscript{th} Semi-Annual Advisory Board Meeting
- Handout
  - Combined Brochure and Slide Copy
- Sign-Up List
  - Please Leave Business Card at Registration Table
Team

Research Associates

- Cem Sarica (Director)
- Holden Zhang (Associate Director)
- Eduardo Pereyra (Research Associate)
- Abdel Al-Sarkhi (KFPMU – Visiting Research Professor)
- Eissa Al-Safran (KU – Collaborator)
Team ...

- **Project Coordinator**
  - Linda Jones
- **Project Engineer**
  - Scott Graham
- **Research Technicians**
  - Craig Waldron
  - Norman Stegall
- **Web Master**
  - Lori Watts
Team …

- **TUFFP Research Assistants**
  - Feras Al-Ruhaimani (Ph.D.) – Kuwait
  - Yasser Al-Saadi (MS) – Saudi Arabia
  - Rosmer Brito (MS) – Venezuela
  - Kiran Gawas (Ph.D.) – India
  - Mujgan Guner (MS) – Turkey
  - Hamid Karami (Ph.D.) – Iran
  - Ge Yuan (MS) – PRC
  - Wei Zheng (MS) – PRC
Team …

- Visiting Research Assistants
  - Jinho Choi, SNU
  - Hoyoung Lee, SNU
Guests

- Dr. Hoang Nhan, PetroVietnam University
- Jerry Martin, Cameron Process Systems
Agenda

- 8:30  Introductory Remarks
- 8:45  Progress Reports
  - Executive Summary
  - Effect of Pipe Inclination on Flow Characteristics of High Viscosity Oil-Gas Two-Phase Flow
- 10:15  Coffee Break
- 10:30  Progress Reports
  - Downward Two-Phase Stratified Flow for Highly Viscous Oils
  - Effect of Medium Oil Viscosity on Two-Phase Oil-Gas Flow Behavior in Horizontal Pipes
  - Characterization of High Viscosity Slug Flow in Horizontal Pipes
Agenda …

- 12:00  Lunch – Chouteau C
- 1:15   Progress Reports
  - Low Liquid Loading in Gas-Oil-Water Pipe Flow
  - Effects of MEG on Multiphase Flow Behavior
  - Modeling of Droplet Entrainment in Co-current Annular Two-Phase Flow: A New Approach
  - High Pressure Test Facility Construction Update
- 3:00   Coffee Break
Agenda ...

3:15 Progress Reports

- Liquid Loading of Gas Wells (Part 1)
- Liquid Loading of Gas Wells (Part 2)
- Simplified Transient Two-Phase Modeling
- Unified Heat Transfer Modeling of Gas-Oil-Water Pipe Flow
Agenda …

- 4:25 TUFFP Business Report
- 4:40 Open Discussion
- 5:10 Adjourn
- 5:30 TUFFP/TUPDP Reception - Atrium, ACAC
Other Activities

★ October 25, 2011
➢ TUHOP Meeting
➢ TUFFP Workshop
 ▶ Excellent Presentations
 ▶ Beneficial for Everybody
➢ Facility Tour
★ October 27, 2011
➢ TUPDP Meeting
Current Projects

- High Viscosity Multiphase Flow
- Low Liquid Loading Flow
- Up-scaling Studies
- Effects of MEG on Multiphase Flow
- Droplet Homo-phase Studies
Current Projects …

- Liquid Loading of Gas Wells
- Simplified Transient Modeling
- Unified Model
- Energy Minimization Modeling
High Viscosity Multiphase Flow

- Significance
  - Discovery of High Viscosity Oil Reserves

- Objective
  - Better Prediction Models

- Past Studies
  - Gokcal (2005), (2008)
    - Indicated Poor Performance of Models for Viscosities Between 200 and 1000 cP
    - Observed Significantly Different Flow Behavior
      - Dominance of Slug Flow
    - Developed
      - New Drift Velocity and Translational Velocity Closure Models
      - New Slug Frequency Correlation
High Viscosity Multiphase Flow

- Past Studies …
  - Kora (2010)
    - Investigated Slug Liquid Holdup
    - No Significant Change for a Liquid Viscosity Range of 181 – 587 cp
    - Gregory *et al.* Correlation and Zhang *et al.* Model Perform better than Other Correlations
  - Developed New Closure Relationship
High Viscosity Multiphase Flow …

Current Studies

- Inclination Angle Effect Investigation (Jeyachandra)
  - Progress
    - Data Acquisition and Analysis for Downward and Upward Flows (-2° and +2°)
    - Evaluation
      - Pressure Drop Models (Unified, Xiao and OLGA)
      - Closure Relationships for Slugs Characteristics
High Viscosity Multiphase Flow ...

- Current Studies …
  - Holistic Analysis of Slug Flow Characteristics in Horizontal Pipes (Al-Safran)
  - Transition from Stratified Smooth to Other Flow Patterns (Brito and Pereyra)

- Progress
  - Experimental and Model Comparison is Completed

- Future Study
  - Lower Oil Viscosities
High Viscosity Multiphase Flow …

- Current Studies …
  - Medium Viscosity Study (20 cp – 200 cp) (Brito)
    - Progress
      - Developed a Comprehensive Data Processing Model and Software
      - Thoroughly Tested and Calibrated Capacitance Sensors
    - Near Future Activity
      - Testing After Fall 2011 ABM
Low Liquid Loading Flow

**Significance**
- Wet Gas Transportation
- Holdup and Pressure Drop Prediction
- Corrosion Inhibitor Delivery (Top of the Line Corrosion)

**Objectives**
- Develop Better Predictive Tools
Low Liquid Loading Flow …

• Past TUFFP Studies
  ➢ Two-phase, Small Diameter, Low Pressure
    ▶ Air-Water and Air-Oil
    ▶ 2-in. ID Pipe with ±2° Inclination Angles from Horizontal
  ➢ Two-phase, Large Diameter, Low Pressure
    ▶ Air-Water
    ▶ 6-in. ID and ±2° Inclination Angles from Horizontal
Low Liquid Loading Flow …

♦ Past TUFFP Studies …
  ➢ Three-phase, Large Diameter, Low Pressure
    ✈ Air-Mineral Oil-Water
    ✈ 6 in. ID, Horizontal Flow
  ✈ Findings
    ✦ Observed and Described Flow Patterns and Discovered a New Flow Pattern
    ✦ Acquired Significant Amount of Data on Various Parameters, Including Entrainment Fraction
  ✈ Remaining Tasks
    ✦ Development of Flow Pattern Detection Model
    ✦ Development of Improved Closure Relationships
Low Liquid Loading Flow …

Current Study (Gawas)
- Three-phase, Large Diameter, Low Pressure Inclined Flow
  - Air-Mineral Oil-Water
  - 6 in. ID and ±2° Inclination Angles from Horizontal

Objectives
- Acquire Similar Data as in Horizontal Flow Study
- Develop Improved Closure Relationships
Low Liquid Loading Flow …

- Progress
  - Design and Construction of a New Isokinetic Device with Multiple Probes
  - Droplet Field Image Capture

- Near Future Activity
  - Data Acquisition and Analysis
Up-Scaling Studies

- **Significance**
  - Better Design and Operation

- **Objective**
  - Testing and Improvement of Existing Models for Large Diameter and Relatively High Pressures

- **Past Studies**
  - Low Pressure and 6 in. ID Low Liquid Loading (Fan and Dong)
  - High Pressure 2 in. ID (Manabe)
Up-Scaling Studies …

- New High Pressure, Large Diameter Facility
  - HAZOP
    - SOP Preparation
    - Third Party Review
    - Chevron will Participate
Up-Scaling Studies …

- First Project
  - Investigation of Low Liquid Loading Flow of Two-phases in Large Diameter Horizontal and Inclined Flow at Elevated Pressures
    - Progress
      - Instrumentation Decided
    - Near Future Activity
      - Implementation
      - Testing and Data Acquisition
Effects of MEG on Multiphase Flow

Objectives

- Collect Flow Pattern, Holdup, Pressure Drop Data on a 6 in. ID Pipe With and Without MEG
- Benchmark Steady State Models and Document Errors
- Propose Improvements If Needed
Effects of MEG on Multiphase Flow

🌿 Progress
- Mr. Hamid Karami, Ph.D. Student Assigned to the Project
- Literature Review Underway

🌿 Near Future Activity
- Test Matrix
- Flow Loop Modification
Droplet Homo-phase Studies

- Significance
  - Better Predictive Tools Lead to Better Design and Practices

- General Objective
  - Development of Closure Relationships

- Past Study
  - Earlier TUFFP Study Showed
    - Entrainment Fraction (FE) is Most Sensitive Closure Parameter in Annular Flow
    - Developed New FE Correlation
      - Utilizing In-situ Flow Parameters
      - Limited Data, Especially for Inclined Flow Conditions
Droplet Homo-phase Studies …

- **Current Study**
  - Liquid Entrainment in Annular Two-Phase Flow in Inclined Pipes
  - Objectives
    - Develop Better Closure Relationships
Droplet Homo-phase Studies ...

- Status
  - Experimental Study is Completed
    - Entrainment Fraction is Found to Vary with Inclination Angle
    - Performance Analysis of the Existing Correlations is Completed
  - Closure Relationship Development
    - A New Relationship Developed Based on TUFFP and Other Data
Liquid Loading of Gas Wells

Objectives

- Explore Mechanism Controlling Onset of Liquid Loading
- Investigate Effects of Well Deviation on Liquid Loading

Ge (Max) Yuan is Research Assistant
Liquid Unloading from Gas Wells ...

✦ Past Studies
  ➢ Primarily on Droplet Transfer {Turner (1969), Coleman (1991), etc.}
  ➢ Film Reversal {Barnea (1987), Veeken (2009)}
  ➢ No Comprehensive Study on Inclination Angle Effect
Liquid Unloading from Gas Wells ...

- Progress
  - Data Acquisition Complete

- Near Future Activity
  - Data Analysis
  - Model Evaluation

- Study will Continue with Ms. Guner in 2012
Transient Modeling

Significance

- Industry has Capable All Purpose Transient Software
  - OLGA, PLAC, TACITE
- Efforts are Well Underway to Develop Next Generation All Purpose Transient Simulators
  - Horizon, LEDA
- Need for a Simple Transient Flow Simulator
Transient Modeling …

- **Objective**
  - Development and Testing of a Simple and Fast Transient Flow Simulator

- **Several TUFFP Studies**
  - Scoggins, Sharma, Dutta-Roy, Taitel, Vierkandt, Sarica, Vigneron, Minami, Gokdemir, Zhang, Tengesdal, and Beltran
Transient Modeling …

胚 Current Study (Choi)
  ➢ Approach is Changed
    ▶ Drift Flux is Chosen
    ▶ Development of a Simplified Isothermal Drift Flux Transient Model
      ✦ Simulator Structure Design
      ✦ Code Development (Explicit Solver)
Transient Modeling …

Future Work

- Properties Determination from Look-up Table Produced by PVTSim
- Extension of the Drift Flux Model to Segregated Flow Patterns
- Inclusion of Heat Transfer Model
- Implicit Scheme Implementation
Unified Model

- **Objective**
  - Develop and Maintain an Accurate and Reliable Steady State Multiphase Simulator

- **Past Studies**
  - Zhang *et al.* Developed “Unified Model” in 2002 for Two-phase Flow
    - Became TUFFP’s Flagship Steady State Simulator
    - Applicable for All Inclination Angles
  - “Unified Model was Extended to Three-phase in 2006
Unified Model …

- **Current Projects**
  - Code and Software Improvement Efforts
  - Extension of Heat Transfer Model to Three Phase Flow (Zheng)
    - Progress
      - Literature Review
      - Model Development Plan
    - Near Future Activity
      - Model Development
Multiphase Flow Modeling Using Energy Minimization Concept

- **Past**
  - Sharma (2009) Successfully Applied the Concept to Oil/Water Flow

- **Objective of Current Project**
  - Apply Energy Minimization Approach for Gas/Liquid Flow
    - Objective Function Determination
      - Energy Equation in Meso-Scale and Macro Scale
    - Definition of Constrain Functions Based on Gas/Liquid Physics
Multiphase Flow Modeling Using Energy Minimization Concept …

🌟 Status

➢ Hoyoung Lee, Visiting Scholar from SNU is Assigned to the Project
➢ Project was on Hold Due to Mr. Lee’s Military Service Obligations in His Home Country
Multiphase Flow Modeling Using Energy Minimization Concept …

Future Work

- Define the Energy Equations and Constrains for Different Gas/Liquid Configurations
- Identify Independent Variables
- Formulation of Minimization Problem
- Model Experimental Data Comparison
Fluid Flow Projects

Effect of Pipe Inclination on Flow Characteristics of High Viscosity Oil-Gas Two-Phase Flow

Benin Chelinsky Jeyachandra

Advisory Board Meeting, October 26, 2011
Outline

- Objectives
- Introduction
- Experimental Program
- Flow Characteristics
  - Test Results
  - Model Comparison
- Conclusions
- Recommendations
Objectives

- Acquire Experimental Data on Flow Characteristics for High Viscosity Oil-Gas Two-Phase Flow
  - Inclination Effects
  - Viscosity Effects
- Validate Models/Correlation with Experimental Results
Introduction

- Increase in High Viscosity Oil Offshore Discoveries
- Current Multiphase Flow Models Developed for Low Viscosity Oils
- Multiphase Flows May Exhibit Significantly Different Behavior for Higher Viscosity Oils
Experimental Matrix

- **Superficial Liquid Velocity**
  - 0.1 – 0.8 m/s
- **Superficial Gas Velocity**
  - 0.1 – 3.5 m/s
- **Temperatures**
  - 21.1 – 37.8 °C (70 – 100 °F)
  - 585 – 181 cP
- **Inclination**
  - -2° and +2° from Horizontal
Two Phase Flow Characteristics

- Flow Pattern
- Pressure Gradient
- Average Liquid Holdup
- Slug Length
- Slug Frequency
- Slug Liquid Holdup
- Translational Velocity
- Drift Velocity
1. Flow Patterns

A. Downward Inclined Flow
Viscosity Effects- 585 cP Viscosity Oil-Air vs. Water-Air Downward Inclined Two-Phase Flow

Graph showing different flow regimes:
- DB (Dominated Bubble)
- SL (Slug)
- SW (Sluggish)
- SS (Slug and Slug)
- Annular

Parameters:
- $v_{SL}$ (m/s)
- $v_{SG}$ (m/s)
Viscosity Effects - 181 cP Viscosity Oil-Air vs. Water-Air Downward Inclined Two-Phase Flow

- Elongated Bubble
- Slug Flow
- Stratified
- Annular

Flow Patterns:
- DB (Diameter Bubble)
- SW (Slug)
- SS (Suspended Slugs)

Graph showing the relationship between $v_{SL}$ (m/s) and $v_{SG}$ (m/s) with different flow regimes indicated.
Downward Inclined Flow vs. TUFFP Model Prediction

Dispersed

Intermittent

Stratified

Annular

585 cP

181 cP
Downward Inclined Flow vs. Barnea Model Prediction

\begin{align*}
\text{v}_{SL} &\quad (\text{m/s}) \\
\text{v}_{SG} &\quad (\text{m/s})
\end{align*}

- **Dispersed Bubble**
- **Elongated Bubble**
- **Slug Flow**
- **Annular**
- **Stratified**

**Properties**

- **585 cP**
- **181 cP**

Advisory Board Meeting, October 26, 2011
Fluid Flow Projects

1. Flow Patterns

B. Upward Inclined Flow

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Viscosity Effects - 585 cP Viscosity Oil-Air vs. Water-Air Two-Phase Flow

The diagram illustrates the viscosities of different flow patterns as a function of superficial velocities. The x-axis represents $v_{SG}$ (m/s), while the y-axis represents $v_{SL}$ (m/s). The flow patterns are labeled as:

- DB: Annular
- EB: Elongated Bubble
- Slug
- Annular
- ST

The data points and lines help to visualize the transition between different flow regimes under varying viscosities.
Inclination Effects- Horizontal vs. Upward Inclined 585 cP Viscosity Oil-Air Flow
Downward Inclined Flow vs. TUFFP Model Prediction

Dispersed Bubble

Intermittent

Annular

585 cP

181 cP

Advisory Board Meeting, October 26, 2011
Upward Inclined Flow vs. Barnea Model Prediction

$v_{SG} (m/s)$

585 cP

181 cP
2. Pressure Gradient

A. Downward Inclined Flow
Inclination Effects - Pressure Gradients for $v_{SL} = 0.1 \text{ m/s}$

The graph shows the relationship between $dP/dL$ (Pa/m) and $v_{SG}$ (m/s) for different dynamic viscosities ($\mu_o$). The graph includes data points for $\mu_o = 0.587 \text{ Pa·s}$, $0.378 \text{ Pa·s}$, $0.257 \text{ Pa·s}$, and $0.181 \text{ Pa·s}$ at various inclinations.
Inclination Effects - Pressure Gradients for $v_{SL}=0.8$ m/s

![Graph showing pressure gradients for different inclinations and viscosities.](image-url)
## Error Analysis

<table>
<thead>
<tr>
<th>Correlation/Model</th>
<th>Statistical Parameters</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$\varepsilon_1$ (%)</td>
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<tr>
<td>TUFFP Unified Model</td>
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<tr>
<td>OLGA-S</td>
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<tr>
<td>Xiao (1990)</td>
<td>-37.29</td>
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</tbody>
</table>
Fluid Flow Projects

2. Pressure Gradient

B. Upward Inclined Flow

Advisory Board Meeting, October 26, 2010
Inclination Effects - Pressure Gradients for $v_{SL}=0.1 \text{ m/s}$

![Graph showing pressure gradients for different viscosity values at various inclinations.]

- $\mu_0=0.587 \text{ Pa} \cdot \text{s}$
- $\mu_0=0.378 \text{ Pa} \cdot \text{s}$
- $\mu_0=0.257 \text{ Pa} \cdot \text{s}$
- $\mu_0=0.181 \text{ Pa} \cdot \text{s}$
- $\mu_0=0.587 \text{ Pa} \cdot \text{s} \ (0^\circ)$
- $\mu_0=0.181 \text{ Pa} \cdot \text{s} \ (0^\circ)$
Inclination Effects - Pressure Gradients for $v_{SL} = 0.8 \text{ m/s}$

The graph illustrates the change in pressure gradient ($dP/dL$) with respect to $v_{SG}$ (m/s) for different viscosities ($\mu_0$) and inclinations. The data points are color-coded to differentiate between various viscosities:

- $\mu_0 = 0.587 \text{ Pa·s}$ (blue diamonds)
- $\mu_0 = 0.378 \text{ Pa·s}$ (red squares)
- $\mu_0 = 0.257 \text{ Pa·s}$ (green triangles)
- $\mu_0 = 0.181 \text{ Pa·s}$ (purple crosses)
- $\mu_0 = 0.587 \text{ Pa·s} (0^\circ)$ (orange dots)
- $\mu_0 = 0.181 \text{ Pa·s} (0^\circ)$ (brown dots)
# Error Analysis

<table>
<thead>
<tr>
<th>Correlation/Model</th>
<th>Statistical Parameters</th>
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<tbody>
<tr>
<td></td>
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<td>TUFFP Unified Model</td>
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<td>Xiao (1990)</td>
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</table>
Fluid Flow Projects

3. Slug Liquid Holdup

A. Downward Inclined Flow
Velocity Effects - Slug Liquid Holdup for 585 cP Viscosity Oil-Air Flow

![Graph showing velocity effects on slug liquid holdup](image)
Inclination Effects - Downward and Horizontal Slug Liquid Holdup for $v_{SL} = 0.3 \text{ m/s}$
Fluid Flow Projects

3. Slug Liquid Holdup

B. Upward Inclined Flow

Advisory Board Meeting, October 26, 2011
Velocity Effects- Slug Liquid Holdup for 585 cP Viscosity Oil-Air Flow

![Graph showing the effect of velocity on slug liquid holdup]
Inclination Effects - Upward and Horizontal Slug Liquid Holdup for \( v_{SL} = 0.3 \text{ m/s} \)
4. Slug Frequency

A. Downward Inclined Flow
Velocity Effects - Slug Frequency for 585 cP Viscosity Oil-Air Flow

![Graph showing velocity effects and slug frequency for 585 cP viscosity oil-air flow.](image)
Downward Slug frequency Comparison with Horizontal for $v_{SL} = 0.3 \text{ m/s}$

![Graph showing the comparison of downward slug frequency with horizontal flow for different viscosities and velocities.](image)
4. Slug Frequency

B. Upward Inclined Flow
Velocity Effects- Slug Frequency for 585 cP Viscosity Oil-Air Flow

\[ n_s (1/s) \]

\[ v_{SG} (m/s) \]

- \( v_{SL} = 0.1 \, m/s \)
- \( v_{SL} = 0.3 \, m/s \)
- \( v_{SL} = 0.5 \, m/s \)
- \( v_{SL} = 0.8 \, m/s \)
Upward Slug frequency Comparison with Horizontal for $v_{SL} = 0.3$ m/s

Graph showing the comparison of upward slug frequency ($n_s$) with horizontal flow for different viscosities ($\mu_o$) and flow rates ($v_{SG}$). The graph includes data points for $\mu_o = 0.587$ Pa·s, $\mu_o = 0.181$ Pa·s, and $\mu_o = 0.587$ Pa·s (0°).
Fluid Flow Projects

5. Slug Length

A. Downward Inclined Flow

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Viscosity Effects in Slug Length

![Graph showing the effect of viscosity on slug length. The graph plots $L_s/D$ against $v_{SG}$ (m/s). Two different viscosities are shown: $\mu_o = 0.587$ Pa·s (blue diamonds) and $\mu_o = 0.181$ Pa·s (red squares).]
Comparison of Downward Inclined and Horizontal Slug Length for 585 cP Viscosity Oil–Air Flow

- $v_{SL}=0.8 \text{ m/s}$ (0°)
- $v_{SL}=0.1 \text{ m/s}$ (0°)
- $v_{SL}=0.1 \text{ m/s}$ (0°)
- $v_{SL}=0.8 \text{ m/s}$ (0°)
5. Slug Length

B. Upward Inclined Flow
Viscosity Effects in Slug Length

$L_s/D (-)$ vs. $v_{SG} (m/s)$

- $\mu_O = 0.587 \text{ Pa} \cdot \text{s}$ (diamonds)
- $\mu_O = 0.181 \text{ Pa} \cdot \text{s}$ (squares)

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Comparison of Downward Inclined and Horizontal Slug Length for 585 cP Viscosity Oil–Air Flow

![Graph showing comparison of downward inclined and horizontal slug length for 585 cP viscosity oil–air flow.](image)

- $L_s/D$ vs $v_{SG} (m/s)$
- Symbols represent different slug velocities:
  - $v_{SL} = 0.1 m/s$
  - $v_{SL} = 0.8 m/s$
  - $v_{SL} = 0.1 m/s (0°)$
  - $v_{SL} = 0.8 m/s (0°)$

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6. Translational Velocity

A. Downward Inclined Flow
Inclination Effects in Translational Velocity

\[ v_T (m/s) \]

\[ v_M (m/s) \]

\[ \mu_0 = 0.587 \text{ Pa}\cdot\text{s} \]

\[ \mu_0 = 0.181 \text{ Pa}\cdot\text{s} \]

\[ \mu_0 = 0.587 \text{ Pa}\cdot\text{s} (0^\circ) \]

\[ \mu_0 = 0.181 \text{ Pa}\cdot\text{s} (0^\circ) \]
6. Translational Velocity

B. Upward Inclined Flow
Inclination Effects in Translational Velocity

\[ v_T (\text{m/s}) \]

\[ v_M (\text{m/s}) \]

- \( \mu_0 = 0.587 \text{ Pa}\cdot\text{s} \)
- \( \mu_0 = 0.181 \text{ Pa}\cdot\text{s} \)

\( \mu_0 = 0.587 \text{ Pa}\cdot\text{s} \text{ (0°)} \)

\( \mu_0 = 0.181 \text{ Pa}\cdot\text{s} \text{ (0°)} \)
Conclusion

- Experimentation for Two Phase Flow Characteristics on -2° and +2° Inclination Completed
- Flow Characteristics
  - Flow Pattern
  - Pressure Gradient
  - Slug Liquid Holdup
  - Slug Length
  - Slug Frequency
  - Translational Velocity
  - Drift Velocity
Fluid Flow Projects

Downward Two-Phase Stratified Flow for Highly Viscous Oils

R. Brito, E. Pereyra and C. Sarica

Advisory Board Meeting, October 26, 2011
Outline

- Introduction
- Objective
- Experimental Program and Results
- Wave Pattern for Stratified Region
- Stratified Smooth – Stratified Wavy Transition
- Stratified – Non-Stratified Transition
- Conclusions
- Future Tasks
Introduction

- Observed Flow Pattern vs. Shoham (1982) Data

![Graph showing observed flow patterns compared to Shoham (1982) data. The x-axis represents V_{SG} (m/s) ranging from 0.01 to 100, and the y-axis represents V_{SL} (m/s) ranging from 0.001 to 10. The graph includes lines labeled D-B, SL, ANN, S-S, and S-W. Shoham (1982) Transition Lines are also indicated.]
Introduction

- Observed Flow Pattern vs. Shoham (1982) Data

![Graph showing observed flow patterns and comparison with Shoham (1982) data. The graph plots $V_{SL}$ (m/s) against $V_{SG}$ (m/s) with different symbols and lines representing flow patterns such as D-B, SL, SS, EB, and ANN. The graph includes data points and curves to illustrate the observed flow patterns.]
Objective

- Experimental and Theoretical Study of Transition Phenomenon from Stratified-Smooth to Stratified-Wavy for Downward flow (-2°) and High Viscosity Oil (181 cP)
Outline

- Introduction
- Objective
- *Experimental Program and Results*
Experimental Program

- 2-in ID High Viscosity Indoor Facility
- Superficial Liquid Velocity
  - 0.01 – 0.8 m/s
- Superficial Gas Velocity
  - 0 – 7.2 m/s
- Inclination
  - Downward (-2°)
Experimental Program ...

- **Test Liquid: Citgo 220 Mineral Oil**
  - Gravity: 27.6 °API
  - Density: 889 kg/m³ @ 60 °F
  - Pour Point: 10 °F
  - Flash Point: 482 °F
  - Viscosity: 181 cP @ 100 °F

- **Test Gas: Air**
Experimental Results

- Observed Flow Pattern vs. Shoham (1982) Data

![Diagram showing observed flow patterns and data points compared to Shoham (1982) data. The diagram includes symbols for different flow patterns and data points plotted against V_{SL} (m/s) and V_{SG} (m/s).]

- **EB**: Error Bars
- **SL**: Shoham Data (1982)
- **SS**: Solid Surface
- **SW**: Slow Water

- **V_{SL} (m/s)**
- **V_{SG} (m/s)**

Data points are scattered across the graph, indicating the observed flow patterns and their comparison with the theoretical data from Shoham (1982).
Outline

- Introduction
- Objective
- Experimental Program and Results
- Wave Pattern for Stratified Region
Wave Pattern

- Andritsos and Hanratty (1986)
  - Studied the Interfacial Instability of Stratified Horizontal Flow
  - $\mu_o = 1 \text{ cP} - 70 \text{ cP}$
  - Three Types of Instabilities has been Observed
    - 2-D Small Amplitude Waves
    - Irregular Large Amplitude Waves
    - Atomization
  - 2-D Waves Region Attenuates as Liquid Viscosity Increases
Wave Pattern...

- Interfacial Instabilities after Andritsos and Hanratty (1986)
Wave Pattern...

- Large Amplitude Waves

*Long Waves*

\[ v_{SG} = 5.5 \text{ m/s and } v_{SL} = 0.03 \text{ m/s} \]

*Breaking Waves*

\[ v_{SG} = 4.5 \text{ m/s and } v_{SL} = 0.09 \text{ m/s} \]
Wave Pattern…

Film Thickness Time Traces for $v_{SG}=4.5$ m/s
Wave Pattern...

Film Thickness Time Traces for $v_{SG}=4.5$ m/s
Wave Pattern...

Film Thickness Time Traces for $v_{SL} = 0.03 \text{ m/s}$
Outline

- Introduction
- Objective
- Experimental Program and Results
- Wave Pattern for Stratified Region
- Stratified Smooth – Stratified Wavy Transition
Stratified Smooth – Stratified Wavy

- Observed Flow Pattern vs. Shoham (1982) Data

![Graph showing different flow patterns and their corresponding velocities.](image-url)
Stratified Smooth – Stratified Wavy …

- Barnea et al. (1982)

- Waves Generated by Gravity in Downward Flow

\[ Fr = \frac{v_L}{\sqrt{g h_L}} \geq 1.5 \]
Stratified Smooth – Stratified Wavy ...

- Froude Number Criterion Sensitivity
Stratified Smooth – Stratified Wavy…

Jeffrey’s Theory

Potential Flow Field
Pressure and Shear Forces > Viscous Dissipation of Waves

\[ v_G \geq \left[ \frac{4 \mu_L (\rho_L - \rho_G) g \cos \theta}{s \rho_L \rho_G v_L} \right]^{0.5} \]

s: fraction of wave exposed to the action of the wind
Stratified Smooth – Stratified Wavy ...

- Sheltering Coefficient Sensitivity

![Graph showing Sheltering Coefficient Sensitivity](graph.png)
Outline

- Introduction
- Objective
- Experimental Program and Results
- Wave Pattern for Stratified Region
- Stratified Smooth - Stratified Wavy Transition
- Stratified – Non-Stratified Transition
Stratified – Non-Stratified

- Slug Flow Stability Analysis (Zhang et al., 2003)
  - $I_F / I_U > 1$ Transition to Stratified or Annular Flow
Stratified – Non-Stratified ...

- Stability of the Gas-Liquid Interface
  - *Kelvin-Helmholtz Analysis*
    - Two Fluid Model
    - Linearization
    - Perturb the Linear Model with a Monochromatic Wave

\[ v_G - v_L < K \sqrt{\left( \rho_L (1 - H_L) + \rho_G H_L \right) \left( \frac{\rho_L - \rho_G}{\rho_L \rho_G} g \cos(\theta) \frac{A}{dA_L} / dh_L \right)} \]
Stratified – Non-Stratified …

**Stability of the Gas-Liquid Interface**

- **Calculate** $h_L/d$

- **Critical Velocity**

- **Stable Interface?**
  - Yes
  - **ST**
  - No
  - **N-ST**

**Equation**

$$v_c = K \sqrt{\left(\rho_L (1-H_L) + \rho_G H_L\right) \frac{\left(\rho_L - \rho_G\right)}{\rho_L \rho_G} g \cos(\theta) \frac{A}{dA_L/dh_L}}$$
## Stability Analysis Models

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<th>Model</th>
<th>Considerations</th>
<th>$K$</th>
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<td>Taitel &amp; Dukler (1976)</td>
<td>Suction force $\geq$ Gravity Force</td>
<td>$K = \left(1 - \frac{h_L}{d}\right)$</td>
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<tr>
<td>IKH</td>
<td>Do not consider viscous effect on stability analysis.</td>
<td>$K=1$</td>
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<td>VKH Barnea (1991)</td>
<td>Consider the viscous effect using the shear stresses between the wall and each phase.</td>
<td>$K = \sqrt{1 - \frac{(C_r - C_w)^2}{(\rho_L - \rho_G) \cdot g \cos(\theta)} \cdot \frac{A}{\partial A_L/\partial h_L}}$</td>
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</table>
Stability Analysis Model …

- Taitel and Dukler (1976) Sensitivity Analysis

![Graph showing VSL vs VSG with different viscosity and angle settings](image-url)
Taitel and Dukler (1976) Sensitivity Analysis
Stratified – Non-Stratified …

Model Comparison

![Graph showing model comparison between stratified (ST) and non-stratified (N-ST) conditions with various model names and data points.](chart.png)
Outline

- Introduction
- Objective
- Experimental Program and Results
- Wave Pattern for Stratified Region
- Stratified Smooth to Stratified Wavy Transition
- Stratified to Non Stratified Transition
- Conclusions
Conclusions

- 2-D Small Amplitude Waves Do not Occur for a High Viscosity Oil (181 cP)
- Gravity Waves Have not been Observed for Downward flow (-2°) and High Viscosity Oil (181 cP)
- Barnea et al. (1982) Does not Apply for the Considered High Viscosity Oil
Conclusions ...

- Transition from Stratified to Dispersed Bubble Has not been Observed as Water-Air Two-Phase Flow
- None of the Model are Completely Satisfactory and Further Modeling Work is Required
Future Tasks

- Further Experiments Will be Run for Different Medium Oil Viscosities to Verify the Transition from Stratified-Smooth to Stratified-Wavy (*Summer-2012*)
Thanks ...
Questions
Fluidd Flow Projects

Effect of Medium Oil Viscosity on Two-Phase Oil-Gas Flow Behavior in Horizontal Pipes

Rosmer Brito

Advisory Board Meeting, October 26, 2011
Outline

- Objectives
- Experimental Program
- Capacitance Sensor Calibration
- Data Acquisition and Processing
- Uncertainty Analysis
- Future Tasks
General Objective

♦ Experimental and Modeling Study of Oil-Gas Two Phase Flow to Investigate the Effects of Medium Viscosity Oil (33 cP - 129 cP)
  ➢ Flow Pattern
  ➢ Pressure Drop
  ➢ Liquid Holdup
  ➢ Slug Characteristics
Specific Objective

- Data Analysis Process

Results Quality
Results Consistency

Time
Random Error
Specific Objectives …

- Uncertainty Analysis for Each Data Point \((v_{SLi}, v_{SGi})\)
  - Flow Conditions
  - Fluid Properties
  - Pressure Gradient
  - Slug Characteristics
Fluid Flow Projects

Experimental Program

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2-in ID High Viscosity Indoor Experimental Facility
- Test Section
- Metering Section
- Heating System
- Cooling System
Test Oil Characteristics

- **Test Liquid: DN-20 Mineral Oil**
  - Gravity: 30.5 °API
  - Density: 873 kg/m³ @ 60 °F
  - Surface Tension: 27.5 dynes/cm
  - Pour Point: -5 °F
  - Flash Point: 435 °F

- **Test Gas: Air**
Test Oil Characteristics ...

**Oil Viscosity vs. Temperature Curve**

- 70 °F ; 129 cP
- 85 °F ; 86 cP
- 105 °F ; 50 cP
- 120 °F ; 33 cP
Experimental Matrix

- Superficial Liquid Velocity
  - 0.01 – 3 m/s

- Superficial Gas Velocity
  - 0.1 – 5 m/s

- Inclination
  - Horizontal
Experimental Matrix ...

Flow Pattern Map 33 cP. TUFFP Unified Model

![Graph showing flow pattern map with markers for INT, STR, and ANN]
Experimental Matrix ...

Flow Pattern Map 129 cP. TUFFP Unified Model

\[ V_{5G} (m/s) \]

\[ V_{SG} (m/s) \]

INT

D-B

ANN

STR

Data Point

INT_STR

INT_D-B

STR_ANNE

Fluid Flow Projects

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Experimental Matrix ...

**Flow Pattern Map 33 cP. Barnea Model**

- **DB**
- **EB**
- **ANN**
- **SS**

Graph showing the relationship between $V_{SL}$ (m/s) and $V_{SG}$ (m/s) with different flow patterns represented by lines and symbols.
Experimental Matrix ...

Flow Pattern Map 129 cP. Barnea Model

- DB
- EB
- ANN
- SS

Graph showing:
- $V_{SL} (\text{m/s})$ on the y-axis
- $V_{SG} (\text{m/s})$ on the x-axis
- Data Points
- Lines indicating different flow patterns:
  - STR_N-S
  - SW_AN
  - SS_SW
  - IN_AN
  - EB_SL

Legend:
- Data Point
Fluid Flow Projects

Capacitance Sensor

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Capacitance Sensor

Ring Type Capacitance Sensor

Capacitance Sensors Location
Capacitance Sensor
Static Calibration

Static Calibration
Capacitance Sensor Static Calibration ...

\[ V' = \frac{V_{\text{read}} - V_{\text{min}}}{V_{\text{max}} - V_{\text{min}}} \]

Static Calibration Curve
Fluid Temperature Effect

Output Voltage vs. Fluid Temperature Curve

Voltage (V) vs. Fluid Temperature (°F)

- FULL PIPE
- 960 CC
- HALF PIPE
- 300 CC
- EMPTY PIPE

ΔV
Fluid Temperature Effect ...

Holdup Measurement Discrepancy

\[ V' = \frac{V_{\text{read}} - V_{\text{min @ 70°F}}}{V_{\text{max @ 70°F}} - V_{\text{min @ 70°F}}} \]
Fluid Temperature Effect...

**Temperature Compensation**

\[ V'_{\text{corrected}} = \frac{V_{\text{read}} - V_{\text{min @ T}_\text{fluid}}}{V_{\text{max @ T}_\text{fluid}} - V_{\text{min @ T}_\text{fluid}}} \]

Graph showing temperature compensation with points for 70 F, 75 F, 80 F, 90 F, and 100 F.
Fluid Flow Projects

Data Acquisition and Processing

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## Input Data

### Quality Validation and Setup

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<tr>
<th>Test Name:</th>
<th>Test Description:</th>
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### SETUP

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### Input Data

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Input Data

Quality Validation and Setup ...
Fluid Flow Projects

Input Data

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Calculations

- Slug Flow
  - Single Case
  - Sensitivity Case
- Stratified Annular Dispersed Bubble
  - Single Case
Calculations
(All Flow Patterns)

Average and Uncertainty for:

- Pressure Gradient
- Pressure
- Temperature
- Fluid Properties:
  - Mass Flow Rate
  - Density
  - Viscosity
- Superficial Velocities
- Mixture Velocity
- Reynolds Number
- Average Liquid Holdup

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Calculations

(Single Case – Slug Flow)

Average and Uncertainty
- $H_{L, av}, H_{L, LS}$ (Dynamic Calibration), $H_{L, LF}$ (Static Calibration)
- $n_{slug}$
- Slug Length Distribution
- Slug Frequency
- Translational Velocity
  - Cross-Correlation
  - Time of Flight ($v_t, v_{tf}, v_{tb}$)
- $L_{slug\_CC}, L_{slug\_FT}$
- $L_{slug\_max\_CC}, L_{slug\_max\_FT}$
- $L_{slug\_min\_CC}, L_{slug\_min\_FT}$
### Calculations

**(Single Case – Slug Flow)**

#### Limitation

Uncertainty for $n_{\text{slug}}$, $\nu$ and $v_t$ cannot be determined.
Calculations
(Threshold Sensitivity Case – Slug Flow)

Average and Uncertainty
- $H_{L, av}$, $H_{L, LS}$, $H_{L, LF}$
- $n_{slug}$
- Slug Length Distribution
- Slug Frequency
- Translational Velocity
  - Cross-Correlation
  - Time of Flight ($v_t$, $v_{tf}$, $v_{tb}$)
- $L_{slug_{CC}}$, $L_{slug_{FT}}$
- $L_{slug_{max_{CC}}}$, $L_{slug_{max_{FT}}}$
- $L_{slug_{min_{CC}}}$, $L_{slug_{min_{FT}}}$

Min $\leq$ Threshold $\leq$ Max
(Monte Carlo)
Calculations
(Threshold Sensitivity Case. Slug Flow) …
Calculations
Flow Behavior Evolution

Fluid Flow Projects

Advisory Board Meeting, October 26, 2011


Uncertainty Analysis

Uncertainty Model

\[ U_{ASME} = \pm 2 \left[ (b_R)^2 + (S_{\bar{X},R})^2 \right]^{0.5} \]

- Pressure Gradient
- Pressure
- Temperature
- Average Liquid Holdup
- Mass Flow Rate

\[ S_{X,i} = \left[ \frac{\sum_{k=1}^{N_i} (X_{i,k} - \bar{X}_i)}{N_i - 1} \right]^{1/2} \]

\[ S_{\bar{X},i} = \frac{S_{X,i}}{\sqrt{N_i}} \]

\[ S_{\bar{X},R} = \left[ \sum_{i=1}^{N_i} (S_{\bar{X},i})^2 \right]^{1/2} \]
Fluid Properties:
- Density
- Viscosity

Superficial Velocities
- Mixed Velocity
- Mixed Reynolds Number
Uncertainty Analysis ...

Slug Characterization

P05

P50

P95

U1

U2
Output Data Quality Validation

High U

• Repeat Point
• Check Instrumentation

Low U

• Export Data point to the Macro Data Base Excel File
## Future Tasks

<table>
<thead>
<tr>
<th>Task</th>
<th>Due Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaluate the Effect of the Inlet Geometry on the Flow Behavior</td>
<td>October 2011</td>
</tr>
<tr>
<td>Experimental Program Execution for Medium Oil Viscosity</td>
<td>February 2011</td>
</tr>
<tr>
<td>Data Analysis</td>
<td>April 2011</td>
</tr>
<tr>
<td>Model Verification or Develop New Ones (if Necessary)</td>
<td>May 2012</td>
</tr>
<tr>
<td>Write Thesis</td>
<td>Jun 2012</td>
</tr>
</tbody>
</table>
Thanks ...
Questions
Characterization of High Viscosity Slug Flow in Horizontal Pipes

Eissa Al-safran (KU/KOC)
Introduction

- Slug Flow Characteristics are Critical in Design and Operation of Multiphase System
- Interrelationship among Slug Flow Characteristics are Critical in Understanding and Predicting Slug Flow
- High Viscosity Effect on Slug Flow Characteristics is Poorly Understood, yet Important
Objectives

- Understand and Model High Viscosity Effect on Slug Liquid Holdup in Horizontal Pipes
- Develop a Physical Model to Explain Slug Flow Characteristics Interaction under the Condition of High Viscosity Flow
Slug Liquid Holdup

- Generally, Gas Bubble Entry Mechanisms into Slug Body Are:
  - Entrainment Due to Shear at Film and Upper Wall
  - Entrainment Due to Slug Front Circulation and Vortex Motion
  - Gas Carryover from Aerated Film
 Slug Liquid Holdup . . .

Gas Entrainment and Transport in Low Liquid Viscosity Slug

\[ q_{Trans} = q_{Shed} = q_{Gen} - q_{Loss} \]
Slug Liquid Holdup . . .

- **High Liquid Viscosity Effect**
  - Low Turbulence Intensity in Mixing Zone and Circulation/Vortex Motion Reduces Gas Entrainment
  - Entrainment Mechanism by Slug Front Folding Entraining Large Bubbles
  - High Bubble Rise Velocity and Loss Rate in Slug Front
 Slug Liquid Holdup . . .

- Gas Carryover by Aerated Liquid Layer Due to High Bubble Retention Time and Short Film Length
- Thick Film Increases Taylor Bubble Velocity and Reduces Entrainment from Taylor Bubble Tail
- Less Bubble Fragmentation Due to Low Turbulence Energy Produces Large Mean Bubble Diameter
Slug Liquid Holdup . . .

- Large Mean Bubble Diameter in Slug Developed Region Increases Bubble Rise Velocity
- Large Bubble Accumulation at Upper Pipe Wall Increases Bubble Shedding Rate
Slug Liquid Holdup . . .

\[ q_{Gen} + q_{C-over} - q_{Loss} = q_{Trans} = q_{Shed} + q_{C-over} \]
 Slug Liquid Holdup . . .

- Slug Front Entrainment Behavior ($v_{SL}=0.01$ m/s, $v_{Sg}=1.5$ m/s)

$\mu=0.590$ Pa.s

$\mu=0.182$ Pa.s
 Slug Liquid Holdup . . .

- Water Slug Liquid Holdup is Higher Than High Viscosity Oil Liquid Holdup
  - Higher Surface Tension Produces Large Bubble Diameters in Mixing Zone
  - Increase in Bubble Rise Velocity, Thus Loss Rate in Slug Front
- High Water Critical Mixture Velocity to Aerate Slug
  - No Gas Carryover in Liquid Film
Slug Liquid Holdup . . .

- **Medium Viscosity Oil**
  - Moderate Aeration Critical Mixture Velocity \( (v_m = 1.8 \text{ m/s}) \)

- **High Viscosity Oil**
  - Lower Aeration Critical Mixture Velocity \( (v_m = 0.6 \text{ m/s}) \)

- Slug Liquid Holdup Matches Beyond Aeration Critical Velocity for Medium and High Viscosity Oils
Modeling Slug Liquid Holdup

Ceyda et al. (2010)

\[ N_{Fr} = \frac{v_m}{(gd)^{0.5}} \sqrt{\frac{\rho_L}{\rho_L - \rho_g}} \]

\[ N_{\mu} = \frac{v_m \mu_L}{gd^2(\rho_L - \rho_g)} \]

\[ H_{Ls} = 1.012e^{(-0.085 F_r N_{\mu}^{0.2})} \quad \text{For } 0.15 < N_{Fr} N_{\mu} 0.2 < 1.5 \]

\[ H_{Ls} = 0.9473e^{(-0.041 F_r N_{\mu}^{0.2})} \quad \text{For } N_{Fr} N_{\mu} 0.2 \geq 1.5 \]

\[ H_{Ls} = 1.0 \quad \text{For } N_{Fr} N_{\mu} 0.2 \leq 0.15 \]
Non-Linear Modeling

\[ H_{Ls} = 0.85 - 0.0752 \left( N_{Fr} N_{\mu}^{0.2} - 0.8956 \right) + 0.0568 \left( N_{Fr} N_{\mu}^{0.2} - 0.8956 \right)^2 + 2.268 \right)^{0.5} \]
Modeling Slug Liquid Holdup . . .

APE (%) -0.0574
AAPE (%) 0.8363
SD (%) 1.024
Slag Characteristics Interaction

- Slug Front (Translational) Velocity Has a Significant Effect on Slug Characteristics
  - Gokcal et al. (2009) Showed a Decreasing Effect of Liquid Viscosity on Slug Front Velocity
  - Slug Front Velocity Increase Results in Slug Aeration and a Decrease in Slug Liquid Holdup
 Slug Characteristics Interaction . . .

\[ v_l \text{ (m/s)} \]

\[ H_l \text{ (-)} \]

- \( \text{vis.}=181 \text{ mPa.s (cp)} \)
- \( \text{vis.}=257 \text{ mPa.s (cp)} \)
- \( \text{vis.}=378 \text{ mPa.s (cp)} \)
- \( \text{vis.}=587 \text{ mPa.s (cp)} \)
Slug Characteristics Interaction

- Slug Frequency is Proportional to Film Thickness and Liquid Viscosity

![Graph showing the relationship between Slug Frequency ($F_s$) and Film Height ($H_{LF}$) with different viscosities. The graph indicates that as viscosity increases, the frequency decreases.](image-url)
 Slug Characteristics Interaction . . .

Slug Liquid Holdup is Proportional to Film Thickness and Liquid Viscosity

![Graph showing the relationship between Slug Liquid Holdup and Film Thickness with varying viscosities.](image)

- Viscosity Increases

- Film Thickness (in.) vs. Slug Liquid Holdup (\( H_{Ls} \))

- Viscosities: 587 mPa.s (cp), 378 mPa.s (cp), 257 mPa.s (cp), 181 mPa.s (cp)
Future Work

- Slug Liquid Holdup Model Uncertainty Analysis
- Slug Liquid Holdup Model Validation and Comparison
- Investigate High Viscosity Slug Characteristics Interactions
- Develop Physical Model for High Viscosity Slug Flow Characteristics
Low Liquid Loading
Gas-Oil-Water Flow

Kiran Gawas
Outline

- Objectives
- Introduction
- Experimental Overview
- Experimental Study
- Near Future Tasks
Objectives

- Acquire Experimental Data of Low Liquid Loading Gas-Oil-Water Flow in Horizontal and Near Horizontal Pipes Using Representative Fluids
- Check Suitability of Available Models for Low Liquid Loading Three Phase Flow and Suggest Improvements If Needed
Introduction

- Low Liquid Loading Flows Correspond to Liquid to Gas Ratio $\leq 1100$ m$^3$/MMsm$^3$
- Small Amounts of Liquid Influences Pressure Distribution – Hydrate Formation, Pigging Frequency, Downstream Equipment Design etc.
- Transport of Additives
- Very Few Experiments For Large Diameter Pipes
- Up-scaling of Available Models
Experimental Overview

- Very Little Data for Three Phase Flow Studies
- Experimental Data for Gas-Liquid Flow in Low Liquid Loading Regimes Also Limited
- Most of the Data for Smaller Diameter Pipes (1 to 3 inches)
- Dong (2007) - Only Study in Three Phase Low Liquid Loading
  - Observed New Liquid-Liquid Flow Pattern
  - Tests for Horizontal Pipe and Oil Viscosity Higher Than Wet Gas Condensate Viscosity
Experimental Study

- Experimental Facility
- Test Section
- Test Fluids
- Measurement Techniques
- Experimental Program
- Results
Experimental Facility
Test Section
Test Fluids

- **Test Fluid**
  - **Gas – Air**
  - **Water – Tap Water**
    \[ \rho = 1000 \text{ kg/m}^3 \]
    \[ \mu = 1 \text{ cP} \]
    \[ \gamma_{\text{air}} = 72 \text{ dynes/cm @ 60° F} \]
  - **Oil – Isopar L**
    \[ \rho = 760 \text{ kg/m}^3 \]
    \[ \mu = 1.35 \text{ cP} \]
    \[ \gamma_{\text{air}} = 24 \text{ dynes/cm @ 60° F} \]
Measurement Techniques

- Pressure and Temperature: PTs and DPs and TTs
- Liquid Film Thickness and Flow Pattern: Conductivity Probes
- Holdup: Quick Closing Valves and Pigging System
- Wetted Wall Perimeter: Scales on Wall
Measurement Techniques ...

- Droplet Flux: Iso-kinetic Sampling System
- High Speed Imaging: Droplet Size Distribution and Flow Regime
- Wave Characteristics
- Surface Tension and Interfacial Tension
- Data Acquisition: DeltaV
Film Thickness & Flow Pattern: Conductivity Probes

- Principle: Conductivity Difference
- Traverse Across Pipe
- Oil-Water Flow Pattern and Water layer Thickness
Holdups: QCVs & Pigging System
Wetted Perimeter

- Scales Attached to the Pipe
- Calibration to Account for Pipe Curvature Effects and Refraction
- At High Gas Flow Rates Large Fluctuations Due to Film Waviness

Pipe Wall

$\theta$
Droplet Flux : Isokinetic Probe

Flow
Direction

3"

0.3"

1.5"

7"

Flow
Meter

Pressure Gauze

Separator

Probe
Droplet Flux

Isokinetic Sampling System
Droplet Flux ...

\[ \frac{h_2}{D} = \frac{1}{4} \]

\[ \frac{h_3}{D} = \frac{1}{2} \]

\[ \frac{h_4}{D} = \frac{3}{4} \]

\[ \frac{h_5}{D} = 1 \]
Isokinetic Sampling System: Calibration

\[ V_{Sg} = 17.75 \pm 0.3 \text{ m/s} \]
\[ V_{SL} = 0.7 \text{ m/s} \]

<table>
<thead>
<tr>
<th>Upward</th>
<th>Downward</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe #</td>
<td>Percentage Error Relative To Mean</td>
</tr>
<tr>
<td>1</td>
<td>5.44</td>
</tr>
<tr>
<td>5</td>
<td>4.76</td>
</tr>
<tr>
<td>9</td>
<td>2.04</td>
</tr>
<tr>
<td>4</td>
<td>0.23</td>
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<tr>
<td>12</td>
<td>2.49</td>
</tr>
</tbody>
</table>
Droplet Size Distribution …


- High Shutter Speeds
- Shadow of Droplets Registered by the Camera
Droplet Size Distribution ...

Original Image
8-Bit Gray
Background Compensation
Gray Scale Image
Threshold
Criterion
Binary Image
Edge Detection
Droplet Diameter

Patruno et al. (2010)
Droplet Size Distribution ...

Pipe

Acrylic Box

5 mm

60 fps

V_{sl} = 0.7 \text{ cm/s}

2.0 \text{ usec}

V_{sg} = 18 \text{ m/s}
Flow Regime Identification

- Dye Injection Method for Flow Regime Identification in Oil-Water Layer
Wave Characteristics

- Three Parallel Wire Capacitance Probe

- Two Probes Set a Certain Distance Apart
- Wave Frequency and Wave celerity
- Wave Celerity Using Cross-Correlation Technique (Magrini 2009)
Experimental Program

- Tests at Low Gas Flow Rates
  - Flow Conditions Used by Dong (2007)

- Tests at High Gas Flow Rates
  - Gas-Oil and Gas-Water Two-phase Tests
  - Gas-Oil-Water Three-phase Tests
Experimental Program …

- Test Ranges
  - Superficial Gas Velocity: 5 to 22.5 m/s
  - Liquid Loading Level: 50 to 1200 m³/MMSm³
  - Water Cut: 0 to 0.15
  - Inclination Angles: 0°, +2°, -2°
## Low Gas Flow Rate Studies

### Test Matrix

<table>
<thead>
<tr>
<th>Superficial Gas Velocity (m/s)</th>
<th>Superficial Liquid Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water Cuts: 0, 5%, 15 %</td>
</tr>
<tr>
<td>5</td>
<td>0.001 0.004 0.007 0.01</td>
</tr>
<tr>
<td>10</td>
<td>0.001 0.004 0.007 0.01</td>
</tr>
<tr>
<td>15</td>
<td>0.001 0.004 0.007 0.01</td>
</tr>
</tbody>
</table>
## High Gas Flow Rate Studies

### Test Matrix

<table>
<thead>
<tr>
<th>Superficial Gas Velocity (m/s)</th>
<th>Superficial Liquid Velocity (m/s)</th>
<th>Water Cuts: 0, 5%, 15%, 100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.5</td>
<td>0.004 0.01 0.02 0.035</td>
<td></td>
</tr>
<tr>
<td>18.5</td>
<td>0.004 0.01 0.02 0.035</td>
<td></td>
</tr>
<tr>
<td>22.5</td>
<td>0.004 0.01 0.02 0.035</td>
<td></td>
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</tbody>
</table>
Modeling Framework

- Modeling of Liquid-Liquid Flow Pattern
  - Stratified to Non-Stratified Flow Based on Kelvin-Helmoltz Linear Stability Criterion
  - Semi-Dispersed Flow or Fully Dispersed Flow Based on Stability of Dispersed Phase Drops
Modeling Framework …

- Liquid-Side Friction Factor
  - Modification of Fan’s Approach
  - Law of Wall Approach

\[ u^+ = \frac{1}{\kappa} \ln y^+ + \beta \]

\[ \kappa(d_{mean}, \phi) \quad \beta(d_{mean}, \phi) \]
Modeling Framework …

- **Droplet Transport**
  - Modeling of Turbulent Diffusion and Trajectory Mechanism
  - Transport Mechanism as Also the Actual Fluxes Depend on Droplet Size
  - Droplet Size Distribution Measured in Current Study
  - Criterion for Droplets to Reach Top of the Pipe
Timeline

- Literature Review: Ongoing
- Testing: March 2011
- Data Analysis: May 2012
- Model Development: July 2012
- Final Report: August 2012
Thank You
Fluid Flow Projects

Effects of MEG on Multiphase Flow Behavior

Hamidreza Karami

Advisory Board Meeting, Oct 26, 2011
Outline

- Introduction
- Objectives
- Literature Review
- Experimental Program
- Future Activities
Introduction

- MEG is Injected Continuously As Hydrate Inhibitor in Offshore Systems
- Its Impact on Flow Pattern, Holdup, Pressure Drop Predictions is Not Well Documented
- Need to Generate Datasets and Improve Model Predictions
Objectives

- Collect Flow Pattern, Holdup, Pressure Drop and Entrainment Data on a 6 in. Pipe With and Without MEG under Steady State, Developing and Start up-Shut down Condition
- Benchmark Existing Models, Document Discrepancies
- Propose Improvements If Needed
Literature Review

- Hamersma & Hart (1987)
  - Correlated Liquid Holdup for Low Liquid Loading
  - Different Coefficients for Air-Water and Air-Water + Glycol Systems
  - Relative Increase in Holdup Observed by Adding Glycol
Literature Review …

- Hamersma & Hart (1989) …
  - Decrease in Interfacial Tension by Adding Glycol or Tween (A Detergent) Results in:
    - No Change in Liquid Holdup or Wetted Wall Fraction
    - Slight Increase in Both Rippling of Liquid Film and Pressure Gradient
Wilson et al. (2004)

- Multiphase Flow Modeling Verification for
  - Gas + Condensate + Fresh Water
  - Gas + Condensate + Water (50 wt% MEG)
  - Gas + Condensate + Water (42 wt% MeOH)

- No Significant Difference in Flow Behavior for Three Different Cases
- No Data Presented
Manfield et al. (2007)

Coulomb Field

- Two-Well Gas/Condensate Development in Gulf of Mexico
- Two Wells: C2 and C3
- Well C3 Contains Higher Wax Content
- Large Emulsion Viscosities When C3 is Produced
Experimental Program

- MEG Weight Percent from 10% to 100%
- Inclination Angles 0° and ±2°
- Conditions To Be Investigated
  - Steady State
  - Developing
  - Start up and Shut down
Experimental Facility

6-in ID Low Liquid Loading Facility
Measurement Techniques

- Pressure and Temperature: PTs, DPs, and TTs
- Holdup: Quick Closing Valves and Pigging System
- Entrainment Rate: Iso-kinetic Sampling
- Droplet Size Distribution
- Capacitance Sensor
- Portable Densitometer
Measurement Techniques ...

- Capacitance Probes
  - Multiple Probes Around Pipe Periphery
Measurement Techniques …

- Densito 30PX
Water+MEG Densities

Density (g/cm³) vs. Temperature (°F)
Testing Range

Phase II
Dec to Mar

Phase I
Jun to Sep
TEG Instead of MEG?

Graph showing the comparison of properties of Density, Viscosity, and Surface Tension of MEG and TEG at different concentrations and temperatures.
Future Activities

- **Project Definition**
  - Preliminary Discussions (Fall 2011)
  - Test Matrix (January 2012)
- **Flow Loop Modification** (Spring 2012)
- **Data Acquisition** (Starting Summer 2012)
- **Model Comparison and Development** (Starting Spring 2013)
Questions and Comments
Modeling of Droplet Entrainment in Co-current Annular Two-Phase Flow: A New Approach

Abdel Al-Sarkhi

Advisory Board Meeting, October 26, 2011
Outline

- Objective
- Introduction
- Entrainment Modeling
- Modeling of Maximum Entrainment Fraction, $F_{E, MAX}$
- Effect of Inclination Angle on $F_{E, MAX}$
- Comparison With the Available Modes
- Conclusions & Recommendations
Objective

- Develop a Simple, Explicit and Accurate Entrainment Model With a Wide Range of Applicability
  - The Model Should not Allow Negative Entrainment Values or a Very Large Value That Exceeds the Maximum Possible Value
Introduction

- Annular Flow, Occurs in Many Industries and Processes
  - Steam Generation and Power Plants
  - Heating and Refrigeration Equipment
  - Transportation of Crude Oil and Natural Gas

- In Annular Flow, Entrainment Fraction Prediction is Important for the Estimation of Pressure Drop, Flow Rate, Liquid Holdup, Dry-out
Entrainment Modeling

- From the Onset of Entrainment to the Asymptotic Condition, the Complete Process can be Divided into Three Parts

(Sawant et al. (2008))
The Trend Observed in Previous Figure has also been Seen in Many Other Processes

- Step Response of Electrical Systems (Start-up of an Electric Motor (Ogata (2003))
- Charging of a Capacitor in Resistance-Capacitance (RC) Circuit
- Fouling of Heat Exchangers (Bott (1995))
Entrainment Modeling ...

- Rate of Fouling Deposition, Depends on the Type of Fouling Mechanism (Sedimentation, Crystallization, Organic Material Growth, etc.)
- Rate of Fouling Removal, Depends on Both the Hardness and Adhesive Strength of the Deposit and the Shear Stress Due to the Flow Velocity, as Well as the Fill Configuration

Various fouling models (Bott (1995))
Entrainment Modeling ...

- The fouling model used for the asymptotic process is given below (Bott (1995)):

\[ R_f = R_f^* (1 - \exp(-t/\tau_c)) \]

Where:
- \( R_f \): the fouling resistance (common units are m²K/W)
- \( t \): time
- \( R_f^* \): the asymptotic value of the fouling resistance
- \( \tau_c \): the time constant, which is the time when fouling resistance reaches 63.2% of the asymptotic value
With the Analogy for the Entrainment Fraction, the Work of Sawant et al. (2008) Leads to the Following Model

\[ F_E = F_{E,max}(1 - \exp(-We_{SG}/We_{SG}^*)) \]

\[
We_{SG} = \frac{\rho_G v_{SG}^2 D}{\sigma} \left( \frac{\rho_L - \rho_G}{\rho_G} \right)^{1/4}
\]

Where

- \( We_{SG} \): Superficial Gas Weber Number
- \( F_{E,max} \): Asymptotic Value of Entrainment Fraction
- \( We_{SG}^* \): Analogous Time Constant, Dimensionless and the Weber Number When Entrainment Fraction is 63.2% of Its Asymptote
Entrainment Modeling ...

✦ Model Validation

➢ Model Contains Two Constants i.e., $F_{E,\text{max}}$ and $\text{We}_{SG}^*$

➢ Two Constants are Currently Determined from the Available Experimental Data

➢ Responses of Several Data Sets Representing Different Operational Conditions, Pipe Diameters and Orientations are Tested
Model Validation

- Model Comparison with Owen et al. (1985)
  Data in Vertical 0.0317 m Diameter Pipe ($Re_{SL} = 3550$)
Model Validation…

Model Comparison with Schadel and Hanratty (1989) Data from Vertical 0.042 m ID Pipe ($Re_{SL} = 2105$)
Model Validation ...

- Comparison of Proposed Model with the Data of Sawant et al. (2008) in a Vertical 0.0094 m ID Pipe
Model Validation …

- Comparison of Proposed Model with the Data of Laurinat (1982) at $Re_{SL} = 6905$ in a 0.0508 m ID Horizontal Pipe
Model Validation …

- **Interpretation of Previous Figures**
  - Proposed Model has a Strong and Clear Potential to Predict Entrainment Fractions in 2-phase Vertical and Horizontal Annular Flow
  - Vertical Flow Data Match the Model Better Than Horizontal Flow Data
  - The Model is not Complex
    - Only Information Required are the Two Constants and $V_{SG}$ or $We_{SG}$
Modeling of $F_{E,max}$

- Few Attempts Available in Literature
  - Pan and Hanratty (2002 a)
    - At Low $Re_{SL}$ Values, $F_{E,max}$ Becomes Negative as Reported By Al-sarkhi and Sarica (2011a)
  - Sawant et al. (2008)
    - At Low $Re_{SL}$, $F_{E,max}$ Goes to a Value Larger Than Unity as Explained in Al-sarkhi and Sarica (2011b)
Modeling of $F_{E,\text{max}}$ ... 

- Sawant et al. (2009) Attempted to Improve Sawant et al. (2008)

\[
F_{E,\text{max}} = 1 - \frac{13N_{\mu_f}^{-0.5} + 0.3(Re_{SL} - 13N_{\mu_f}^{-0.5})^{0.95}}{Re_{SL}}
\]

\[
N_{\mu_f} = \frac{\mu_f}{\left(\rho_f \sigma \sqrt{\frac{\sigma}{g \Delta \rho}}\right)^{1/2}} \quad \text{Viscosity Number}
\]

\[
Re_{SL} = \frac{\rho_f V_{SL} D}{\mu_f} \quad \text{Superficial Liquid Reynolds Number}
\]
Modeling of $F_{E,\text{max}}$ ...

- Sawant et al. (2009)

$$F_{E,\text{max}} = 1 - \frac{13N\mu_f^{-0.5} + 0.3(Re_{SL} - 13N\mu_f^{-0.5})^{0.95}}{Re_{SL}}$$

- Two Issues

  - Asymptotic Value is Always Around 0.8 Even for Very Large (Unreasonably Large) Values of $Re_{SL}$
  - Numerical Results are Invalid at Low Liquid Flow Rate of Annular Flows for

$$Re_f < 13N\mu_f^{-0.5} \quad \text{OR} \quad (Re_{SL} - 13N\mu_f^{-0.5}) < 0$$
Variation of $F_{E,\text{max}}$ vs. $Re_{SL}$
(Vertical (V) and Horizontal (H) Pipes)

Exp. Data: (Sawant et al. (2008); Owen et al. (1985), Schadel and Hanratty (1989); Deryabina et al. (1989), Magrini (2009); Assad et al. (1998); Mantilla (2008); Dallman (1978), Laurinat (1982) and Williams (1990))
Modelling of $F_{E,max}$ ...

Following Closure Relationship is Proposed

$$F_{E,max} = F_{E,max,lim} \left[ 1 - \exp \left( - \left( \frac{Re_{SL}}{Re_{SL}^*} \right)^{0.6} \right) \right]$$

Where

$Re_{SL}$ : Superficial Liquid Reynolds Number

$F_{E,max,lim}$ : Asymptotic or Limiting Value of $F_{E,max}$

$Re_{SL}^*$ : Analogous Time Constant in the Form of a Reynolds Number When Maximum Entrainment Fraction Reaches 63.2% of Its Limiting Value
$F_{E,max}$ Closure Relationship

- Two Constants
  - Can be Determined Based on the Experimental Data Shown in the Previous Figure

- If All Thermo-physical Properties Remain Constant in the Reynolds Numbers, the Superficial Liquid Velocity, $v_{SL}$, can be Used Instead of $Re_{SL}$
$F_{E,max}$ Closure Relationship …

- Limiting Value, $F_{E,max,lim}$, would be Very Close to One
  - Good Reasonable Value would be Just One
- A Value of 1400 was Determined for $Re_{SL}^*$ (Reynolds Number When $F_{E,max}$ Reaches 63.2% of Its Limiting Value of One)
Validation of $F_{E,\text{max}}$ Closure Relationship

$F_{E,\text{max}}$ vs $Re_{SL}$

- Current Model
- Experimental data (V)
- Sawant et al. (2008)
- Pan & Hanratty (2002)
- Experimental Data (H)
- Sawant et al. (2009)
Validation of $F_{E,\text{max}}$ Closure Relationship ...

Validation of $F_{E,max}$ Closure Relationship ...

![Graph showing validation of $F_{E,max}$ closure relationship with data points from various sources: Sawant (2008V), Assad (1998V), Owen (1985V), Schadel (1988V), Deryabina (1989V). The graph compares prediction to measurement, with markers indicating +10% and -7% deviation.]
Validation of $F_{E,\text{max}}$ Closure Relationship …

The graph shows the validation of $F_{E,\text{max}}$ using various models:

- Mantilla (2008H)
- Dallman (1978H)
- Laurinat (1982H)
- Williams (1990H)

The graph includes data points for each model, with percentage deviations indicated for comparison.

Advisory Board Meeting, October 26, 2011
Comparison With Others

- Sawant et al. (2009) Under Predicts at High $Re_{SL}$ and Over Predicts at Low $Re_{SL}$
- Sawant et al. (2008) and Pan and Hanratty (2002) Cannot Predict Maximum Entrainment Fraction at Very Low Liquid Reynolds Numbers ($\sim Re_{SL} < 400$)
- Sawant et al. (2009) also has Similar Problems at Low $Re_{SL}$
- Proposed Equation Predicts the Experimental Data Very Well
Effect of Inclination Angle on $F_{E,\text{max}}$
Conclusions

- Entrainment Fraction was Successfully Modeled Using Experimental Data from Various Sources in the Literature
- Only Information Required are the Superficial Liquid and Gas Velocities
- Proposed Maximum Entrainment Fraction Prediction Equation Provide the Best Results Compared With Any Equation in the Literature
Recommendations

- More Investigation is Needed for the Second Constant, $W_e_{SG}$

- Significant Experimental Work Still Need to Be Performed for Very High ($F_{E,max} > 0.85$) and Low ($F_{E,max} < 0.5$) Maximum Entrainment Fraction Region Using Air-water Two-phase Flow and Other Two-phase Fluid Flow Combinations
Fluid Flow Projects

High Pressure Test Facility Construction Update

Eduardo Pereyra and Abdel Al-Sarkhi

Advisory Board Meeting, October 26, 2011
Outline

- Objectives
- Facility
- Basic Instrumentation
- Specialty Instrumentation
- Construction Schedule
Objectives

- Scale-up of Small Diameter and Low Pressure Results to the Large Diameter and High Pressure Conditions
Facility
Test Fluids

- Test Fluid
  - Nitrogen – Oil
- Nitrogen is Selected as Gas Phase
- Oil Resembling Wet Gas Condensate is Selected
  - Isopar L
# Basic Instrumentation

<table>
<thead>
<tr>
<th></th>
<th>Pressure (psig)</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Flow Rate</td>
<td>600</td>
<td>18 MMSCFD</td>
</tr>
<tr>
<td>Water Flow Rate</td>
<td>600</td>
<td>200 GPM</td>
</tr>
<tr>
<td>Oil Flow Rate</td>
<td>600</td>
<td>200 GPM</td>
</tr>
<tr>
<td>Differential Pressure</td>
<td>500</td>
<td>0 – 50 in H₂O</td>
</tr>
<tr>
<td>Pressure</td>
<td>600</td>
<td>0 – 800 psi</td>
</tr>
<tr>
<td>Temperature</td>
<td>500</td>
<td>0-100 °C</td>
</tr>
<tr>
<td>Quick Closing Valves</td>
<td>600</td>
<td>6 in. ID</td>
</tr>
</tbody>
</table>
Specialty Instrumentation

- Quick Closing Valves
- Visual Observation
- Capacitance Sensors
- Iso-kinetic Sampling
- Pitot Tube
Quick Closing Valves

Two and Three Phase Flow

Two Wire Capacitance Sensor
For Oil-Water Level

10 D
Visual Observation

Custom Made High Pressure Sight Flow (Canty)

- Integral Light and Camera
- Disturbance Free Flow
- Cost $41,510
Custom Made High Pressure Sight Flow (Canty)

Visual Observation ...

Side Window for High Speed Video Camera
Capacitance Sensors

Two Wires

- Waves Characteristics
  - Length
  - Celerity
  - Frequency
  - Amplitude

10 D
Capacitance Sensors ...

Film Distribution

- Film thickness distribution
Capacitance Sensors …

Capacitance and Resistance Tomography

- Film Thickness Distribution
- Gas-Oil-Water (Water Continuous Only)
Capacitance and Resistance Tomography

- **Industrial Tomography Systems (ITS)**
  - Cost = $236,870.00
  - Includes Software and Electronics
Capacitance Sensors ...

Wire Mesh Sensor
- Film thickness distribution
Capacitance Sensors ...

Wire Mesh Sensor

- GWT-TUD
  - Cost = $ 85,645.00 (32 by 32 Wires)
  - Include Software and Electronics
  - Rental Option
Iso-kinetic Sampling

Multiple Probe Design
Iso-kinetic Sampling ...

Fluid Flow Projects

Advisory Board Meeting, October 26, 2011
Pitot Tube

- Previously Used
  - Gas-Liquid Flow: Kawaji et al. (1987) and Andreussi et al. (1986)
- Static and Dynamic Lines Filled with Liquid

Omega High Accuracy Pitot Tube
Pitot Tube ...
Pitot Tube ...

- High Pressure Industrial O-ring
- Tube, 0.5 inch OD
- Pipe wall
- Welding
- Support
- Threaded block
- 0.28”
Completion Dates

- HAZOP: January 2012
- Electrical, Data Acquisition and Control Systems: April 2012
- Facility Commissioning: May 2012
- Preliminary Test (Special Instrumentation Installed): October 2012
Construction Schedule

HAZOP by COGNASCENTS

1. Process Hazards Analysis (PHA) Preparation
   1. P&IDs and PFDs
   2. Standard Operating Procedures (SOP)
   3. Project Scope Documents

2. PHA Session
Construction Schedule ...

HAZOP by COGNASCENTS

3. PHA Deliverables
   1. HAZOP Worksheets with Recommendations
   2. Supporting Documentation
   3. PHA Session Sign-in Sheets
   4. PHA Report
   5. All Electronic Files Generated Specifically for the University of Tulsa
Questions/Comments
Fluid Flow Projects

Liquid Loading of Gas Wells

Ge (Max) Yuan

Advisory Board Meeting, October 26, 2011
Dr. Taras Makogon, BP

- High Speed Camera to Get Gas Fraction in Liquid Film

Response:
- Limited Focus Depth of the Lens
Comments from Last ABM …

Mr. Mack Shippen, Schlumberger

- Adding Tests in Well Deviation Range of 0-15°

Response:

- Limited Time
- Studies to Be Continued with Another MS Student
- Mechanism Investigated by Comparing Vertical and 15° Well Deviation Cases
Comments from Last ABM ...

- Mr. Rob Sutton, Marathon
  - Video Showing Liquid Flooding Near Inlet Section
  - Response:
    - Accepted
    - Observed in Some Cases
    - Good Indicator of Liquid Loading in Some Cases
Outline

- Objectives
- Introduction
- Experimental Program
- Experimental Results
- Conclusion
- Near Future Tasks
Objectives

- Explore Mechanisms Controlling Onset of Liquid Loading
- Investigate Effect of Well Deviation on Liquid Loading
Introduction

Gas Production Flow Regime Changes from Mist (a) to Annular (b) to Slug/Churn Flow (c) and Eventually Loads up (d).
Introduction …

- Critical Gas Flow Velocity
  - Minimum Gas Velocity Required to Move Liquid Droplets Upward
  - Gas Rate at Flow Pattern Transition
  - Gas Rate Required to Move Liquid Film Upward
Experimental Program

- Test Section Design

Test Fluids
- Gas – Air
- Water – Tap Water
Experimental Program …

- Test Ranges
  - Superficial Gas Velocity: 10 to 30 m/s
  - Superficial Liquid Velocity: 0.005, 0.01, 0.02, 0.05 and 0.1 m/s
  - Well Deviation: 0º, 15º, 30º, 45º, 60º
Instrumentation

- Pressure and Temperature: PTs and DPs and TTs
- Holdup: Quick Closing Valves
- Capacitance Sensor
  - Wave Characteristics
- High Speed Camera
Capacitance Sensor

- **Type:** Two Parallel Wires
- **Range:** 5 – 40 mm
Capacitance Sensor ...

❄️ Static Calibration

![Graph showing voltage outputs vs. water volume of injection with fluid temperature at 72°F.](image)
Capacitance Sensor ...

💧 Sample Output for Annular Flow

![Graph showing sample output for annular flow with two probes. The x-axis represents test time in seconds with a scan rate of 0.01s, and the y-axis represents output signal in volts. The graph compares the output signal between Probe 1 (green line) and Probe 2 (red line).]
Experimental Results

- Criteria of Liquid Loading
  - Flow Pattern (Videos)
  - Differential Pressure Drop
  - Liquid Holdup

- Transient Phenomena
Experimental Results ...

Criteria of Liquid Loading

Differential Pressure Drop (Vertical)

![Graph showing differential pressure drop (vertical) vs. V_{SG} (m/s). The graph has points for V_{sl}=0.01 and V_{sl}=0.1.](image)
Criteria of Liquid Loading

Liquid Holdup (Vertical)

- Liquid Holdup (Vertical)

- Churn Flow Starts

- Churn Flow Starts

- $v_{SG} \text{ (m/s)}$

- $V_{sl}=0.01$

- $V_{sl}=0.1$
Experimental Results …

 Criteria of Liquid Loading

 Differential Pressure Drop (15° Well Deviation)
### Experimental Results …

#### Criteria of Liquid Loading

- Liquid Holdup (15° Well Deviation)

<table>
<thead>
<tr>
<th>$v_{SG}$ (m/s)</th>
<th>Liquid Holdup</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>0.0200</td>
<td>0.0500</td>
</tr>
<tr>
<td>0.0400</td>
<td>0.1000</td>
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<tr>
<td>0.0600</td>
<td>0.1500</td>
</tr>
<tr>
<td>0.0800</td>
<td>0.2000</td>
</tr>
<tr>
<td>0.1000</td>
<td>0.2500</td>
</tr>
<tr>
<td>0.1200</td>
<td>0.3000</td>
</tr>
<tr>
<td>0.1400</td>
<td>0.3500</td>
</tr>
<tr>
<td>0.1600</td>
<td>0.4000</td>
</tr>
<tr>
<td>0.1800</td>
<td>0.4500</td>
</tr>
</tbody>
</table>

- Slug Flow Starts
- Slug Flow Ends

---

**Diagram:**

- Points for $V_{sl}=0.01$ and $V_{sl}=0.1$
- Graph showing the relationship between $v_{SG}$ (m/s) and Liquid Holdup.
Flow Pattern

High Speed Videos (Vertical)

Video 1

![Image of Video 1]

Graph showing Pressure Gradient (Pa/m) vs. $V_{SG}$ (m/s) for two different VSL values: $V_{SL}=0.01$ and $V_{SL}=0.1$. The graph includes data points for each VSL value.
Flow Pattern ...

High Speed Videos (Vertical)

Video 2

Pressure Gradient (Pa/m) vs. $V_{SG}$ (m/s)

- $V_{SI} = 0.01$
- $V_{SI} = 0.1$

Fluid Flow Projects

Advisory Board Meeting, October 26, 2011
Flow Pattern ...

High Speed Videos (Vertical)

Video 3

**Video 3**

- High Speed Videos (Vertical)

Graph showing the relationship between Pressure Gradient (Pa/m) and $V_{SG}$ (m/s) for different values of $V_{Sl}$:

- $V_{Sl}=0.01$
- $V_{Sl}=0.1$

Graph highlights the impact of $V_{Sl}$ on the Pressure Gradient for varying $V_{SG}$ values.
Flow Pattern …

High Speed Videos (Vertical)

Video 4

![Video 4 Image]

Graph showing pressure gradient (Pa/m) vs. $V_{SG}$ (m/s) with data points for $V_{sl}=0.01$ and $V_{sl}=0.1$. The graph includes a linear trend for each speed.

Video 4
Flow Pattern ...

- High Speed Videos (15° Well Deviation)

Video 1

- Pressure Gradient (Pa/m)
- $V_{SG}$ (m/s)

- Video 1

$V_{sl}=0.01$
$V_{sl}=0.1$
Flow Pattern …

High Speed Videos (15° Well Deviation)

Video 2

![Video 2 Image]

---

**Graph:**

- **Axes:**
  - Y-axis: Pressure Gradient (Pa/m)
  - X-axis: $V_{SG}$ (m/s)

- **Data Points:**
  - $V_{sl}=0.01$ (Blue Squares)
  - $V_{sl}=0.1$ (Green Diamonds)

---

Fluid Flow Projects

Advisory Board Meeting, October 26, 2011
Flow Pattern …

High Speed Videos (15° Well Deviation)

Video 3

![Video 3 Image]

![Graph Image]

- Video 3

![Graph Image]

- Video 3
Flow Pattern ...

High Speed Videos (15° Well Deviation)

Video 4

![Image of Flow Pattern]

![Graph showing Pressure Gradient vs. VSG]

- Video 4

- Pressure Gradient (Pa/m)

- $V_{SG}$ (m/s)

Legend:
- $V_{sl}=0.01$
- $V_{sl}=0.1$
Criteria of Liquid Loading

- **Vertical Wells**
  - Film Flow Reversal
  - Flow Pattern Changes to Churn Flow

- **Deviated Wells**
  - Film at the Bottom Flows Downward
  - Flow Pattern Changes to Intermittent Flow
Experimental Results …

Test Results for Vertical Wells

- Taitel Model
- Barnea Model
- TUFFP Model
- No Loading
- Loading
- Onset of Liquid Loading

Intermittent Flow

Annular Flow
Experimental Results ...

Test Results for 15° from Vertical

- Barnea Model
- TUFFP Model
- No Loading
- Onset of Liquid Loading
- Loading

\( v_{SL} \) (m/s) vs. \( v_{SG} \) (m/s)

Intermittent Flow

Annular Flow
Transient Phenomena

- Liquid Accumulation in Pipe Section
- Waves Flowing Downward
- Wave Growth
- Liquid Flooding Near the Inlet

HD VIDEO
Conclusion

For Vertical Wells

- Droplets Flowing Upward with Gas Core Even Though Liquid Loading Occurs
- Controlled by Film Flow Reversal and Droplet Deposition

For Deviated Wells

- Wave Growth at Gas-Liquid Interphase is Main Mechanism
Near Future Tasks

Data Analysis  November 2011
Model Comparison  November 2011
Final Report  December 2011
Questions/Comments
Fluid Flow Projects

Liquid Loading of Gas Wells (Part 2)

Mujgan Guner
Outline

- Objective
- Literature Review
- Proposed Study
- Instrumentation
- Near Future Tasks
Objective

- Explore Mechanisms Controlling Onset of Liquid Loading in Vertical and Inclined Pipe Configurations
Literature Review

- Liquid Loading in Annular Flow
  - Zabaras et al. (1986)
Literature Review

Liquid Loading in Annular Flow

Belt et al. (2007)
- Air and Water Flow
- 12.5 m Test Section and 2 in. ID Facility
- Main Motivation of the Study is to Relate Liquid Loading to Film Reversal Rather Than Droplets Transportation
  - Inclination Effect on Film Thickness
Literature Review …

- Belt et al. (2007) …
  - Mechanisms That Determine the Film Distribution Around the Circumference and the Film Dynamics are Investigated
    - Interfacial Friction
    - Action of Roll Waves
    - Secondary Flow On The Film Distribution
Proposed Study

- **Experimental Study of Film Reversal Mechanisms in Annular Flow**
  - Effects of Inclination
  - Entrance Effects
- **Exploratory Experiments from Ge (Max)Yuan** Will be Utilized to Generate the Test Matrix
- **Improved Instrumentation Will be Implemented**
Proposed Study ...

- Parameters to Investigate
  - Pressure Gradient
  - Liquid Holdup
  - Liquid Entrainment
  - Film Thickness
  - Wave Characteristics
    - Wave Celerity
    - Wave Frequency
    - Wave Amplitude
Instrumentation

Liquid Holdup

- Quick Closing Valves
  - Multiple QCVs
  - Three Trapping Sections
Instrumentation …

- Liquid Entrainment
  - Isokinetic Sampling Device
  - Located in the Center of the Pipe

---

Flow control valve to maintain iso-kinetic sampling

Supporting block
**Instrumentation ...**

- **Wave Characteristics**
  - Capacitance Probes
  - Multiple Probes Around Pipe Periphery
Wave Characteristics

- Capacitance Probes Calibration Device
- Motorized Linear Slide
Instrumentation …

- Hydrogen Bubble Wire
  - Observation of Velocity Distribution
  - Onset of Film Reversal

Wire - hydrogen bubbles by electrolysis of water

Wall

Flow
Instrumentation …

- Boundary Layer Study
  - Bussman et al.
Instrumentation ...

- **Visual Observation**
  - Flow Pattern Evaluation Videos from the Bottom of the Test Section to the Top by Utilizing Outdoor Surveillance Cameras
  - High Speed Camera
    - Video Quality Will be Improved
**Instrumentation** …

- **Visual Observation**
  - **Boroscope**
  - Boroscope Will be Utilized to Observe the Film Flow Mechanism
Near Future Tasks

- Literature Review: Ongoing
- Instrumentation: March 2012
- Experimentation: October 2012
- Data Analysis: October 2012
- Final Report: December 2012
Questions & Comments
Fluid Flow Projects

Simplified Transient Two-Phase Flow Modeling

Jinho Choi

Advisory Board Meeting, October 26, 2011
Outline

- Objectives
- Preliminary Simplified Transient Model
- Activities Summary
  - Simulator Composition
  - Simulator Validation
- Future Work
Objectives

- Develop a Simplified Transient Model and Simulator for Gas-Liquid Two-Phase Flow in Pipelines
- Test Model and Simulator Against Available Experimental Data
Activities Summary

- Development of a Simplified Isothermal Drift Flux Transient Model
- Simulator Structure Design
- Preliminary Code (Explicit Solver)
- Preliminary Code Validation
Preliminary Simplified Transient Model

Control Volume and Boundary Conditions

Node for \( P, H_L \)

\[ \dot{m}_G \rightarrow \cdots \cdots \cdots \rightarrow \dot{m}_G \] 

\[ \cdots \cdots \cdots \rightarrow \dot{m}_L \rightarrow \cdots \cdots \cdots \rightarrow \dot{m}_L \] 

Velocities

\[ \dot{m}_{G, in} \rightarrow V = A \cdot \delta z \rightarrow \dot{m}_{G, out} \] 

\[ \dot{m}_{L, in} \rightarrow \delta z \rightarrow \dot{m}_{L, out} \]
Preliminary Simplified Transient Model

 Fired Continuity

- **Assumption**
  - Constant Liquid Density

\[
\frac{dH_L}{dt} = \frac{u_{SL.in} - u_{SL.out}}{\delta z}
\]

Gas Continuity

- **Assumptions**
  - Isothermal Flow
  - Constant Gas density

\[
u_{SL.in} - u_{SL.out} + u_{SG.in} - u_{SG.out} = 0
\]
**Preliminary Simplified Transient Model**

- **Drift Flux Closure Relationship**

\[
    u_G = \frac{u_{SG}}{1 - H_L} = C(u_{SL} + u_{SG}) + u_D
\]

\[
    u_{SL} = \frac{u_{SL, in} + u_{SL, out}}{2}
\]

\[
    u_{SG} = \frac{u_{SG, in} + u_{SG, out}}{2}
\]

\[
    \frac{1}{2} \left( \frac{u_{SG, in} + u_{SG, out}}{1 - H_L} \right) = \frac{C}{2} \left( u_{SG, in} + u_{SG, out} + u_{SL, in} + u_{SL, out} \right) + u_D
\]
Preliminary Simplified Transient Model

Equation Summary

Input: $u_{SG.in}$, $u_{SL.in}$, $P_{out}$

1. \[
\frac{dH_L}{dt} = \frac{u_{SL.in} - u_{SL.out}}{\delta z}
\]

2. \[
u_{SG.out} = (1 - H_L) \left[ 2C(u_{SG.in} + u_{SL.in}) + 2u_D \right] - u_{SG.in}
\]

3. \[
u_{SL.out} = u_{SG.in} + u_{SL.in} - u_{SG.out}
\]

4. \[
\frac{dp}{dz} = 2f_M \frac{\rho_M u_M^2}{d} + \rho_M g \sin \theta
\]
Simulator Composition

Main
- Read Data
  - Pipeline Profile
  - Simulation Condition
  - Operation Data
  - Densities & Viscosities & Surface Tension
  - Pipeline Profile
    - Length, Angle, Diameter, etc.
  - Simulation Condition
    - Max. time, Time step size, Flowing Fluid Condition (L-L, L-G)
  - Operation Data
    - Inlet Flow Rates, Separator Pressure
  - Densities & Viscosities & Surface Tension
    - fmGarcia2003
      - Friction Factor
    - DPDLGarcia2003
      - Pressure Gradient
    - C0v Function
      - Distribution Parameter, Now set as constant (ex, 1.0)
    - Ud Function
      - Drift Velocity, Now set as Bendiksen(1984)'s eq.
    - Ug Function
      - Drift Flux Model, Ug=C0v*Um+Ud
- Modules
  - Fluid Properties
  - DPDL module
  - Variables and Types
- File Out
  - Initialization
  - Transition
  - Holdup and Pressure Calculation

Fluid Flow Projects

Advisory Board Meeting, October 26, 2011
Excel UI
Simulator Flow Chart

Start

Read Input Data
(Pipeline Profiles, Operation Conditions)

Initialization
(Pressure, Liquid Holdup, Superficial Velocities)

Calculate boundary values
(Gas & liquid superficial velocities, separator pressure)

Calculate gas and liquid densities and viscosities using previous pressure values

Calculate gas and liquid superficial velocities and liquid holdups

Calculate pressure gradient using the Garcia et al.’s correlation, mixture velocity, and mixture density

Calculate pressures from the separator pressure
\[ P(i) = P(i+1) + dPdL(i) \times dL \]

Compare new pressure to previous pressure at the first segment. Is the difference of pressures is under the tolerance value?

YES

Calculate gas and liquid densities and viscosities using previous pressure values

Final Time Step?

YES

Record targeted data to output data file

END

NO
Simulator Validation

Experiments by Vigneron et al. (1995)

- Air and Kerosene
- Horizontal Pipe $L=420$ m, $d=77.9$ mm
- Two Test Sections @ 61.4m, 395.7m
- Transient Caused By:
  - Liquid flow rate change
  - Gas flow rate change
  - Liquid blow out
  - Start up
# Simulator Validation

**Experiments by Vigneron et al. (1995)**

<table>
<thead>
<tr>
<th>Test#</th>
<th>Initial(I) Final(F)</th>
<th>Flow Rate</th>
<th>Flow Patten</th>
<th>P$_{sep}$ (Bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Liquid (m3/d)</td>
<td>Gas (Sm3/d)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Slug</td>
<td>Slug</td>
<td>1.67</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SS</td>
<td>SW</td>
<td>1.67</td>
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<td></td>
<td></td>
<td>SW</td>
<td>SW</td>
<td>1.69</td>
</tr>
</tbody>
</table>

## Liquid Flow Rate Changes

<table>
<thead>
<tr>
<th>Test#</th>
<th>Initial(I) Final(F)</th>
<th>Flow Rate</th>
<th>Flow Patten</th>
<th>P$_{sep}$ (Bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Liquid (m3/d)</td>
<td>Gas (Sm3/d)</td>
<td></td>
</tr>
<tr>
<td>1A</td>
<td>I</td>
<td>32.5</td>
<td>815</td>
<td>Slug</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>168.4</td>
<td>815</td>
<td>Slug</td>
</tr>
<tr>
<td>1B</td>
<td>I</td>
<td>8.4</td>
<td>400</td>
<td>SS</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>31.8</td>
<td>400</td>
<td>SW</td>
</tr>
</tbody>
</table>

## Gas Flow Rate Changes

<table>
<thead>
<tr>
<th>Test#</th>
<th>Initial(I) Final(F)</th>
<th>Flow Rate</th>
<th>Flow Patten</th>
<th>P$_{sep}$ (Bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Liquid (m3/d)</td>
<td>Gas (Sm3/d)</td>
<td></td>
</tr>
<tr>
<td>2A</td>
<td>I</td>
<td>8.0</td>
<td>850</td>
<td>SS</td>
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<td></td>
<td>F</td>
<td>8.0</td>
<td>4520</td>
<td>SW</td>
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<tr>
<td>2B</td>
<td>I</td>
<td>20.2</td>
<td>340</td>
<td>SS</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>20.2</td>
<td>2530</td>
<td>SW</td>
</tr>
</tbody>
</table>

## Liquid Blow Out

<table>
<thead>
<tr>
<th>Test#</th>
<th>Initial(I) Final(F)</th>
<th>Flow Rate</th>
<th>Flow Patten</th>
<th>P$_{sep}$ (Bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Liquid (m3/d)</td>
<td>Gas (Sm3/d)</td>
<td></td>
</tr>
<tr>
<td>3A</td>
<td>I</td>
<td>48.8</td>
<td>4825</td>
<td>SW</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>0.0</td>
<td>4825</td>
<td>Single</td>
</tr>
<tr>
<td>3B</td>
<td>I</td>
<td>204.0</td>
<td>5880</td>
<td>Slug</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>0.0</td>
<td>5880</td>
<td>Single</td>
</tr>
</tbody>
</table>
Simulator Validation

Test 1A – Liquid Flow Rate Change

\( Q_L = 32.5 \text{ m}^3/\text{d} \rightarrow 168.4 \text{ m}^3/\text{d} \) at 120s, \( Q_G = 815 \text{ Sm}^3/\text{d} \)
Simulator Validation

**Test 1A – Liquid Flow Rate Change**

( $Q_L = 32.5\,(m^3/d) \rightarrow 168.4\,(m^3/d) \text{ at } 120\,s, \, Q_G = 815\,(Sm^3/d)$ )

![Graph showing pressure vs. time for different scenarios.](image-url)
Simulator Validation

**Test 1B** – Liquid Flow Rate Change

\( Q_L = 8.38 \text{ (m}^3/\text{d) } \rightarrow 31.7 \text{ (m}^3/\text{d) @190s , } Q_G = 401 \text{ (Sm}^3/\text{d) } \)
 Simulator Validation

Test 1B – Liquid Flow Rate Change
( $Q_L=8.38\,(m^3/d) \rightarrow 31.7\,(m^3/d) \, @190\,s \, , \, Q_G=401\,(Sm^3/d)$ )
Simulator Validation

- **Test 2A** – Gas Flow Rate Change
  
  \[ Q_L = 8.00 (m^3/d), \; Q_G = 852.9 (Sm^3/d) \rightarrow 4519.4 (Sm^3/d) @ 120s \]
Simulator Validation

- **Test 2A** – Gas Flow Rate Change
  
  \[ Q_L = 8.00 \text{ (m}^3/\text{d}) \ , \ Q_G = 852.9 \text{ (Sm}^3/\text{d}) \rightarrow 4519.4 \text{ (Sm}^3/\text{d}) @ 120s \]

![Graph showing pressure vs. time for different scenarios: Experiment, This Work, OLGA.](image-url)
Simulator Validation

Test 2B – Gas Flow Rate Change

\( Q_L = 20.14 \text{(m}^3/\text{d}) \), \( Q_G = 339.8 \text{(Sm}^3/\text{d}) \rightarrow 2528.1 \text{(Sm}^3/\text{d}) @130s \)
Simulator Validation

Test 2B – Gas Flow Rate Change

\( Q_L = 20.14 \text{(m}^3\text{/d)} \), \( Q_G = 339.8 \text{(Sm}^3\text{/d)} \) \( \rightarrow 2528.1 \text{(Sm}^3\text{/d)} \) @ 130s
Simulator Validation

- **Test 3A – Liquid Blow Out**
  \[ Q_L = 48.77 \text{ (m}^3\text{/d)} \rightarrow 0 \text{ (m}^3\text{/d)} @ 120 \text{s}, \quad Q_G = 4528.2 \text{ (Sm}^3\text{/d)} \]
 Simulator Validation

- **Test 3A** – Liquid Blow Out
  
  \[
  Q_L = 48.77\text{(m}^3/\text{d}) \rightarrow 0\text{(m}^3/\text{d}) @ 120\text{s, } Q_G = 4528.2\text{(Sm}^3/\text{d})
  \]
Simulator Validation

- **Test 3B** – Liquid Blow Out
  \( Q_L = 204.12 \text{(m}^3/\text{d}) \rightarrow 0 \text{(m}^3/\text{d}) @95\text{s}, \ Q_G = 5929.55 \text{(Sm}^3/\text{d}) \)
Simulator Validation

- Test 3B – Liquid Blow Out
  \[ Q_L = 204.12 \text{(m}^3/\text{d}) \rightarrow 0 \text{(m}^3/\text{d}) @95s, \quad Q_G = 5929.55 \text{(Sm}^3/\text{d}) \]
Improvement of the Model

Vigneron et al. (1995)

\[ U_M = U_{sl} + U_{sg} \]

\[ U_G = C U_M + U_D \]

- \( U_M \): Mixture Velocity
- \( U_{sl} \): Liquid Superficial Velocity
- \( U_{sg} \): Gas Superficial Velocity
- \( U_G \): Gas Velocity
- \( C \): Distribution Parameter
- \( U_D \): Drift Velocity
Near Future Work

- Properties Determination from Lookup Table Produced by PVTSim (Nov., 2011)
- Improvement of Drift Flux Model (Nov., 2011)

  - Distribution Parameter (Cv)
    \[ f(u_{sl}, u_{sg}, \rho_{liquid}, \rho_{gas}), \text{ or } f(Fr_M, Re_s, \beta), \text{ etc.} \]

  - Drift Velocity (Ud)
    \[ f(u_{sg}, \rho_{liquid}, \rho_{gas}, \sigma), \text{ or } f(N_f, E_0, \beta), \text{ etc.} \]

  - Liquid – Liquid (Oil-Water) Extension
Near Future Work …

- Application of Other Friction Factor Models (November 2011)
- Implicit Scheme Implementation (November 2011)
- Inclusion of Heat Transfer Model (December 2011)
- Test of Model and Simulator (December 2011)
- Final Report & Paper Work (December 2011)
Questions and Comments
Fluid Flow Projects

Unified Heat Transfer Modeling of Gas/Oil/Water Pipe Flow

Wei Zheng

Advisory Board Meeting, October 26, 2011
Outline

- Comments from May ABM 2011
- Objective
- Introduction
- Model Approaches
- Preliminary Result
- Research Plan
- Project Schedule
Comments from May ABM 2011

- Mack Shippen, Schlumberger
  - Suggested Kaminsky Model
- Thomas Danielson, ConocoPhillips
  - Suggested to Consider Pressure Effects Over the Pipe Temperature
Comments from May ABM 2011

- John Friedemann, GE
  - Suggest to Study J-Factor in Boiling Water

- Brill, University of Tulsa
  - Recommend Paper “Comparison of 20 Two-Phase Heat Transfer Correlations with Seven Sets of Experimental Data, Including Flow Pattern and Tube Inclination Effects” from OSU
Objective

- Develop a Unified Heat Transfer Model for Gas/Oil/Water Three-Phase Flow in Pipes
Introduction

- Accurate Temperature Profile of Fluids Flowing in Pipes Crucial for Production System Design and Flow Assurance
- No Mechanistic Heat Transfer Model for Gas/Oil/Water Pipe Flow Found
Model Approaches

- **First Approach**
  - Gas/Pseudo-Liquid Phase

- **Second Approach**
  - Gas/Liquid Flow Pattern
  - Oil/Water Flow Pattern
First Approach

- Combine Oil and Water as Single Phase Liquid
- Liquid Physical Properties Estimated Based on Water Fraction
- Calculation Using Unified Two-Phase Heat Transfer Model
First Approach …

- Liquid Physical Properties
  - Liquid Viscosity: Brinkman Correlation
  - Liquid Surface Tension: Continuous Phase
  - Inversion Point: Brauner Model
First Approach ... 

- Zhang et al. (2005)
  - Bubble Flow
  - Stratified/Annular Flow
  - Slug Flow
Second Approach

- Flow Pattern and Hydrodynamics
  Predictions from Three-Phase Unified
  Hydrodynamic Model

- Flow Pattern Oriented Heat Transfer
  Model
Second Approach ...

Hydrodynamic Model

Input: $d$, $\varepsilon$, $\theta$, $v_{SG}$, $v_{SO}$, $v_{SW}$, $\rho_{G}$, $\rho_{O}$, $\rho_{W}$, $\mu_{G}$, $\mu_{O}$, $\mu_{W}$, $\sigma_{GO}$, $\sigma_{GW}$, $\sigma_{OW}$

- Single-phase gas, oil, or water? Yes $\rightarrow$ Single-phase calculation
  - No $\rightarrow$
  - Oil-water flow? Yes $\rightarrow$ Oil-water flow calculation
    - No $\rightarrow$
  - Gas-liquid flow? Yes $\rightarrow$ Gas-liquid flow calculation
    - No $\rightarrow$
  - Three-phase flow calculation

Output: flow pattern, $dp/dz$, $H_L$, ...
Second Approach ...

- Flow Pattern
  - Bubble and Dispersed Bubble Flow
    - Oil & Water Fully Mixed
  - Annular Flow
    - Oil & Water Fully Mixed
  - Stratified Flow
    - Oil & Water Stratified
Second Approach ...

- **Slug Flow**
  - Oil & Water Fully Mixed in Slug Body and Film Region
  - Oil & Water Stratified in Slug Body and Film Region
  - Oil & Water Stratified in Film Region and Mixed in Slug Body
Bubble and Dispersed Bubble Flow

- Bubble and Dispersed Bubble Flow with Fully Mixed Oil and Water
- Pseudo Single-Phase
- Liquid Properties: Oil & Water Mixture

\[
\frac{\partial T_M}{\partial l} = - \frac{4U_M (T_M - T_0)}{d_I (\rho_L C_{PL} \nu_{SL} + \rho_L C_{PG} \nu_{SG})}
\]
Annular Flow

❖ Annular Flow with Fully Mixed Oil and Water in Film
➢ Liquid Properties: Oil & Water Mixture

\[
\frac{\partial T}{\partial l} = - \frac{U_F S_F (T_F - T_O) + U_C S_C (T_C - T_O)}{A(\rho_L C_{PL} \nu_{SL} + \rho_G C_{PG} \nu_{SG})}
\]
Stratified Flow

Stratified Flow with Stratified Oil and Water

Assume

\[
\frac{\partial T_C}{\partial l} = \frac{\partial T_O}{\partial l} = \frac{\partial T_W}{\partial l}
\]

\[
T_M = \frac{T_{oil} + T_W + T_C}{3}
\]
Stratified Flow ...

- Heat Loss between Layers Neglected
- Heat Balance Equation

\[
(T_{c1} - T_{c2})\rho_c A\nu_{sc} C_{pc} = q_c S_c dl \\
(T_{o1} - T_{o2})\rho_o A\nu_{so} C_{po} = q_o S_o dl \\
(T_{w1} - T_{w2})\rho_w A\nu_{sw} C_{pw} = q_w S_w dl
\]

\[
\frac{\partial T}{\partial l} = \frac{U\pi d_I (T_M - T_O)}{\rho_c A\nu_{sc} C_{pc} + \rho_o A\nu_{so} C_{po} + \rho_w A\nu_{sw} C_{pw}}
\]
Stratified Flow …

- Overall Heat Transfer Coefficient

\[ U = \frac{q_C S_C + q_O S_O + q_W S_W}{\pi d_I (T_M - T_O)} \]

\[ U = \frac{U_C S_C (T_C - T_O)}{\pi d_I (T_M - T_O)} + \frac{U_O S_O (T_{Oil} - T_O)}{\pi d_I (T_M - T_O)} + \frac{U_W S_W (T_W - T_O)}{\pi d_I (T_M - T_O)} \]
Stratified Flow …

.scrollTopToView();

Overall Heat Transfer Coefficient

\[
T_C - T_O = \frac{\rho_C \nu_{SC} C_{PC}}{\rho_O \nu_{SO} C_{PO}} \frac{U_O S_O}{U_C S_C} (T_{oil} - T_O)
\]

\[
T_C - T_O = \frac{\rho_C \nu_{SC} C_{PC}}{\rho_W \nu_{SW} C_{PW}} \frac{U_W S_W}{U_C S_C} (T_W - T_O)
\]

\[
T_M - T_O = \frac{T_{oil} - T_O}{3} + \frac{T_W - T_O}{3} + \frac{T_C - T_O}{3}
\]

\[
B_1 = \frac{\rho_C \nu_{SC} C_{PC}}{\rho_O \nu_{SO} C_{PO}} \frac{U_O S_O}{U_C S_C}
\]

\[
B_2 = \frac{\rho_C \nu_{SC} C_{PC}}{\rho_W \nu_{SW} C_{PW}} \frac{U_W S_W}{U_C S_C}
\]
Stratified Flow ...

Overall Heat Transfer Coefficient

\[
\frac{T_M - T_O}{T_C - T_O} = \frac{1}{3B_1} + \frac{1}{3B_2} + \frac{1}{3} \\
\frac{T_M - T_O}{T_W - T_O} = \frac{B_2}{3B_1} + \frac{1}{3} + \frac{B_2}{3} \\
\frac{T_M - T_O}{T_{Oil} - T_O} = \frac{B_1}{3B_2} + \frac{1}{3} + \frac{B_1}{3}
\]

\[
U = \frac{U_C S_C}{\pi d_I \left( \frac{1}{3B_1} + \frac{1}{3B_2} + \frac{1}{3} \right)} + \frac{U_O S_O}{\pi d_I \left( \frac{B_1}{3B_2} + \frac{1}{3} + \frac{B_1}{3} \right)} + \frac{U_W S_W}{\pi d_I \left( \frac{B_2}{3B_1} + \frac{1}{3} + \frac{B_2}{3} \right)}
\]
Slug Flow

General Calculation

\[ T_{UA} = \frac{\int_{0}^{t_F} T_F \, dt + \int_{0}^{t_S} T_S \, dt}{l_U / \nu_T} \]

\[ \frac{\partial T}{\partial l} = -\frac{(T_{UA} - T_o)}{\left(\frac{b}{a} l_F - \frac{f}{e} l_s\right) + \left(\frac{b}{a} - \frac{f}{e}\right)\left(\frac{1}{e} - \frac{1}{a}\right)\left(1 - e^{-al_F}\right)\left(1 - e^{-el_s}\right)} \]
 Slug Flow …

- Slug Flow with Oil & Water Fully Mixed in Slug Body and Film Region
  - Same as First Approach
Slug Flow …

 Slug Flow with Stratified Oil and Water

Diagram showing the flow pattern with labels $l_S$, $l_F$, and $l_U$.
Slug Flow with Stratified Oil and Water

Film Region

\[
\frac{1}{\nu_T} \frac{\partial T_W}{\partial t} A(\nu_T - \nu_{WF}) H_{WF} \rho_W C_{PW} = \frac{\Delta T_U}{l_U} \nu_{WF} H_{WF} A \rho_W C_{PW} - U_{WF} (T_{WF} - T_O) S_{WF}
\]

\[
\frac{1}{\nu_T} \frac{\partial T_{Oil}}{\partial t} A(\nu_T - \nu_{OF}) H_{OF} \rho_O C_{PO} = \frac{\Delta T_U}{l_U} \nu_{OF} H_{OF} A \rho_O C_{PO} - U_{OF} (T_{OF} - T_O) S_{WF}
\]

\[
\frac{1}{\nu_T} \frac{\partial T_C}{\partial t} A(\nu_T - \nu_{CF})(1 - H_{WF} - H_{OF}) \rho_C C_{PC} = \frac{\Delta T_U}{l_U} \nu_{CF}(1 - H_{WF} - H_{OF}) A \rho_C C_{PC} - U_{CF} (T_{CF} - T_O) S_{CF}
\]
Slug Flow with Stratified Oil and Water ...

Film Region

Assume

\[ \frac{\partial T_W}{\partial t} = \frac{\partial T_{Oil}}{\partial t} = \frac{\partial T_C}{\partial t} = \frac{\partial T_F}{\partial t} \]

\[ \frac{1}{v_T} \frac{\partial T_F}{\partial t} = b\Delta T_U - a(T_F - T_O) \]

\[ b = \frac{\nu_{WF} H_{WF} \rho_W C_{PW} + \nu_{OF} H_{OF} \rho_O C_{PO} + \nu_{CF} (1 - H_{WF} - H_{OF}) \rho_C C_{PC}}{l_U \left[ (\nu_T - \nu_{WF}) H_{WF} \rho_W C_{PW} + (\nu_T - \nu_{OF}) H_{OF} \rho_O C_{PO} + (\nu_T - \nu_{CF}) (1 - H_{WF} - H_{OF}) \rho_C C_{PC} \right]} \]

\[ a = \frac{U_{WF} S_{WF} + U_{OF} S_{OF} + U_{CF} S_{CF}}{A \left[ (\nu_T - \nu_{WF}) H_{WF} \rho_W C_{PW} + (\nu_T - \nu_{OF}) H_{OF} \rho_O C_{PO} + (\nu_T - \nu_{CF}) (1 - H_{WF} - H_{OF}) \rho_C C_{PC} \right]} \]
Slug Flow with Stratified Oil and Water ...

 Slug Body

\[
\frac{1}{\nu_T} \frac{\partial T_{OS}}{\partial t} A (\nu_T - \nu_{OS}) (1 - H_{WS}) (1 - \alpha_{OS}) \rho_O C_{PO} = \frac{\Delta T_U}{l_U} \nu_{OS} (1 - H_{WS}) (1 - \alpha_{OS}) A \rho_O C_{PO} - U_{OS} (T_{OS} - T_O) S_{OS}
\]

\[
\frac{1}{\nu_T} \frac{\partial T_{WS}}{\partial t} A (\nu_T - \nu_{WS}) H_{WS} (1 - \alpha_{WS}) \rho_W C_{PW} = \frac{\Delta T_U}{l_U} \nu_{WS} H_{WS} (1 - \alpha_{WS}) A \rho_W C_{PW} - U_{WS} (T_{WS} - T_O) S_{WS}
\]
Slug Flow with Stratified Oil and Water …

 Slug Body

▲ Assume

\[
\frac{\partial T_{WS}}{\partial t} = \frac{\partial T_{OS}}{\partial t} = \frac{\partial T_{S}}{\partial t}
\]

\[
\frac{1}{\nu_T} \frac{\partial T_S}{\partial t} = f \Delta T_U - e(T_S - T_o)
\]

\[
f = \frac{\nu_{OS}(1 - H_{WS})(1 - \alpha_{OS})\rho_O C_{PO} + \nu_{WS}H_{WS}(1 - \alpha_{WS})\rho_W C_{PW}}{l_U[(\nu_T - \nu_{OS})(1 - H_{WS})(1 - \alpha_{OS})\rho_O C_{PO} + (\nu_T - \nu_{WS})H_{WS}(1 - \alpha_{WS})\rho_W C_{PW}]}
\]

\[
e = \frac{U_{OS}S_{OS} + U_{WS}S_{WS}}{A[(\nu_T - \nu_{OS})(1 - H_{WS})(1 - \alpha_{OS})\rho_O C_{PO} + (\nu_T - \nu_{WS})H_{WS}(1 - \alpha_{WS})\rho_W C_{PW}]}
\]
Slug Flow with Stratified Oil and Water ...

General Calculation

\[ T_{UA} = \frac{\int_{0}^{t_F} T_F \, dt + \int_{0}^{t_S} T_S \, dt}{l_U / \nu_T} \]

\[ \frac{\partial \bar{T}}{\partial l} = -\frac{T_{UA} - T_o}{\left( \frac{b}{a} \left( \frac{F}{e} \right) l_F - f \, l_s \right) + \left( \frac{b}{a} - \frac{f}{e} \right) \left( \frac{1}{e} - \frac{1}{a} \right) \left( 1 - e^{-al_F} \right) \left( 1 - e^{-el_s} \right)} \]
Slug Flow

- Slug Flow with Stratified Oil and Water in Film Region
 Slug Flow with Stratified Oil and Water in Film Region

Film Region

\[
\frac{1}{\nu_T} \frac{\partial T_F}{\partial t} = b \Delta T_U - a (T_F - T_O)
\]

\[
a = \frac{U_{WF} S_{WF} + U_{OF} S_{OF} + U_{CF} S_{CF}}{A (\nu_T - \nu_{WF}) H_W \rho_W C_{PW} + (\nu_T - \nu_{OF}) H_O \rho_O C_{PO} + (\nu_T - \nu_{CF}) (1 - H_W - H_O) \rho_C C_{PC}}
\]

\[
b = \frac{\nu_{WF} H_W \rho_W C_{PW} + \nu_{OF} H_O \rho_O C_{PO} + \nu_{CF} (1 - H_W - H_O) \rho_C C_{PC}}{l_U (\nu_T - \nu_{WF}) H_W \rho_W C_{PW} + (\nu_T - \nu_{OF}) H_O \rho_O C_{PO} + (\nu_T - \nu_{CF}) (1 - H_W - H_O) \rho_C C_{PC}}
\]
 Slug Flow with Stratified Oil and Water in Film Region ...

**Slug Body**

\[
\frac{1}{\nu_T} \frac{\partial T_S}{\partial t} = f \Delta T_U - e(T_S - T_O)
\]

\[
e = \frac{U_S \pi d_l}{\rho_L c_{PL} H_L S A (\nu_T - \nu_M)}
\]

\[
f = \frac{\nu_M}{l_U (\nu_T - \nu_M)}
\]
Slug Flow with Stratified Oil and Water in Film Region …

General Calculation

\[
T_{UA} = \int_0^{t_F} T_F \, dt + \int_0^{t_S} T_S \, dt
\]

\[
\frac{\partial T}{\partial l} = -\left( \frac{b}{a} \frac{l_F}{l_s} - \frac{f}{e} \right) + \left( \frac{b}{a} - \frac{f}{e} \right) \left( \frac{1}{e} - \frac{1}{a} \right) \frac{\left( T_{UA} - T_o \right)}{\left( 1 - e^{-al_F} \right) \left( 1 - e^{-el_S} \right)}
\]
Preliminary Result

First Approach (Software Inputs)

<table>
<thead>
<tr>
<th>Fluid Properties</th>
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<tbody>
<tr>
<td>Superficial Oil Velocity</td>
<td>m/s</td>
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<td>Superficial Water Velocity</td>
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<td>Oil Viscosity</td>
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<tr>
<td>Gas Viscosity</td>
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<tr>
<td>Liquid Viscosity at Wall</td>
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<tr>
<td>OW Surface Tension</td>
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<td>OG Surface Tension</td>
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<td>GW Surface Tension</td>
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<tr>
<td>Inlet Temperature</td>
<td>°F</td>
<td>69</td>
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First Approach (Software Inputs)

<table>
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<tr>
<th>Pipe Profile</th>
<th>Total Pipe Number</th>
<th>Inner Diameter in</th>
<th>Outer Diameter in</th>
<th>Length m</th>
<th>Number of Section</th>
<th>Elevation m</th>
<th>Absolute Roughness mm</th>
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<td>40</td>
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<thead>
<tr>
<th>Heat Transfer Input</th>
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<tbody>
<tr>
<td>Oil Heat Capacity</td>
<td>J/(Kg.C°)</td>
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<tr>
<td>Water Heat Capacity</td>
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<td>Gas Heat Capacity</td>
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<tr>
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<td>Gas Thermal Conductivity</td>
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<td>Pipe Thermal Conductivity</td>
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<td>Geothermal Temperature Gradient</td>
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<td>Outside Heat Transfer Coefficient</td>
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<td>2396.28</td>
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Preliminary Result ...

• First Approach (Software Outputs)

![Temperature Profile](image_url)
## Verification

### Gas/Liquid Heat Transfer Model

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</tr>
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<td>Liquid Density</td>
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<td>Superficial Gas Velocity</td>
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<tr>
<td>Water Density</td>
<td>kg/m³</td>
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</tr>
<tr>
<td>Gas Density</td>
<td>kg/m³</td>
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</tr>
<tr>
<td>Oil Viscosity</td>
<td>Pa.s</td>
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<tr>
<td>Water Viscosity</td>
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<tr>
<td>Gas Viscosity</td>
<td>Pa.s</td>
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<tr>
<td>Liquid Viscosity at Wall</td>
<td>cp</td>
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<tr>
<td>OW Surface Tension</td>
<td>N/m</td>
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<tr>
<td>OG Surface Tension</td>
<td>N/m</td>
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</tr>
<tr>
<td>GW Surface Tension</td>
<td>N/m</td>
<td>0.076</td>
</tr>
<tr>
<td>Inlet Pressure</td>
<td>psia</td>
<td>1001</td>
</tr>
<tr>
<td>Inlet Temperature</td>
<td>F°</td>
<td>69</td>
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</table>
Verification

Gas/Liquid Heat Transfer Model

<table>
<thead>
<tr>
<th>Pipe Profile</th>
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<tbody>
<tr>
<td>Total Pipe Number</td>
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<td>1</td>
<td>2</td>
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<tr>
<td>Inner Diameter</td>
<td>in</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Outer Diameter</td>
<td>in</td>
<td>6.4</td>
<td>6.7</td>
</tr>
<tr>
<td>Length</td>
<td>m</td>
<td>1000</td>
<td>2000</td>
</tr>
<tr>
<td>Number of Section</td>
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<td>20</td>
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<tr>
<td>Elevation</td>
<td>m</td>
<td>500</td>
<td>800</td>
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<tr>
<td>Absolute Roughness</td>
<td>mm</td>
<td>0.004</td>
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<table>
<thead>
<tr>
<th>Heat Transfer Input</th>
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<tr>
<td>Oil Heat Capacity</td>
<td>J/(Kg.C°)</td>
<td>1980</td>
</tr>
<tr>
<td>Water Heat Capacity</td>
<td>J/(Kg.C°)</td>
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</tr>
<tr>
<td>Gas Heat Capacity</td>
<td>J/(Kg.C°)</td>
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<tr>
<td>Oil Thermal Conductivity</td>
<td>W/(m.C°)</td>
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<tr>
<td>Water Thermal Conductivity</td>
<td>W/(m.C°)</td>
<td>0.1609</td>
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<tr>
<td>Gas Thermal Conductivity</td>
<td>W/(m.C°)</td>
<td>0.0403</td>
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<tr>
<td>Pipe Thermal Conductivity</td>
<td>W/(m.C°)</td>
<td>16.29</td>
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<tr>
<td>Initial Ambient Temperature</td>
<td>F°</td>
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<td>Geothermal Temperature Gradient</td>
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<td>-0.02</td>
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<tr>
<td>Outside Heat Transfer Coefficient</td>
<td>W/(m².C°)</td>
<td>2396.28</td>
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Verification

Results Comparison
Research Plan

Model–1st Approach       August 2011
Model–2nd Approach        February 2012
Model Evaluation          March 2012
Software Implementation   May 2012
Project Schedule

- Literature Review: Complete
- Model–1st Approach: Complete
- Model–2nd Approach: Complete
- Model Evaluation: Ongoing
- Software Implementation: Ongoing
- Final Report: May 2012
Questions/Comments
Membership and Collaboration Status

- **Current Membership Status**
  - Membership Steady at 16
    - 15 Industrial and MMS

- **Efforts Continue to Increase TUFFP Membership**
  - Saudi Aramco and Statoil are Expected to Rejoin for 2012

- **Collaboration with Seoul National University Continues**
  - Visiting Research Scholars and Financial Contribution
Publications and Papers


Next Advisory Board Meetings

✦ Tentative Schedule

➢ April 25, 2012
   ▶ TUHOP Meeting
   ▶ TUFFP Workshop
   ▶ Facility Tour
   ▶ TUHOP/TUHFP/TUFFP Reception

➢ April 26, 2012
   ▶ TUFFP Meeting
   ▶ TUFFP/TUPDP Dinner

➢ April 27, 2012
   ▶ TUPDP Meeting

✦ Venue is The University of Tulsa
Financial Report

- Year 2011 Update
  - TUFFP Industrial Account
  - TUFFP BSEE Account
- Year 2012 Proposed
  - TUFFP Industrial Account
  - TUFFP BSEE Account
# 2011 Industrial Account Summary

(Prepared October 10, 2011)

## Anticipated Reserve Fund Balance on January 1, 2011

($29,760)

## Income for 2011

- **2011 Anticipated Membership Fees (15 @ $55,000 - excludes MMS)**: $825,000
- **Facility Utilization Fee (SNU)**: $55,000
- **Facility Utilization Fee (Foam Project)**: $60,000

## Total Budget

$910,240

## Projected Budget/Expenditures for 2011

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>11/3/10</th>
<th>Revised Budget April 2011</th>
<th>2011 Expenditures 10/10/11</th>
<th>Revised Budget 10/10/11</th>
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<tbody>
<tr>
<td>90101 - 90103</td>
<td>Faculty Salaries</td>
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<td>38,481.88</td>
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<tr>
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<td>Professional Salaries</td>
<td>71,906.23</td>
<td>51,656.23</td>
<td>32,193.70</td>
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<td>90700 - 90703</td>
<td>Staff Salaries</td>
<td>28,306.09</td>
<td>31,289.67</td>
<td>20,310.56</td>
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<td>90800</td>
<td>Part-time/Temporary</td>
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<td></td>
<td>19,272.67</td>
<td>20,339.35</td>
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<td>91000</td>
<td>Student Salaries - Monthly</td>
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<td>43,950.00</td>
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<tr>
<td>91100</td>
<td>Student Salaries - Hourly</td>
<td>15,000.00</td>
<td>15,000.00</td>
<td>7,195.78</td>
<td>10,000.00</td>
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<tr>
<td>91800</td>
<td>Fringe Benefits (35 %)</td>
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<td>42,500.00</td>
<td>23,487.31</td>
<td>36,177.00</td>
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<tr>
<td>92102</td>
<td>Fringe Benefits (Students)</td>
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<td>2,460.00</td>
<td>3,516.00</td>
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<td>81801</td>
<td>Tuition &amp; Student Fees</td>
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<td>10,492.00</td>
<td>19,223.00</td>
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<td>81806</td>
<td>Fellowship</td>
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<td>2,786.50</td>
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<td>Research Supplies</td>
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<td>92,236.98</td>
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<td>93102</td>
<td>Copier/Printer Supplies</td>
<td>500.00</td>
<td>500.00</td>
<td>75.08</td>
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<td>93104</td>
<td>Computer Software</td>
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<td>93150</td>
<td>Computers ($1000 - $4999)</td>
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<td>1,423.23</td>
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<td>93200</td>
<td>Postage and Shipping</td>
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<td>500.00</td>
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<td>Printing and Duplicating</td>
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<td>2,202.74</td>
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<td>93400</td>
<td>Telecommunications</td>
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<td>3,000.00</td>
<td>1,500.00</td>
<td>2,500.00</td>
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<td>93500</td>
<td>Membership</td>
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<td>500.00</td>
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<td>93601</td>
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<td>10,000.00</td>
<td>3,030.52</td>
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<tr>
<td>93602</td>
<td>Travel - Foreign</td>
<td>10,000.00</td>
<td>10,000.00</td>
<td>8,609.55</td>
<td>9,000.00</td>
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<td>16,000.00</td>
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<td>94813</td>
<td>Outside Services</td>
<td>20,000.00</td>
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<td>95103</td>
<td>Equipment Rental</td>
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<td>11,518.05</td>
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<td>95200</td>
<td>F&amp;A (52.4%)</td>
<td>103,565.56</td>
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<td>98901</td>
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<td>40.00</td>
<td>32.00</td>
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</table>

## Total Anticipated Expenditures

$776,792.73 $810,527.78 $498,237.59 $704,773.09

## Anticipated Reserve as of 12/31/11

$205,466.65

(Prepared October 10, 2011)
### 2011 BSEE Account Summary

(Prepared October 11, 2011)

<table>
<thead>
<tr>
<th>Description</th>
<th>Budget</th>
<th>Revised Budget April 2011</th>
<th>2011 Expenditures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reserve Balance as of 12/31/10</td>
<td>12,781.55</td>
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<td>2011 Budget</td>
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<td><strong>Total Budget</strong></td>
<td>60,781.55</td>
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#### Projected Budget/Expenses for 2011

- **91000 Students - Monthly**
  - Budget: 29,000.00
  - Revised Budget: 36,425.00
  - Expenditures: 35,700.00

- **91202 Student Fringe Benefits**
  - Budget: 2,320.00
  - Revised Budget: 2,914.00
  - Expenditures: 2,856.00

- **95200 F&A**
  - Budget: 15,196.00
  - Revised Budget: 20,252.00
  - Expenditures: 19,849.20

**Total Anticipated Expenditures as of 12/31/11**: 46,516.00

**Total Anticipated Reserve Fund Balance as of 12/31/11**: 2,376.35
# 2012 Proposed Industrial Account Budget

(Prepared October 11, 2011)

<table>
<thead>
<tr>
<th>Anticipated Reserve Fund Balance on January 1, 2012</th>
<th>$205,466.65</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Income for 2012</strong></td>
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<tr>
<td>2012 Anticipated Membership Fees (15 @ $55,000 - excludes MMS)</td>
<td>$825,000.00</td>
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<tr>
<td>Facility Utilization Fee (SNU)</td>
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<tr>
<td><strong>Total Income</strong></td>
<td>$1,085,466.65</td>
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<tr>
<td><strong>2009 Anticipated Expenditures</strong></td>
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</tr>
<tr>
<td>90101-90103 Faculty Salaries</td>
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<tr>
<td>90600-90609 Professional Salaries</td>
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<td>90700-90703 Staff Salaries</td>
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<td>91000 Graduate Students</td>
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<td>91100 Undergraduate Students</td>
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<td>91800 Fringe Benefits (35%)</td>
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<td>93101 Research Supplies</td>
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<td>93102 Copier/Printer Supplies</td>
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<td>93106 Office Supplies</td>
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<td>93200 Postage/Shipping</td>
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<td>93300 Printing/Duplicating</td>
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<td>93500 Memberships/Subscriptions</td>
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<td>94813 Outside Services</td>
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<td>95200 Indirect Costs (52.4%)</td>
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<tr>
<td>98901 Employee Recruiting</td>
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<tr>
<td>99001 Equipment</td>
<td>300,000.00</td>
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<tr>
<td><strong>Total Expenditures</strong></td>
<td>$982,304.84</td>
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| Anticipated Reserve Fund Balance on December 31, 2012 | $103,161.81 |

(Prepared October 11, 2011)
2012 Proposed BSEE Account Budget

(Prepared October 11, 2011)

<table>
<thead>
<tr>
<th>Account Balance - January 1, 2011</th>
<th>$2,376.35</th>
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<tbody>
<tr>
<td>Income for 2012</td>
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<tr>
<td>2012 Membership Fee</td>
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<td>Remaining Balance</td>
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<table>
<thead>
<tr>
<th>2009 Anticipated Expenditures</th>
<th>Projected Budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>90101-90103 Faculty Salaries</td>
<td>-</td>
</tr>
<tr>
<td>90600-90609 Professional Salaries</td>
<td>-</td>
</tr>
<tr>
<td>90700-90703 Staff Salaries</td>
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<tr>
<td>91000 Graduate Students</td>
<td>28,700.00</td>
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<tr>
<td>92102 Student Fringe Benefits (8%)</td>
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<tr>
<td>95200 Indirect Costs (55.6%)</td>
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</table>

Total Expenditures                  $46,953.20

Anticipated Reserve Fund Balance on December 31, 2012 $3,423.15
History – Membership

[Graph showing the relationship between the number of members and oil price over the years.]
History – Membership Fees
History - Expenditures

The graph shows the history of expenditures over the years, with expenditure values ranging from $0 to $1,200,000. The years are represented on the x-axis, and the expenditure amounts on the y-axis.

The highest expenditure is observed in the year 2011, with a significant drop in subsequent years. The expenditure trend is generally upward, indicating increased investment in fluid flow projects over time.
Membership Fees

- 2011 Membership Dues
  - All Paid
  - Thank You
<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
<th>Presenter</th>
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</thead>
<tbody>
<tr>
<td>8:00 a.m.</td>
<td>Breakfast – Allen Chapman Activity Center – Gallery</td>
<td></td>
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<tr>
<td>8:30</td>
<td>Introductory Remarks</td>
<td>Cem Sarica</td>
</tr>
<tr>
<td>8:45</td>
<td>TUFFP Progress Reports</td>
<td>Cem Sarica</td>
</tr>
<tr>
<td></td>
<td>Executive Summary</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Effect of Pipe Inclination on Flow Characteristics of High Viscosity</td>
<td>Benin Jeyachandra</td>
</tr>
<tr>
<td></td>
<td>Oil-Gas Two-Phase Flow</td>
<td></td>
</tr>
<tr>
<td>10:15</td>
<td>Coffee Break</td>
<td></td>
</tr>
<tr>
<td>10:30</td>
<td>TUFFP Progress Reports</td>
<td>Rosmer Brito</td>
</tr>
<tr>
<td></td>
<td>Downward Two-Phase Stratified Flow for Highly Viscous Oils</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Effect of Medium Oil Viscosity on Two-Phase Oil-Gas Flow Behavior in</td>
<td>Rosmer Brito</td>
</tr>
<tr>
<td></td>
<td>Horizontal Pipes</td>
<td></td>
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<tr>
<td></td>
<td>Characterization of High Viscosity Slug Flow in Horizontal Pipes</td>
<td>Eissa Alsafran</td>
</tr>
<tr>
<td>12:00 p.m.</td>
<td>Lunch – Allen Chapman Activity Center - Chouteau C</td>
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<td>1:15</td>
<td>TUFFP Progress Reports</td>
<td>Kiran Gawas</td>
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<td></td>
<td>Low Liquid Loading Gas-Oil-Water Flow</td>
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<td>Effects of MEG on Multiphase Flow Behavior</td>
<td>Hamidreza Karami</td>
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<td></td>
<td>Modeling of Droplet Entrainment in Co-current Annular Two-Phase Flow</td>
<td>Abdel Al-Sarkhi</td>
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<tr>
<td></td>
<td>Flow: A New Approach</td>
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<td></td>
<td>High Pressure Test Facility Construction Update</td>
<td>Eduardo Pereyra/</td>
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<td>Abdel Al-Sarkhi</td>
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<td>3:00</td>
<td>Coffee Break</td>
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<td>3:15</td>
<td>TUFFP Progress Reports</td>
<td>Ge (Max) Yuan</td>
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<td>Low Liquid Loading of Gas Wells (Part 1)</td>
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<tr>
<td></td>
<td>Low Liquid Loading of Gas Wells (Part 2)</td>
<td>Mujgan Guner</td>
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<td>Simplified Transient Two-Phase Modeling</td>
<td>Jinho Choi</td>
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<td>4:25</td>
<td>TUFFP Business Report</td>
<td>Cem Sarica</td>
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<td>4:40</td>
<td>Open Discussion</td>
<td>Cem Sarica</td>
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<td>5:10</td>
<td>Adjourn</td>
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5:30  TUFFP/TUPDP Reception - Allen Chapman Activity Center - Atrium