McDougall School of Petroleum Engineering

Fluid Flow Projects

Seventy Eighth Semi-Annual Advisory Board Meeting Brochure and Presentation Slide Copy

April 25, 2012

Tulsa University Fluid Flow Projects
Seventy Eighth Semi-Annual Advisory Board Meeting Agenda
Wednesday, April 25, 2012

Tuesday, April 24, 2012

Tulsa University High-Viscosity Oil Projects
Advisory Board Meeting
Spirit Bank Event Center – South Banquet
10441 South Regal Blvd.
Tulsa, Oklahoma
8:00 a.m. – 11:45 a.m.

Tulsa University High-Viscosity Oil Projects and Tulsa University Fluid Flow Projects
Workshop Luncheon
Spirit Bank Event Center – South Banquet
10441 South Regal Blvd.
Tulsa, Oklahoma
11:45 a.m. – 1:00 p.m.

Tulsa University High-Viscosity Oil Projects and Tulsa University Fluid Flow Projects
Tour of Test Facilities
University of Tulsa North Campus
2450 East Marshall
Tulsa, Oklahoma
1:00 – 3:00 p.m.

Tulsa University Fluid Flow Projects Workshop
Spirit Bank Event Center – South Banquet
10441 South Regal Blvd.
Tulsa, Oklahoma
3:30 – 5:30 p.m.

Tulsa University High-Viscosity Oil Projects and Tulsa University Fluid Flow Projects
Reception
Spirit Bank Event Center – South Banquet
10441 South Regal Blvd.
Tulsa, Oklahoma
6:00 – 9:00 p.m.

Wednesday, April 25, 2012

Tulsa University Fluid Flow Projects
Advisory Board Meeting
Spirit Bank Event Center – South Banquet
10441 South Regal Blvd.
Tulsa, Oklahoma
8:00 a.m. – 5:20 p.m.

Tulsa University Fluid Flow Projects and Tulsa University Paraffin Deposition Projects
Reception
Spirit Bank Event Center – South Banquet
10441 South Regal Blvd.
Tulsa, Oklahoma
5:30 – 9:00 p.m.

Thursday, April 26, 2012

Tulsa University Paraffin Deposition Projects
Advisory Board Meeting
Spirit Bank Event Center – South Banquet
10441 South Regal Blvd.
Tulsa, Oklahoma
8:30 a.m. – 1:15 p.m.

Tulsa University Fluid Flow Projects
Seventy Eighth Semi-Annual Advisory Board Meeting
Agenda
Wednesday, April 25, 2012

8:00 a.m.	**Breakfast**	
8:30	**Introductory Remarks**	Cem Sarica
8:45	**TUFFP Progress Reports**	
	Executive Summary	Cem Sarica
	Low Liquid Loading in Gas-Oil-Water Flow	Kiran Gawas
	Effects of MEG on Multiphase Flow Behavior	Hamid Karami
10:15	**Coffee Break**	
10:30	**TUFFP Progress Reports**	
	Effect of Inlet Geometry on High Oil Viscosity Two-Phase Oil-Gas Flow Behavior in Horizontal Pipes	Rosmer Brito
	Effect of Medium Oil Viscosity on Two-Phase Oil-Gas Flow Behavior in Horizontal Pipes	Rosmer Brito
	Characterization of High Oil Viscosity Slug Flow in Horizontal Pipes	Eissa Alsafran
12:00 p.m.	**Lunch**	
1:15	**TUFFP Progress Reports**	
	Experiments of High-Viscosity Oil/Gas Slug Flow in Upward Vertical Pipes	Yue Lin
	Effect of High Oil Viscosity on Two-Phase Oil-Gas Flow Behavior in Vertical and Highly Deviated Pipes	Feras Alruhamani
	Liquid Loading of Gas Wells (completed)	Ge (Max) Yuan
	Liquid Loading of Gas Wells (current)	Mujgan Guner
	Unified Heat Transfer Modeling of Gas-Oil-Water Pipe Flow	Wei Zheng
3:00	**Coffee Break**	
3:15	**TUFFP Progress Reports**	
	Simplified Transient Two-Phase Modeling	Jinho Choi
	A Modeling of Hydrodynamics of Gas-Liquid Pipe Flow using Energy Minimization Concept	Hoyoung Lee
	Instrumentation and Facility Improvement Update	
	Evaluation of Capacitance Sensor for Liquid Holdup Measurement in	Rosmer Brito

	High Oil Viscosity Two-Phase Flow	
	HAZOP Study Update of 6” High Pressure Facility	Eduardo Pereyra
	New Research Initiative	
	Tulsa University Horizontal Well Artificial Lift Projects (TUHWALP)	Cem Sarica
4:45	**TUFFP Business Report**	Cem Sarica
5:00	**Open Discussion**	Cem Sarica
5:20	**Adjourn**	
5:30	**TUFFP/TUPDP Reception**	

Table of Contents

Executive Summary **1**

Introductory Presentation **5**

TUFFP Progress Reports

Executive Summary of Research Activities – Cem Sarica
Presentation 13

Low Liquid Loading Gas-Oil-Water Flow – Kiran Gawas
Presentation 29
Executive Summary 49

Effects of MEG on Multiphase Flow Behavior – Hamidreza Karami
Presentation 53
Executive Summary 67

Inlet Geometry Effects on Two-Phase High Viscosity Oil-Gas Flow in Horizontal Pipes – Rosmer Brito
Presentation 71
Executive Summary 101

Effects of Medium Oil Viscosity on Two-Phase Oil-Gas Flow Behavior in Horizontal Pipes – Rosmer Brito
Presentation 105
Executive Summary 115

Characterization of High Viscosity Slug Flow in Horizontal Pipes – Eissa Al-safran
Presentation 117
Executive Summary 133

Experiments of High-Viscosity Oil/Gas Slug Flow in Upward Vertical Pipes – Yue Lin
Presentation 135
Executive Summary 151

Effect of High Oil Viscosity on Two-Phase Oil-Gas Flow Behavior in Vertical and Highly Deviated Pipes – Feras Alruhaimani
Presentation 155
Executive Summary 165

Liquid Loading of Gas Wells (Completed) – Ge (Max) Yuan
Presentation 169
Executive Summary 191

Liquid Loading of Gas Wells (Current Study) – Mujgan Guner
Presentation 195
Executive Summary 209

Unified Heat Transfer Modeling of Gas/Oil/Water Pipe Flow – Wei Zheng
Presentation 211
Executive Summary 229

Simplified Transient Two-Phase Flow Modeling – Jinho Choi
Presentation 231
Executive Summary 247

Modeling of Hydrodynamics of Gas-Liquid Pipe Flow using Energy Minimization Concept – Hoyoung Lee
Presentation 251
Executive Summary 259

Evaluation of Capacitance Sensor for Liquid Holdup Measurement in High Viscosity Oil and Gas Flow – Rosmer Brito, Scott Graham, Eduardo Pereyra and Cem Sarica
Presentation 261
Executive Summary 273

Update on High Pressure Test Facility – Eduardo Pereyra, Scott Graham and Cem Sarica
Presentation 277

TUFFP Business Report
Presentation 291
Business Section 299

Appendices
Appendix A – Fluid Flow Projects Deliverables 319
Appendix B – Fluid Flow Projects Advisory Board Representatives 325
Appendix C – History of Fluid Flow Projects Membership 333
Appendix D – Contact Information 339

Executive Summary

Progress updates on each research project are given later in this Advisory Board Brochure. A brief summary of the activities is given below.

- *"Investigation of Gas-Oil-Water Flow".* Three-phase gas-oil-water flow is a common occurrence in the petroleum industry. The ultimate objective of TUFFP for gas-oil-water studies is to improve the TUFFP unified model based on theoretical and experimental analyses. There are several projects underway addressing the three-phase flow.

- *"High Viscosity Oil Two-phase Flow Behavior".* Earlier TUFFP studies showed that the performances of existing models are not sufficiently accurate for high viscosity oils with a viscosity range of 200 – 1000 cp. It was found that increasing oil viscosity had a significant effect on flow behavior.

  Our recent efforts resulted in development of new translational velocity, slug liquid holdup and slug length closure relationships. Moreover, TUFFP unified model was modified for high viscosity oil two-phase flow based on the experimental findings. This project continues at multiple fronts:

  1. *Inclination Angle Effects:* The objective is to conduct a study for inclination angles of -2° and +2°. During the past reporting period, the upward and downward inclination tests were completed and the data were analyzed and compared with horizontal data acquired by Gokcal (2005 and 2008) and Kora (2010). A final report was also posted at the TUFFP website. Further performance analysis of the used capacitance sensors indicated that some of the holdup data need to be retaken. This is scheduled for the summer of 2012.

  2. *Effects of Inlet Geometry:* During this period, an additional testing program has been carried out to specifically investigate the effects of inlet geometry. Three capacitance sensor pairs placed at different locations along the test section have been used. The data analysis indicates the flow development along the test section. Moreover, the flow for both configurations can be considered developed at the main measurement location of the facility.

  3. *Characterization of Slug Flow in Horizontal Pipes:* Dr. Eissa Al-Safran of Kuwait University continues to investigate the slug flow for high viscosity oils. This study is aimed at understanding the interaction of slug flow characteristics of slug frequency, liquid holdup, length and velocity.

  4. *Medium Viscosity Oil Study:* Only few experimental studies for medium oil viscosity ($20cP<\mu_O<200cP$) has been published in the literature. Furthermore, current two-phase flow models are based on experimental data with low and high viscosity liquids. Thus, there is a need of experimental and modeling investigation for medium viscosities in order to characterize the two-phase flow behavior for the entire range of possible viscosities.

     During this period, the instrument calibration and data processing models have been completed. The facility modifications are completed. Experimental testing will start right after the Spring Advisory Board meeting.

- *"Up-scaling Studies".* One of the most important issues that we face in multiphase flow technology development is scaling up of small diameter and low pressure results to large diameter and high pressure conditions. Studies with a large diameter facility would significantly improve our understanding of flow characteristics in actual field conditions. Therefore, our main objective in this study is to investigate the effect of pipe diameter and pressures on flow behavior using a larger diameter flow loop.

  This project is one of the main activities of TUFFP, and a significant portion of the TUFFP budget is allocated to the construction of a 6" high pressure flow loop. The first TUFFP study to be conducted utilizing the new facility is "Effect of Pressure on Liquid Loading".

  The facility generator has been successfully commissioned. Preparation of Standard Operating Procedures has been completed. Moreover, a detailed HAZOP review of the facility has recently been completed.

- *"Low Liquid Loading Gas-Oil-Water Flow in Horizontal and Near Horizontal Pipes".* Low liquid loading exists widely in wet gas pipelines. These pipelines often contain water and hydrocarbon condensates. Small amounts of liquids can lead to a significant increase in pressure loss along a pipeline. Moreover, existence of water can significantly contribute to the problem of corrosion and hydrate formation problems. Therefore, understanding of flow characteristics of low liquid loading gas-oil-water flow is of great importance in transportation of wet gas.

The main objectives of this study are to acquire experimental data of low liquid loading gas-oil-water flow in horizontal and near horizontal pipes using representative fluids and check the suitability of available models for low liquid loading three phase flow and suggest improvements if needed.

Since the last ABM significant amount of data have been acquired for ± 2° inclinations for both two-phase and three-phase flows. The data analysis reveals a unique relationship for radial droplet flux distribution that does not require interface droplet concentration.

- *"Effect of MEG on Multiphase Flow Behavior."* This project is rated very high in TUFFP questionnaire. 6 in. ID low pressure facility will be used for this project after the completion of three-phase low liquid loading project. It is anticipated that testing will start during summer of 2012.

  Since the last Advisory Board meeting, a literature search has been completed and preliminary lab testing to understand the mixing characteristics of water, oil and MEG has been conducted.

- *"Simplified Transient Flow Studies"*. The objective is to develop a simplified transient model which is fast and easy to use. Previously, two simplified transient models using two-fluid and drift flux approaches were proposed. Although the model predictions were reasonable for each flow pattern, the requirement of a flow pattern prediction model and utilization of two different modeling approaches are considered to be disadvantages of the model.

  A new model based on the drift flux approach for all flow patterns have already been developed during 2011. The developed model has been improved and verified with the TUFFP experimental data and OLGA simulation results.

- *"Liquid Loading of Gas Wells."* Liquid loading in the wellbore has been recognized as one of the most severe problems in gas production. At early times of the production, natural gas carries liquid in the form of mist since the reservoir pressure is sufficiently high. As the gas well matures, the reservoir pressure decreases reducing gas velocity. The gas velocity may go below a critical value resulting in liquid accumulation in the well. The liquid accumulation increases the bottom-hole pressure and reduces gas production rate significantly.

  Although significant effort has been made to predict the liquid loading of gas wells, experimental data are very limited. The objective of this project is to better understand of the mechanisms causing the loading. Flow characteristics are observed and measured along the pipe for various deviation angles. The effects of well deviation to the liquid loading are being investigated. The Turner model and its modified versions along with other models (including the TUFFP unified model) are evaluated with experimental results.

  The facility modifications and the first data acquisition campaign are complete. The preliminary data analysis revealed significant findings not only for liquid loading but also for the transition from annular flow. The results are available through TUFFP website.

  Further analysis of the data has since been conducted and the results indicate a correlation between wave characteristics and the liquid loading. This study is bing continued with two MS students. Ms. Mujgan Guner and Mr. Yasser Al-Saadi will further investigate liquid loading for inclination angle ranges of 90° to 45° and 45° - 0°, respectively.

- "*Unified Mechanistic Model*". TUFFP maintains, and continuously improves upon the TUFFP unified model. Collaborative efforts with Schlumberger Information Systems continue to improve the speed and the performance of the software.

  On the model improvement front, a new unified heat transfer model for gas/oil/water flow in pipes of all inclinations -90° to +90° is being developed. The resultant model will be included in the TUFFP Excel VBA software package for wellbore and pipeline thermal calculations.

TUFFP membership has risen from 16 to 17 (16 industrial companies and BOEMRE) for 2012 with the addition of Saudi Aramco. Efforts continue to further increase the TUFFP membership level. We expect one more new member for 2012. A detailed financial report is provided in this report.

Several related projects are underway. The related projects involve sharing of facilities and personnel with TUFFP. The Paraffin Deposition consortium, TUPDP, is into its fourth phase with 9 members. Tulsa University High Viscosity Oil Projects (TUHOP) Joint Industry Projects is into its third year. TUHOP currently has currently five members.

The University of Tulsa was recently selected by a group of companies and Artificial Lift Research and Development Council (ALRDC) to form a new consortium on horizontal well artificial lift. The efforts are underway to form a consortium called "Tulsa University Horizontal Well Artificial Lift Projects" TUHWALP. The consortium primarily will address the artificial lift needs of horizontal wells drilled into gas and oil shales. TUHWALP will start its activities in July 2012. The membership fee is $50,000. BP, Chesapeake, ConocoPhillips and Shell have already joined the consortium.

Fluid Flow Projects

78th Fluid Flow Projects Advisory Board Meeting

Welcome

Advisory Board Meeting, April 25, 2012

Safety Moment

- Emergency Exits
- Assembly Point
- Tornado Shelter
- Emergency
  - Call 911
- Restrooms

Fluid Flow Projects

Advisory Board Meeting, April 25, 2012

Introductory Remarks

- 78^{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
  - Don Harris
- Web Administrator
  - Lori Watts

Team …

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

Team …

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

Guests

- Hans Eikum, Galp Energia
- Meijuan Suo, PetroChina
- Tod Canty, J M Canty

Agenda

- 8:30 Introductory Remarks
- 8:45 Progress Reports
  - Executive Summary
  - Low Liquid Loading in Gas/Oil/Water Pipe Flow
  - Effects of MEG on Multiphase Flow Behavior
- 10:15 Coffee Break

Agenda …

- 10:30 Progress Reports
  - Effect of Inlet Geometry on High Oil Viscosity Two-Phase Oil-Gas Flow Behavior in Horizontal Pipes
  - Effect of Medium Oil Viscosity on Two-Phase Oil-Gas Flow Behavior in Horizontal Pipes
  - Characterization of High Oil Viscosity Slug Flow in Horizontal Pipes

Agenda …

- 12:00 Lunch
- 1:15 Progress Reports
  - Experiments of High-Viscosity Oil/Gas Slug Flow in Upward Vertical Pipes
  - Effect of High Oil Viscosity on Two-Phase Oil-Gas Flow Behavior in Vertical and Highly Deviated Pipes
  - Liquid Loading of Gas Wells (Completed)
  - Liquid Loading of Gas Wells (Present)
  - Unified Heat Transfer Modeling of Gas/Oil/Water Pipe Flow
- 3:00 Coffee Break

Agenda …

- 3:15 Progress Reports
  - Simplified Transient Gas-Liquid Two-Phase Flow Modeling
  - Modeling of Hydrodynamics of Gas-Liquid Pipe Flow Using Energy Minimization Concept
- Instrumentation and Facility Improvement Update
  - Evaluation of Capacitance Sensor for Holdup Measurement in High Oil Viscosity Two-Phase Flow
  - HAZOP Study Update of 6 in. High Pressure Facility
- New Research Initiative
  - Tulsa University Horizontal Well Artificial Lift Projects (TUHWALP)

Agenda …

- 4:25 TUFFP Business Report
- 4:40 Open Discussion
- 5:10 Adjourn
- 5:30 TUFFP/TUPDP Reception

Other Activities

- April 24, 2012
  - TUHOP Meeting
  - TUFFP Workshop
    - Excellent Presentations
    - Beneficial for Everybody
  - Facility Tour
- April 26, 2012
  - TUPDP Meeting

Fluid Flow Projects

Executive Summary of Research Activities

Cem Sarica

Advisory Board Meeting, April 25, 2012

Current Projects

- High Viscosity Multiphase Flow
- Low Liquid Loading Flow
- Up-scaling Studies
- Effects of MEG on Multiphase Flow

Current Projects …

- Liquid Loading of Gas Wells
- Simplified Transient Modeling
- Unified Model
- Energy Minimization Modeling

Fluid Flow Projects

Advisory Board Meeting, April 25, 2012

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
    - Observed Significantly Different Flow Behavior
    - Developed
      - Drift Velocity and Translational Velocity Closure Models
      - Slug Frequency Correlation
  - Kora (2010)
    - Investigated Slug Liquid Holdup
    - Developed New Closure Relationship

Fluid Flow Projects

Advisory Board Meeting, April 25, 2012

High Viscosity Multiphase Flow …

- Past Studies …
  - Jeyachandra (2011)
    - Inclination Angle Effect Investigation
      - Data Acquisition and Analysis for Downward and Upward Flows (- 2° and +2°)
      - Evaluation of Pressure Drop Models (Unified, Xiao and OLGA) and Closure Relationships for Slugs Characteristics
  - Brito and Pereyra (2011)
    - Transition from Stratified Smooth to Other Flow Patterns Experimental and Model Comparison

High Viscosity Multiphase Flow …

- Current Studies …
  - Holistic Analysis of Slug Flow Characteristics in Horizontal Pipes (Al-Safran)
  - Effect of Inlet Geometry on Two-Phase High Viscosity Oil-Gas Flow (Brito)

High Viscosity Multiphase Flow …

- Current Studies …
  - Medium Viscosity Study (20 cp – 200 cp) (Brito)
    - Progress
      - Facility Preparation
      - Oil Change
    - Near Future Activity
      - Testing After Spring 2012 ABM

Fluid Flow Projects Advisory Board Meeting, April 25, 2012

High Viscosity Multiphase Flow …

- Future Studies
  - High Viscosity Multiphase Flow in Vertical and Deviated Wells
    - Collaborative Effort with TUHOP
      - TUFFP 2 in. InclinableThree-phase Outside Facility
      - TUHOP Student (Yue Lin, MS Student)
      - Pressure Drop and Holdup Measurements and Visual Observations
      - Shared Deliverables
    - Further Detailed Experimental and Modeling Study (Al-Ruhaimani, Ph.D. Student)
      - Closure Relationship Testing and Development

Fluid Flow Projects Advisory Board Meeting, April 25, 2012

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 Data on Various Parameters, Including Entrainment Fraction
    - Remaining Tasks
      - 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 $\pm 2^\circ$ Inclination Angles from Horizontal
    - Objectives
      - Acquire Similar Data as in Horizontal Flow Study
      - Develop Improved Closure Relationships

Low Liquid Loading Flow …

- Progress
  - New Positioning Device for HSVC
  - Data Acquisition and Analysis for $\pm 2^{\circ}$ Inclination Angles
    - Unique Relationship for Radial Droplet Flux Distribution
- Near Future Activity
  - Continue Data Acquisition and Analysis
  - Completion by August 2012

Fluid Flow Projects

Advisory Board Meeting, April 25, 2012

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)

Fluid Flow Projects

Advisory Board Meeting, April 25, 2012

Up-Scaling Studies …

- New High Pressure, Large Diameter Facility
  - HAZOP
    - SOP Preparation
    - Third Party Review

Fluid Flow Projects

Advisory Board Meeting, April 25, 2012

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

Fluid Flow Projects

Advisory Board Meeting, April 25, 2012

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
  - Literature Review
  - Preliminary Lab Testing of MEG-Water-Oil Interaction
- Near Future Activity
  - Test Matrix Development
  - Flow Loop Modification

Liquid Loading of Gas Wells

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

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 and Analysis for 0°, 15°, and 30° Deviations
  - Film Reversal as Loading Mechanism
  - More Insights on Transient from Annular Flow
  - Wave Characteristics Indicates Loading
- **Near Future Activity**
  - Instrumentation Improvement
  - Further Data Acquisition for 0°, 15°, 30°, and 45° Deviations
- **Future Activity**
  - Data Acquisition for 60°, 75°, 85°, 90° and 95° Deviations

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 …

- Current Study (Choi)
  - Drift Flux Approach
  - Development of a Simplified Isothermal Model
    - Simulator Structure Design
    - Code Development (Explicit Solver)
    - Extended to Segregated Flow Patterns

Transient Modeling …

- Future Work
  - Properties Determination from Look-up Table Produced by PVTSim
  - 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
      - Model Development
    - Near Future Activity
      - Competition and Implementation

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
  - Concept is Successfully Applied to Stratified Flow
- Near Future Work
  - Implement the Concept to Other Flow Patterns

Fluid Flow Projects

Low Liquid Loading Gas-Oil-Water Flow

Kiran Gawas

Outline

- Objectives
- Introduction
- Experimental Study
- Model Comparison
- 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 ≤ 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

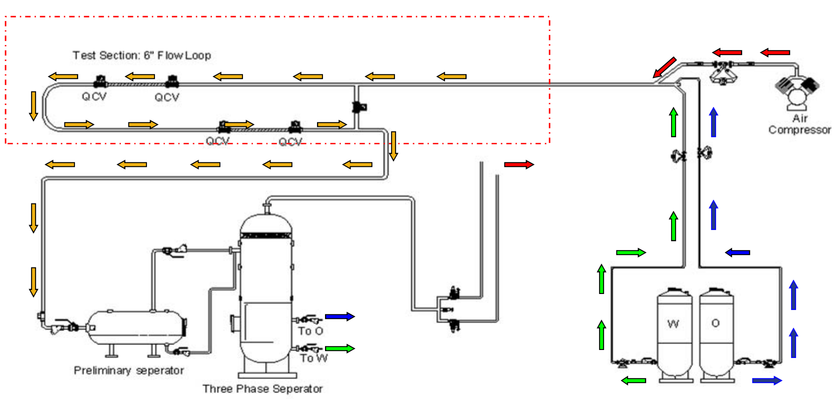
Experimental Study

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

Fluid Flow Projects

Advisory Board Meeting, April 25, 2012

Experimental Facility



Fluid Flow Projects

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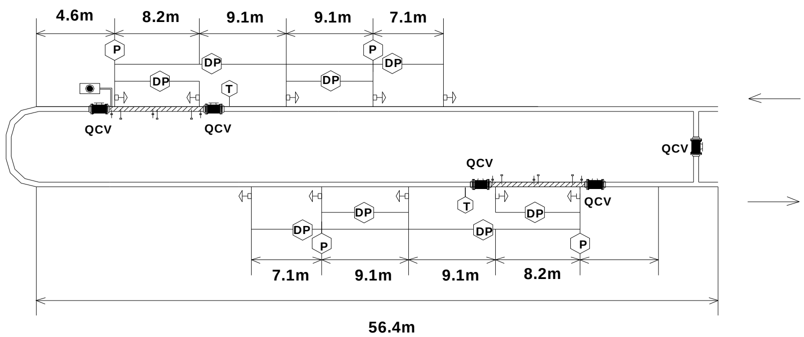
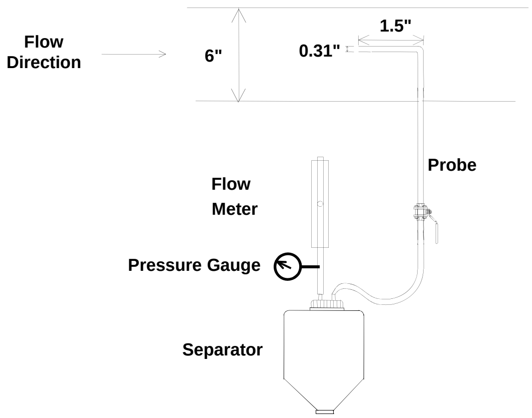
Test Section



Test Fluids

- Test Fluid
  - Gas – Air
  - Water – Tap Water
    - ρ = 1000 kg/m^3
    - μ = 1 cP
    - γ_{air} = 72 dynes/cm @ 60° F
  - Oil – Isopar L
    - ρ = 760 kg/m^3
    - μ = 1.35 cP
    - γ_{air} = 24 dynes/cm @ 60° F

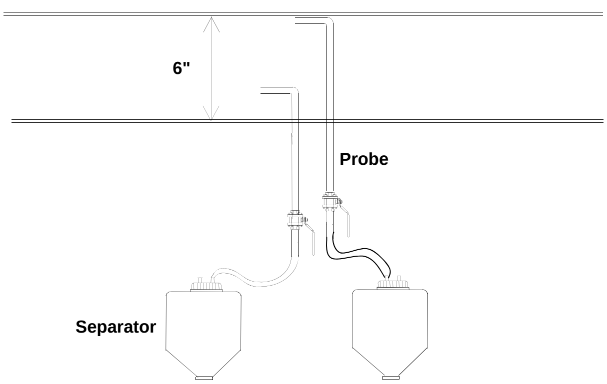
Droplet Flux : Isokinetic Probe



Fluid Flow Projects

Advisory Board Meeting, April 25, 2012

Droplet Flux



Isokinetic Sampling System
(Multiple Probes)

Fluid Flow Projects

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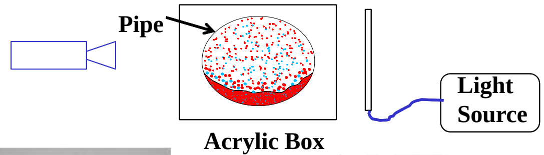
Droplet Visualization System

- Backlit Imaging Technique (Hay *et al.* 1998, Rodríguez and Shedd 2004, Patruno *et al.* 2009)



- Droplet Shadows Recorded at Very High Shutter Speed (< 5 µs)
- Motorized Translation Stage for Accurate Positioning

Droplet Size Distribution …

Original Image

8-Bit Gray ↓ Background Compensation

Gray Scale Image

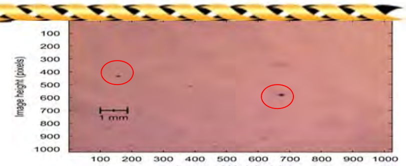
Threshold ↓ Criterion

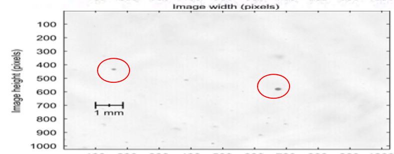
Binary Image

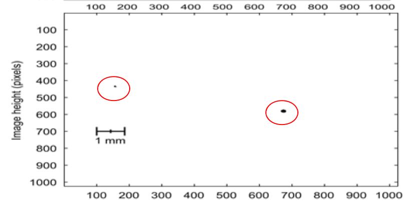
Edge ↓ Detection

Droplet Diameter

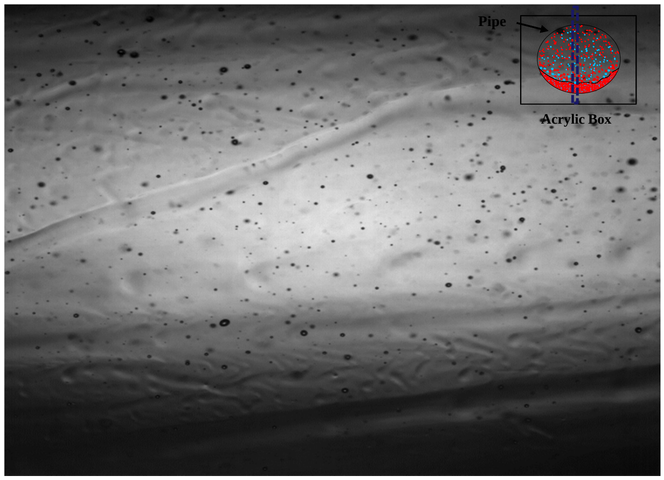
Patruno et al. (2010)







Droplet Size Distribution …



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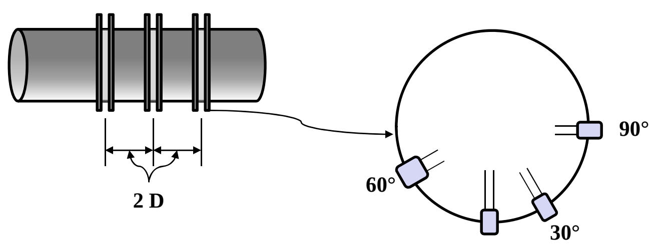
Wave Characteristics

- Three Parallel Wire Capacitance Probe



- Two Probes Set at Distance 2D Apart
- Wave Frequency and Wave celerity
- Wave Celerity using Cross-Correlation Technique (*Magrini 2009*)

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Experimental Program …

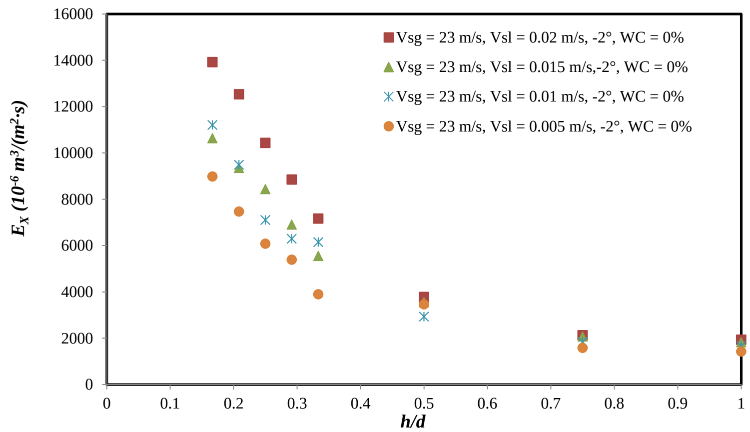
- Test Ranges
  - Superficial Gas Velocity:
    16.5 to 23 m/s
  - Liquid Loading Level :
    50 to 1200 $m^3/MMsm^3$
  - Water Cut:
    0, 10%, 100%
  - Inclination Angles:
    +2º, -2º

Experimental Results

- Two-Phase Test
  - Effect of Gas Flow Rate
  - Effect of Liquid Loading
  - Effect of Inclination
  - Effect of Fluid Properties
- Three Phase Test
  - Effect of Water Cut

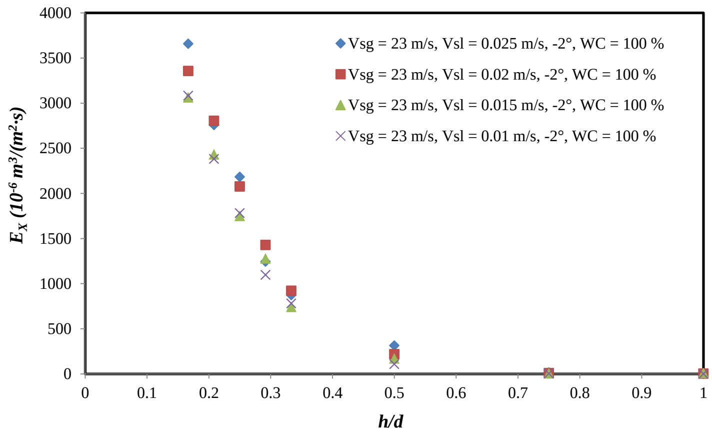
Droplet Flux Profile

Air - Oil



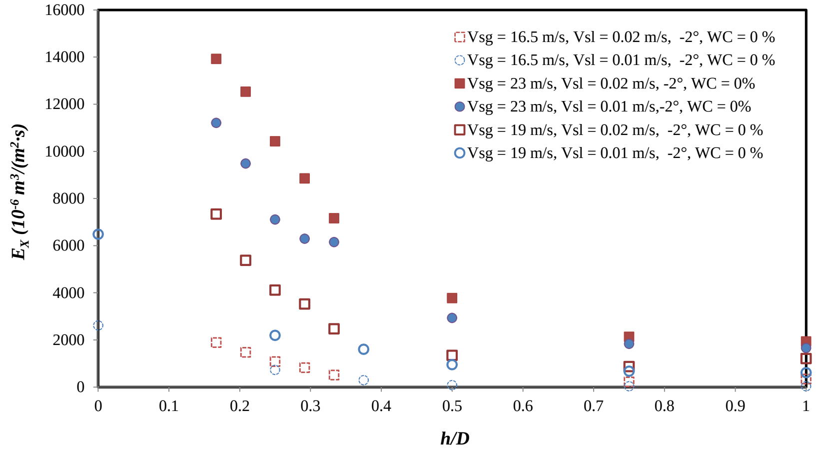
Droplet Flux Profile …

Air - Water



Effect of Gas and Liquid Flow Rate

Air - Oil



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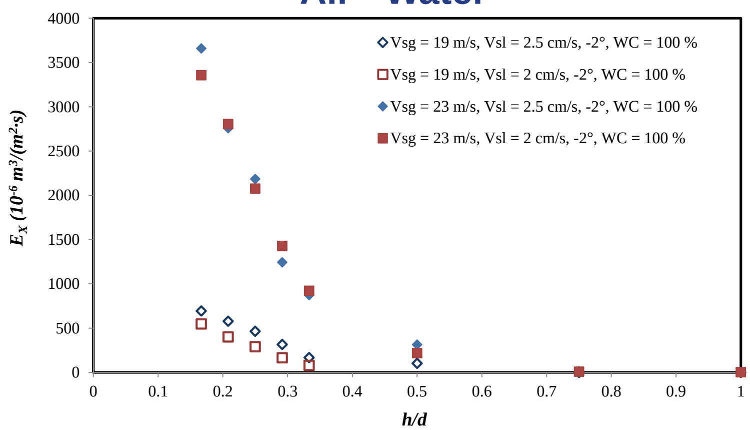
Effect of Gas and Liquid Flow Rate

Air - Water



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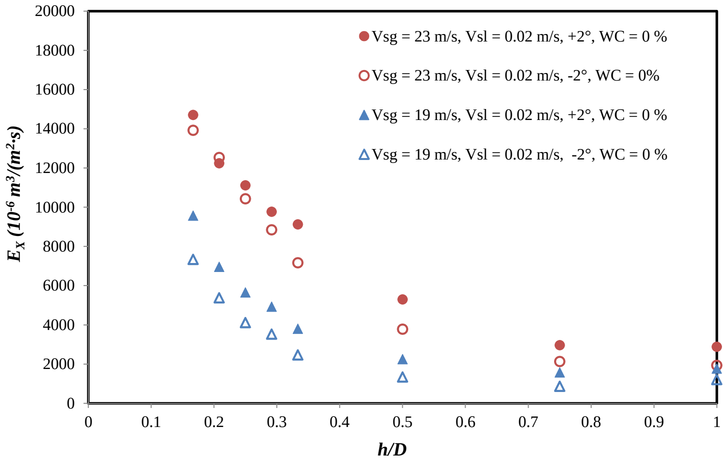
Effect of Inclination …

Air - Oil



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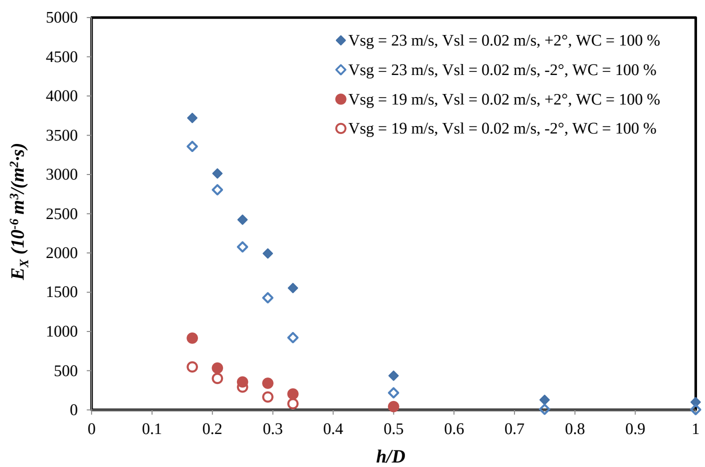
Effect of Inclination

Air - Water



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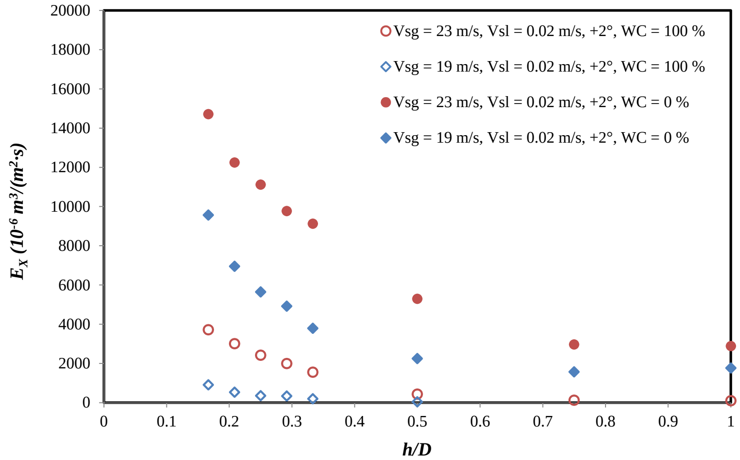
Effect of Fluid Properties



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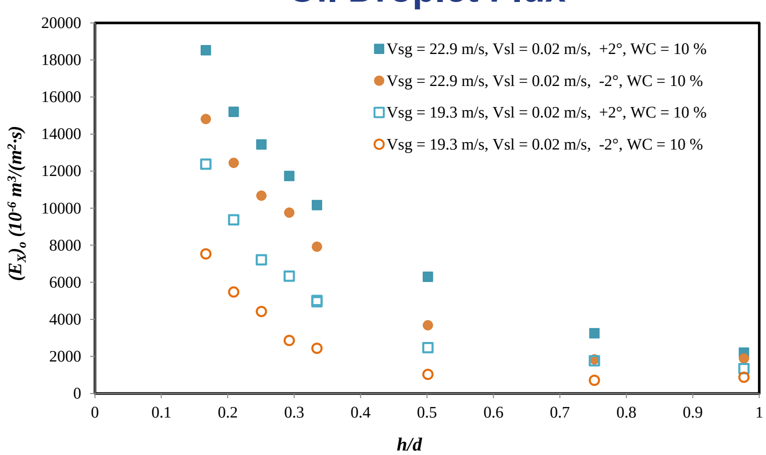
Experimental Results – Three Phase Flow

Oil Droplet Flux



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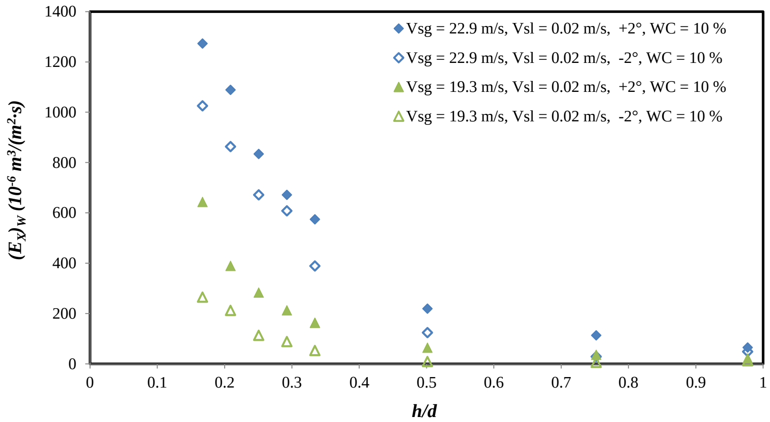
Experimental Results – Three Phase Flow …

Water Droplet Flux



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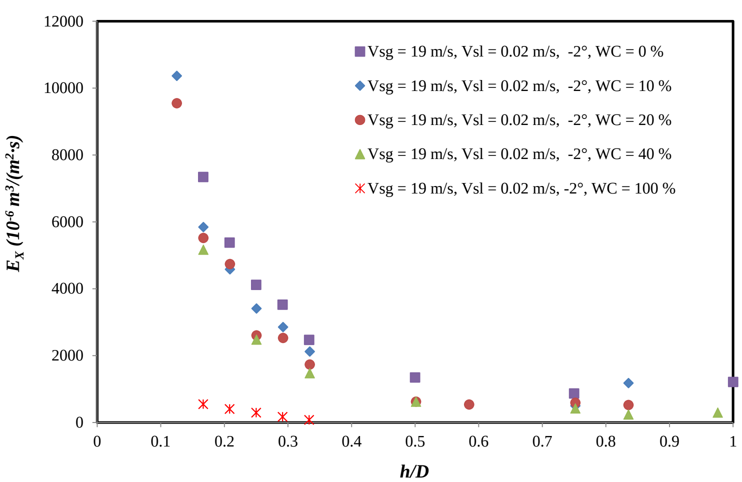
Effect of Water Cut



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Model Comparison

- **Paras and Karabelas (1991)**

$$\varepsilon \frac{dC}{dy} + u_T C = a(y)$$

- **Pan and Hanratty (2002)**

$$a(y) \equiv -D \int \frac{R_A - R_D}{(D/2)^2 - y^2} dy - B$$

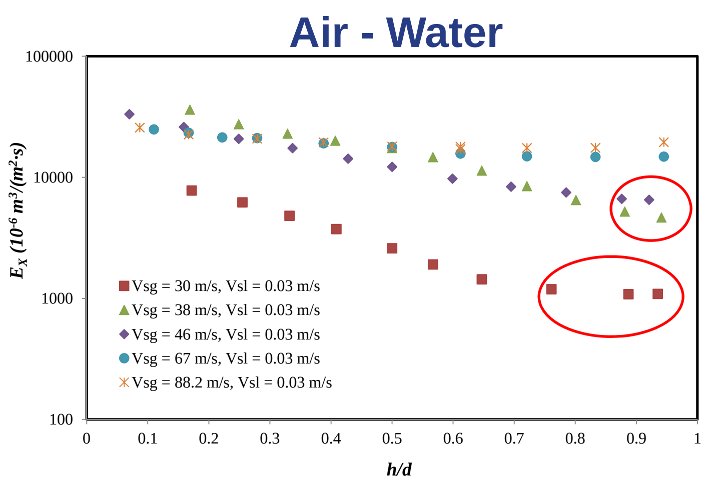
$$a(y) = 0$$

$$C = C_0 \exp\left(-\frac{u_T}{\varepsilon} y \right)$$

$$\langle C \rangle = \frac{1}{A} \int C_0 \exp\left(-\frac{u_T}{\varepsilon} y \right) dA$$

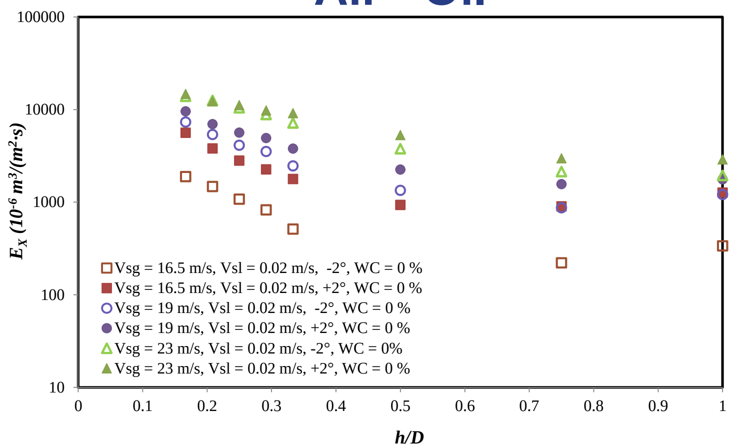
$$\varepsilon = \zeta (D/2) u^*$$

Williams (1996)



Current Experiment Results

Air - Oil



Droplet Distribution Model

- **Pan and Hanratty (2002)**
  - ζ = 0.04 for 9.53 cm pipe
  - ζ = 0.08 for 5.08 cm pipe

  $\varsigma \times D = const$
- **ζ Should be Independent of Diameter**
- **Use of Single Characteristic Droplet Size Instead of Droplet Size Distribution**
- **Ballistic Droplets Unaccounted**
- **Secondary Flow, Turbophoresis, Staffman Lift Force ?**

Droplet Distribution Model

- Skartlein et al. (2011)
  - Directly Accounted for Differences in Droplet Diameter
  - Linearization of Correlation for Settling Velocity about Mean Diameter

$$u_T = k\left(d/\bar{d}\right) + b$$

$$k = \alpha u_T\left(\bar{d}\right)$$

$$b = (1-\alpha)u_T(\bar{d})$$

Droplet Distribution Model

- Droplet Size Distribution is Fully Developed in a Relatively Thin Zone Above the Interface
- Gamma Distribution for Droplet Size

$$f_v(t) = \frac{\lambda^{\lambda+3}}{\Gamma(\lambda+3)} t^{\lambda+2} \exp(-\lambda t)$$

$$C(y) = C_0 \int_0^\infty f_v(t) \exp\left(-\frac{y}{\varepsilon}(kt+b)\right) dt$$

$$C(y) = C_0 \exp\left(-\frac{b}{\varepsilon} y\right)\left(1+\sigma_d^2 \frac{ky}{\varepsilon}\right)^{-(\sigma_d^{-2}+3)}$$

Preliminary Model Comparison

- Droplets Distribution Fully Developed
- Effect of Secondary Flow Neglected
- Droplet Settling Velocity – Intermediate Region i.e. α = 0.8
- Friction Velocity – Pressure Drop Measurement And Hydraulic Diameter Based on Two-Fluid Model
- Droplet Diameter – Al Sarkhi and Hanratty (2004)
- ζ = 0.167 (Baik and Hanratty, 2003)
- C_0 – Extrapolation
- σ_D – Tuning parameter (0.4 – 0.6)

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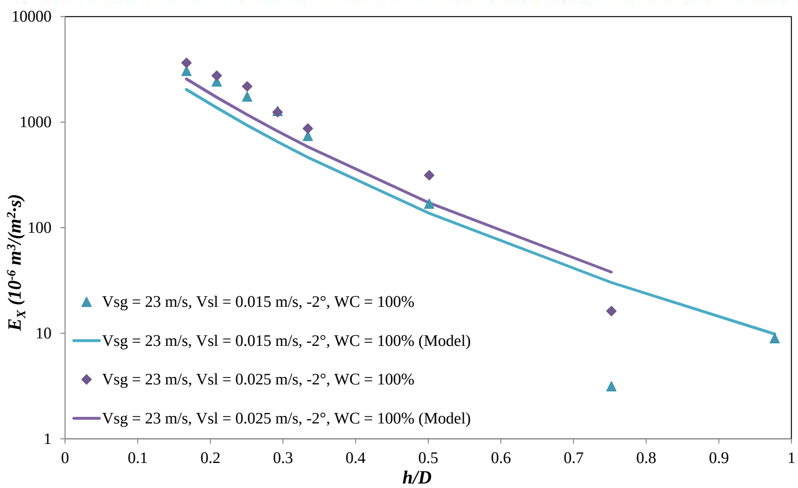
Preliminary Model Comparison



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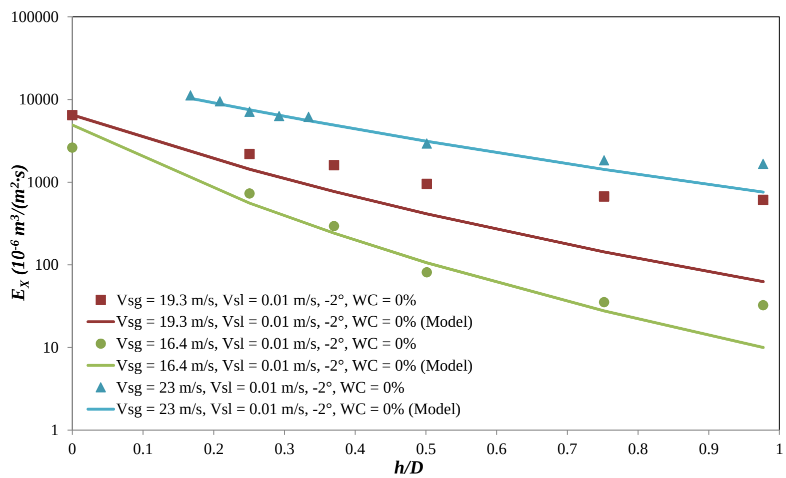
Preliminary Model Comparison



Model Improvements

- Effect of Form of Droplet Size Distribution Function
- Better Estimation for C_0
- Modeling of Droplet Transport in Three Phase Flow
  - Skartlien *et. al.* (2011)
    - Majority Phase Dominated Rate of Atomization
    - Uniform Mixing in the Liquid Phase
    - No Interaction between Oil and Water Droplets
  - Influence of Inclination on Liquid Mixing

Near Future Tasks

Literature Review	Ongoing
Testing	May 2012
Data Analysis	June 2012
Model Development	July 2012
Final Report	August 2012

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Thank You

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Low Liquid Loading in Gas-Oil-Water Pipe Flow

Kiran Gawas

Project Completion Dates

Literature Review	Ongoing
Experimentation	May 2012
Data Analysis and Model Comparison	June 2012
Model Validation	July 2012
Final Report	August 2012

Objectives

The main objectives of this study are

- 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 gas-oil-water flow is widely encountered in wet gas pipelines. Even though the pipeline is fed with single phase gas, the condensation of the gas along with traces of water results in three-phase flow. The presence of these liquids can result in significant changes in pressure distribution. Hydrate formation, pigging frequency, and downstream facility design are strongly dependent on pressure and holdup. Several authors have published papers on flow pattern identification and modeling of three-phase flow. However, most of them do not cover the range of low liquid loading flow, which is the main focus of this study. The experimental program will be conducted in a 6 in. ID flow loop. The main focus of this study is measurement of droplet flux, droplet size distribution and wave characteristics for horizontal and near horizontal pipes. Additionally, oil-water flow pattern in the liquid phase will be studied for different liquid loading levels and waters cuts.

Activities Summary

Experimental Facility

The flow loop consists of two runs of 6 in. (0.15 m) ID pipes, each run being 56.4 m in length. Acrylic visualization sections about 8 m in length are provided at the end of each run. Experiments can be conducted for inclination angles between -2° to +2°. The test fluids selected are Isopar L™, air and water. Tap water from the Tulsa city water supply is used as the water phase. The water density, viscosity and surface tension at standard conditions are 998 kg/m3, 0.001 Pa·s and 0.067 N/m, respectively. Isopar L™ is used as the oil phase. The oil density, viscosity and surface tension at standard conditions are 760 kg/m3, 0.0013 Pa·s and 0.024 N/m, respectively.

DeltaV™ digital automation system is used as the data acquisition system. Gas flow rate is measured using the micro motion flow meter CMF300, while CMF100 and CMF050 are used to measure oil and water flow rates, respectively. Pressure, temperature and pressure gradients are measured using Rosemount pressure and temperature transmitters and Rosemount differential pressure transducers, respectively. Fisher Scientific Semi-automatic Model 21 Surface Tensiomat™ tensiometer is used for measurement of surface tension of oil and water and interfacial tension between the two liquids. An iso-kinetic sampling system is used for determination of flux of droplets entrained in the gas phase. The system consists of an isokinetic probe, a separator and air flow meter. The isokinetic probe can be traversed vertically across the pipe cross section and entrainment flux at different positions can be recorded. A new setup was designed consisting of four isokinetic probes placed a foot apart from each other. Each probe was calibrated individually. Calibration was also done to ensure that the presence of a probe at the upstream location does not influence the readings of probe at the downstream locations. Two such sampling systems were built one each for the upward and downward test sections.

Droplet transport mechanism strongly depends on droplet size. A new high speed imaging technique has been developed for determining size distribution of droplets entrained in the gas phase. The high speed camera used for current study is Photron FASTCAM SA3 with pixel size of 17 µm. Tamron SP AF90 F/2.8 Di lens was used to capture the images. Arrilux Pocket Par 200™ is used for illumination from the back of the pipe so that the light source and camera face each other. A frosted flood lens is used between light source and the pipe so as to get even backlighting. A new motorized X-Z translation stage with repeatability of less than 2.5 µm and accuracy of less than ±8 µm was built for accurate focusing and positioning of the camera. Images are recorded at 3 different locations along the vertical axis of the pipe. Image processing algorithm similar to that used by Hay *et al.* (1998) will be used for determination of droplet size from raw images. The raw images are cropped and converted to 8-bit grayscale. The histogram is modified to enhance the contrast. The gray scale image is converted to binary by defining a suitable grayscale cutoff point. Thus the gray scale values below cutoff point become black and those above become white. The cutoff point is based on the calibration done using the calibration grid. Thus, all the droplets in the plane of focus would appear black while those out of focus will be neglected. Finally, the processed images are analyzed to determine droplet size distribution.

A new capacitance probe system for determination of wave characteristics is also designed. It will be used for determination of wave celerity, wave frequency and wave amplitude for the case of air-oil two-phase flow.

Experimental Study

Experimental Program

Experiments for determination of droplet flux for air-oil and air-water two phase flows and air-oil-water three phase flow for different gas flow rates, liquid loading levels and water cuts were performed.

Droplet flux becomes measurable only for gas superficial velocity above 12 m/s for air-oil flows and 15 m/s for air-water flows. Entrainment measurements were done for superficial gas velocities in the range of 16.5 to 23 m/s, liquid loading in the range of 200 to 1350 $m^3/MMsm^3$, inclination angles of -2° and +2° and for water cuts of 0 %, 10 %, 20 % and 100 %.

Experimental Results

Effect of gas and liquid flow rate and the effect of inclination angle were studied for the case of air-water and air-oil two phase flow. In addition to this, for the case of air-oil-water three phase flows, effect of water cut was also studied.

Unlike droplet entrainment in vertical flow entrainment in horizontal flow is highly asymmetric. Williams *et al.* (1996) and Paras and Karabelas (1991) observed that droplet flux variation in horizontal planes perpendicular to vertical axis was negligible. Droplet flux was hence measured at different locations along the vertical axis of the pipe above the interface. Droplet flux decreased substantially close to the interface and the rate of change tended to level off away from the interface. Also, droplet flux changed significantly with change in gas flow rate. The rate of change of droplet flux with distance from the interface was found to be a function of only gas flow rate and fluid properties. It was independent of liquid flow rate and inclination angle. Presence of water in the liquid phase tended to lower the amount of liquid entrained.

Model Comparison

Most of the models currently used for droplet transport are based on method proposed by Paras and Karabelas (1991). Droplet concentration distribution in horizontal gas-liquid flow is based on balance between turbulent diffusion and settling due to gravity. Assuming droplet size distribution is represented by a volume averaged characteristic diameter, and a constant turbulent diffusivity of the droplets, an analytical solution to the model can be obtained. As a result of these simplifications the concentration of droplets is found to be an exponential function of vertical distance from bottom of the pipe, for given flow conditions. Thus, this model predicts that a semi-log plot of concentration of droplets versus vertical distance would be linear. However, the results of current experiments show that there is significant deviation from linear behavior especially far away from the interface. Skartlien *et al.* (2011) used a similar approach but explicitly accounted for droplet size distribution by considering the dependence of terminal settling velocity on droplet size. It was found that the resulting droplet concentration profile has slight positive curvature instead of a straight line, as predicted by the previous model, which is also observed in the current set of experiments. This approach was hence used for modeling the distribution of droplet concentration observed in this study. Droplet distribution of oil and water was modeled using similar approach assuming no interaction between the oil and water droplets.

Future Work

- Complete testing for proposed test matrix.
- Analyze experimental data.
- Model development and comparison
- Final Report Submission

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Skartlein, R., Nuland, S., Amundsen, J. E.: “Simultaneous entrainment of oil and water droplets in high Reynolds number gas turbulence in horizontal pipe flow”, *International Journal of Multiphase Flow*, 37, 1282-1293, 2011.

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Fluid Flow Projects

Effects of MEG on Multiphase Flow Behavior

Hamidreza Karami

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 Understood
- Need to Generate Experimental Data and Improve Model Predictions

Objectives

- Collect Flow Pattern, Holdup, Pressure Drop and Entrainment Data Using TUFFP's 6 in. ID Low Pressure Test Facility With and Without MEG under Different Flow Conditions
- Benchmark Existing Models, Document Discrepancies
- Propose Improvements If Needed

Literature Review

- Hamersma & Hart (1987)
  - Correlated Liquid Holdup with Different Parameters With and Without Glycol
  - Relative Increase in Holdup Observed by Adding Glycol
- Hamersma & Hart (1989)
  - Slight Increase in Both Rippling of Liquid Film and Pressure Gradient by Adding Glycol or a Detergent

Literature Review

- Nyborg & Dugstad (1993 & 2003)
  - Decrease in the Aqueous Phase Droplet Formation in the Presence of Oil Phase
  - Glycol Content of Droplet Increases by Increasing Superficial Gas Velocity
  - Glycol Content in Gas Phase is Always Much Higher than What is Expected by Vapor Pressure of Glycol

Literature Review …

- Wilson *et al*. (2004)
  - No Significant Difference in Flow Behavior for Different Cases With and Without Glycol
  - No Data Presented

Literature Review …

- Danielson & Joosten (2006)
  - Froude Number as a Correlating Parameter for both Droplet Creation and Liquid Mixing
  - Fr > 2, Suggested for Effective Glycol Distribution
  - At Fr = 16, 30 Meters Past the Inlet Needed to Achieve Better than 80% Mixing Efficiency

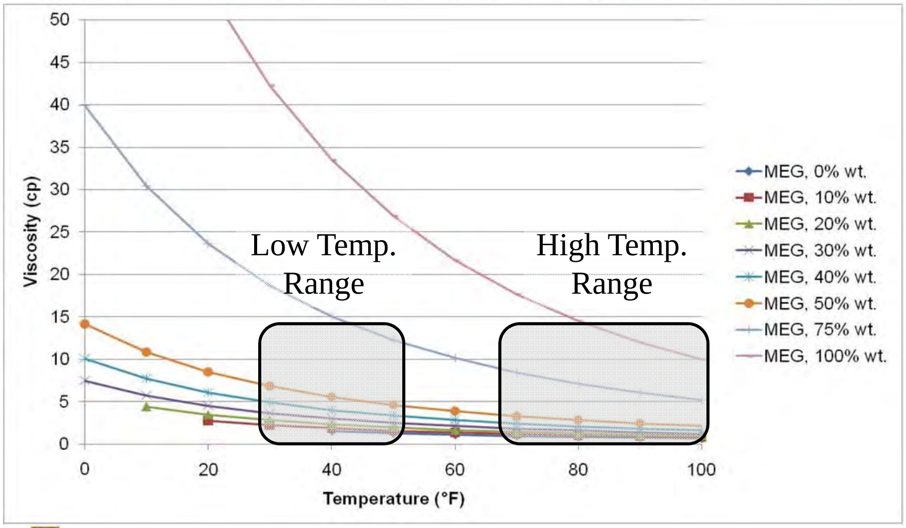
Literature Review

- Nyborg & Dugstad (2007)
  - For Normal Water Condensation Rates Found in Wet Gas Pipelines, It is the Limiting Factor for Top of Line Corrosion
  - By Counteraction of Increased Volume of Condensed Aqueous Phase and Reduced Iron Solubility, Top of Line Corrosion is not Affected by Presence of Glycol

Experimental Program

- MEG Weight Percent: 10%, 20%, 35%, 50%, 75%
- Inclination Angles 0° and ±2°
- Water Cuts 5%,10%,100%
- Initial Tests Under Steady State Conditions

Testing Range



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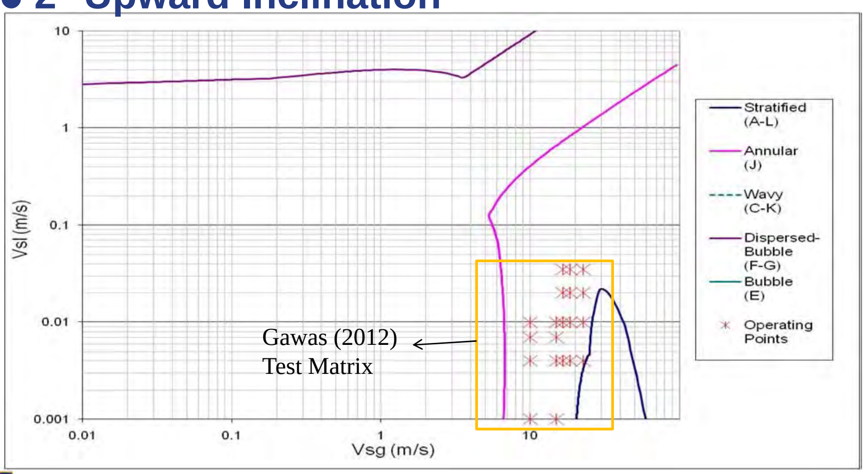
Test Matrix

- 2° Upward Inclination



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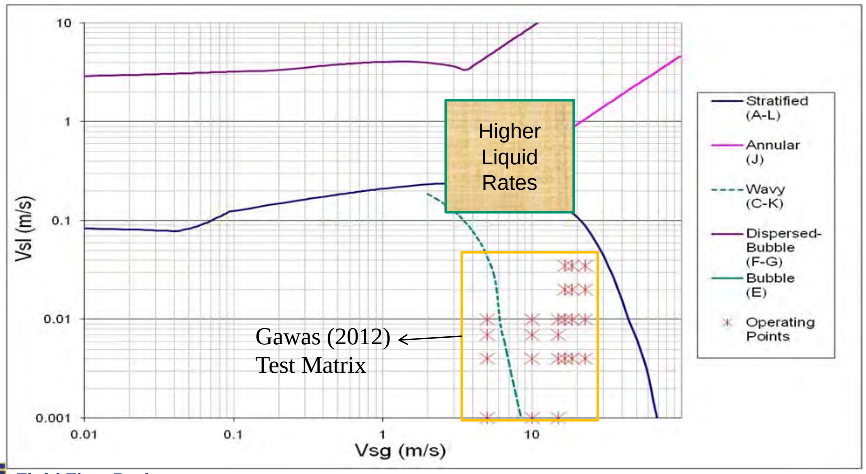
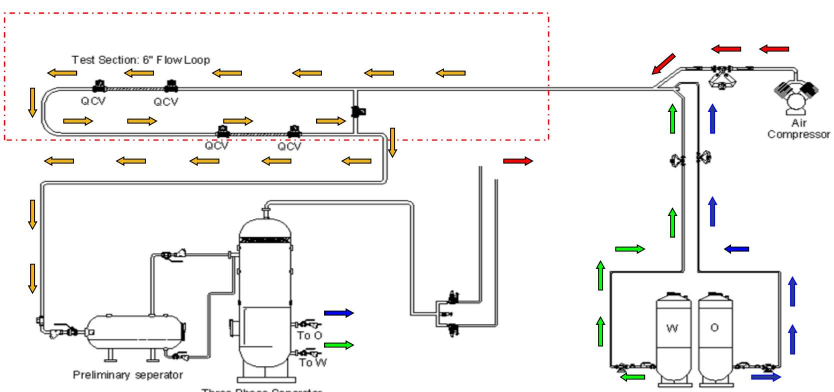
Test Matrix

- Horizontal Flow



Experimental Facility

6-in ID Low Liquid Loading Facility



Measurement Techniques

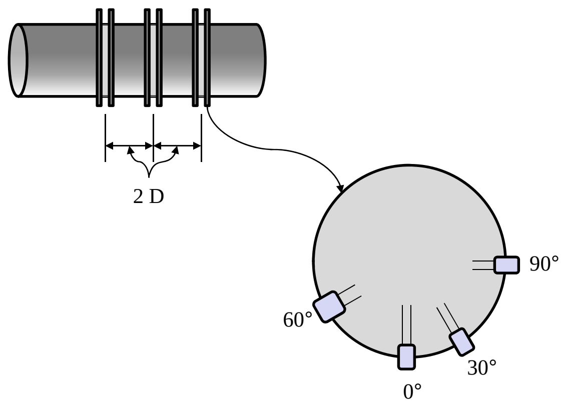
- Pressure and Temperature: PTs, DPs, and TTs
- Holdup: Quick Closing Valves and Pigging System
- Entrainment Rate: Iso-kinetic Sampling
- Droplet Size Distribution
- Capacitance Sensor
- Portable Densitometer

Capacitance Sensors …

- Measuring Waves Characteristics
  - Length
  - Celerity
  - Frequency
  - Amplitude
- Film Distribution
  - Film Thickness

Capacitance Sensors …

- Proposed Schematic



Capacitance Sensors …

- Sensor Construction Feb. 2012
- Sensor Calibration Apr. 2012
- Sensor will be First Used by Gawas in May 2012

Separation Tests …

- Different Mixing and Separation Tests Conducted with High Shear Mixing
- Separation of Water, Glycol and Oil Was Tested

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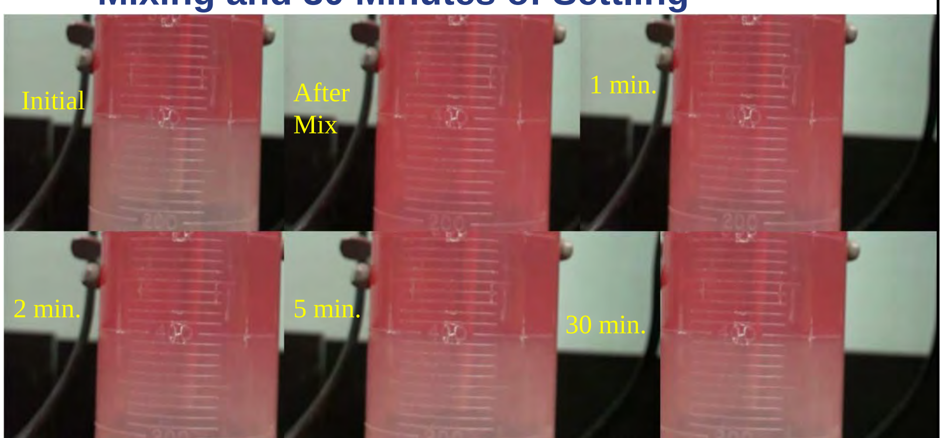
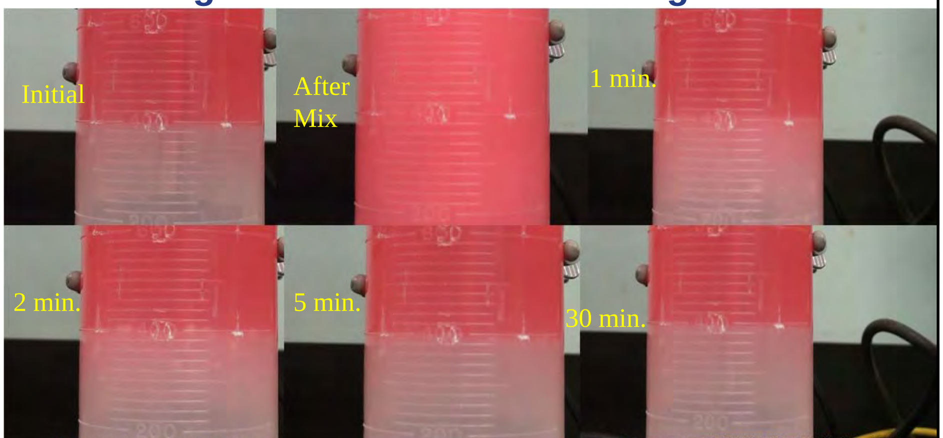
Separation Tests …

- 400 ml Glycol + 600 ml Oil, 7 Minutes of Mixing and 30 Minutes of Settling



Separation Tests …

- 400 ml Water + 600 ml Oil, 7 Minutes of Mixing and 30 Minutes of Settling

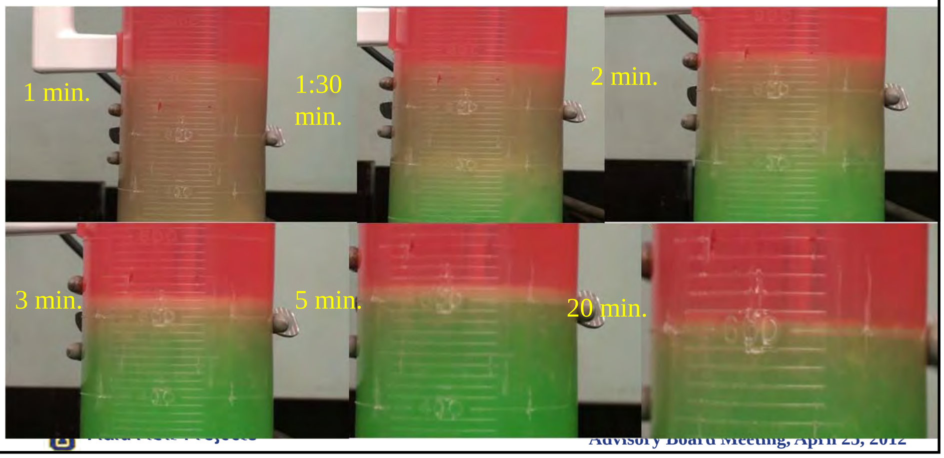


Separation Tests …

- 400 ml Water + 600 ml Oil, 200 ml of Glycol Added, 3 Minutes of Mixing and 30 Minutes of Settling

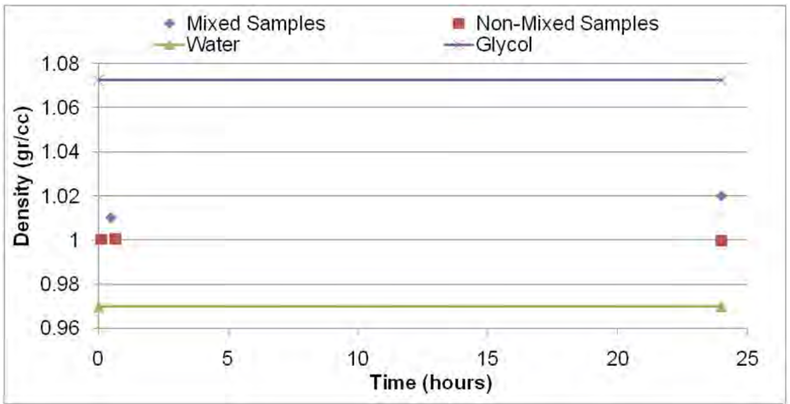
Separation Tests …

- 400 ml Water + 600 ml Oil, 200 ml of Glycol Added, 3 Minutes of Mixing and 30 Minutes of Settling



Separation Tests …

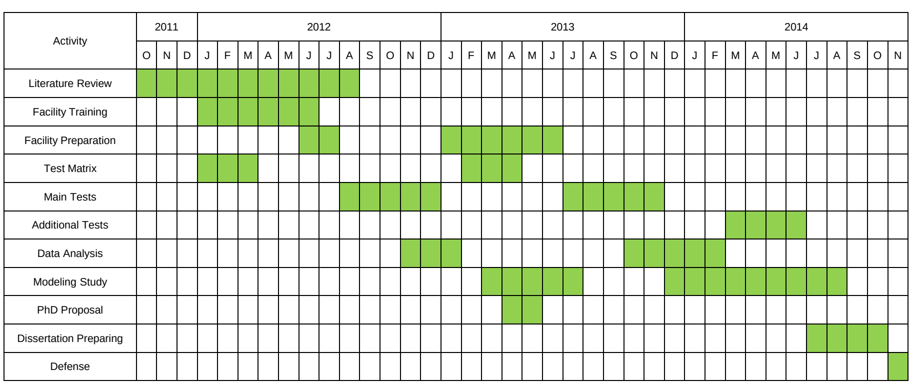
- Water-Glycol Gravitational Segregation Tests Conducted



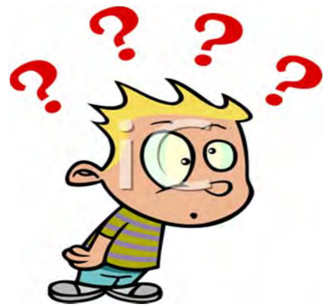
Close Future Activities

- Literature Review (Ongoing)
- Facility Preparation (Summer 2012)
- First Phase Experiments (Fall 2012)
- Facility Modification (January 2013)

Research Schedule



Questions and Comments



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Advisory Board Meeting, April 25, 2012

Effects of MEG on Multiphase Flow Behavior

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Project Completion Dates

Literature Review .... Ongoing
Facility Modification .... Summer 2012
Data Acquisition .... Fall 2012
Data Analysis .... Spring 2013
Model Comparison and Development .... Fall 2013

Objectives

The objectives of this study are:

- Acquire Flow Pattern, Holdup, Pressure Drop and Entrainment Data using a 6" ID Pipe With and Without MEG under Different Flow Conditions;
- Benchmark Existing Models, Document Discrepancies;
- Propose Improvements If Needed.

Introduction

Monoethylene glycol (MEG) is used continuously in deep water gas production systems as a hydrate inhibitor. It is injected at the subsea tree upstream of the choke. Thermodynamic partitioning of MEG between different phases has been studied from a phase behavior standpoint allowing predictions of MEG concentration in the different phases. Some work has been done at The University of Tulsa Hydrates Flow Performance and South West Research Institute on settling and effectiveness of MEG injection under quiescent conditions. The objective is to inhibit pooled water in a wellbore or a jumper. However, MEG mixing in multiphase flow and its effect on flow parameters such as liquid holdup, flow pattern, pressure gradient and entrainment rate are not well understood.

Major gas projects are developing online Production Management Systems for real time virtual metering, MEG tracking, hydrate check, rate change slugs, etc. Considering the significance of liquid inventory and hydrate management on these large gas tiebacks, it is needed to generate datasets for the open literature that can be used by model developers.

Literature Review

There have been several studies in the past, investigating the effect of different parameters on flow characteristics in multiphase flow. Most of these studies have been conducted for two-phase flow, but there are some experimental and modeling studies for three-phase gas-oil-water flow. Among these studies, only few of them are focused on low liquid loading flow.

On the other hand, MEG is an additive that is injected frequently in different production systems to inhibit hydrate formation and corrosion. It is important to know its impact on liquid holdup and pressure gradient, flow pattern and wetted wall fraction by liquid phases. Only few studies have investigated the effect of MEG on multiphase flow parameters. Hamersma & Hart (1987) presented experimental results for an air-water and an air-water-ethyleneglycol system with low liquid holdup values. From the collected experimental holdup data, the authors proposed a correlation based on three parameters; namely, ratio of gas, liquid densities and superficial velocities. Liquid density takes into account the effect of MEG concentration on liquid holdup.

Later, Hamersma & Hart (1989) conducted another study on air-water two-phase flow by adding glycol and a detergent (Tween). By decreasing the interfacial tension, from adding these additives, they observed no effect on the value of liquid holdup and the wetted wall fraction. However, a slight increase in rippling of the liquid and the pressure gradient, and earlier transition from wavy to annular flow was observed. Wilson *et al.* (2004) conducted an experimental study on a 3 in. ID flow loop looking at gas-condensate-water-MEG systems to benchmarked OLGA2000. Experimental work was conducted in four campaigns: gas-condensate, gas-condensate-fresh water, gas-condensate-fresh water including 50 wt% of MEG, gas-condensate-fresh water including 42 wt% of MeOH. Using three different water phases, they observed no major differences in flow behavior between them. However, no data was presented in the paper.

Nyborg and Dugstad conducted a series of experimental studies, presented in 1993 and later in 2003. The experiments were conducted under three phase conditions, including glycol in aqueous phase, and with glycol tracing utilization. They observed a sharp decrease in aqueous phase droplet formation by adding the hydrocarbon phase to the system. By increasing superficial gas velocity, the glycol content in the droplet remains constant at first. Then, by changing the flow pattern from stratified wavy to annular flow, it increases sharply. The observed glycol content in gas phase is always much higher than the predicted by vapor pressure of glycol. Nyborg and Dugstad (2007) conducted another study on top of line corrosion in wet gas pipelines. For normal water condensation rate values, this parameter was the limiting factor for top of line corrosion. Additionally, in the presence of glycol, its increasing effect on the volume of condensed aqueous phase and reducing effect on iron solubility counteracted and top of line corrosion was not changed significantly.

Danielson and Joosten (2006) proposed a Froude Number useful for correlating droplet creation and liquid mixing in low liquid loading multiphase flow. They suggested Froude number values higher than 2, for efficient glycol distribution. Looking at the efficiency of glycol mixing in the aqueous phase, for flow conditions equivalent to Froude number of 16 about 30 meters after the glycol injection point was required estimation to reach 80% of mixing efficiency.

Experimental Program

TUFFP's 6 in. ID low liquid loading facility will be utilized to conduct the experimental part of this study. The current measurement instruments, along with new instrumentation, will be used. Pressure and temperature will be acquired using different transducers installed in the facility. Holdup will be measured by means of four quick closing valves and available pigging system. Iso-kinetic sampling probe will be utilized to measure entrainment rate at different locations of the pipe. And, a portable densitometer, Densito 30PX, is considered to monitor MEG concentration for different experiments.

New capacitance system, including multiple probes around the pipe periphery, will be used to measure wave characteristics. Wave length, celerity, frequency, amplitude, and film distribution will be reported for all experimental conditions. Three capacitance systems will be installed 12 inches apart. Each capacitance system includes different probes at 0°, 30°, 60°, and 90° from the bottom of the pipe. Static calibration of the probes is underway.

A series of mixing and separation tests were conducted in the lab to investigate the level of miscibility between water, glycol, and oil. Aqueous phase, including glycol concentrations of 0%, 50%, and 100%, was mixed with the oil phase under different shear conditions. Settling time under the different conditions has been recorded. For all cases, separation of phases was completed after a short period of time (less than 5 minutes), and no stable emulsions was observed between oil and aqueous phase. Faster separation was observed for higher water concentration cases.

Miscibility of water and glycol in the aqueous phase was tested by means of gravitational segregation. For the cases where water and glycol were mixed, even with a very low shear, no segregation was observed, even after 24 hours. Even for the non-mixed samples, the density of the sample taken from top of the mixture was very close to the average density indicating that water and glycol are quite miscible.

Adding MEG to the aqueous phase changes its characteristics. The phase density increases slightly with the increase of MEG concentration. However, the change in viscosity is more drastic, and makes denser phase, namely, water, more viscous than oil phase. This may result in different flow characteristics such as the droplet entrainment rate and onset of entrainment.

First phase of the experiments will be conducted during fall 2012 over the same test matrix of Gawas (2012). This includes low liquid loading three phase experiments with superficial gas velocity ranging from 5 to about 23 m/s, and superficial liquid velocity ranging from about 0.1 to 3 cm/s. Different water cuts, namely, 5%, 10%, and 100%, and MEG concentrations from 10 wt% to 75 wt% and inclination angles of 0° and ±2° will be considered. Experiments can be conducted under different flowing conditions. Decisions are yet to be made whether water and glycol need to be fully mixed before entering the test section or glycol is injected separately at the inlet of the test section.

References

Danielson, T.J., Joosten, M.W., "Use of Dimensional Analysis for Evaluation of Corrosion Inhibitor Effectiveness in Wet Gas Pipelines", International Corrosion Conference & Expo, Paper No. 06569 (2006).

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Hart, J., Hamersma, P.J., and Fortun, J.M.H., "Correlations Predicting Frictional Pressure Drop and Liquid Holdup during Horizontal Gas-Liquid Pipe Flow with a Small Liquid Holdup", International Journal of Multiphase Flow, Vol. 15, No. 6 (1989), pp. 947-964.

Nyborg, R., and Dugstad, A., "Top of Line Corrosion and Water Condensation Rates in Wet Gas Pipelines", International Corrosion Conference & Expo, Paper No. 07555 (2007).

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Wilson, A., Overaa, S.J., Holm, H., "Ormen Lange-Flow Assurance Challenges", Offshore Technology Conference, Paper# 16555 (2004).

Fluid Flow Projects

Inlet Geometry Effects on Two-Phase High Viscosity Oil-Gas Flow in Horizontal Pipes

Rosmer Brito

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Outline

- Objective
- Experimental Program
- Inlet Configurations
- Data Analysis Methodology
- Experimental Results
- Conclusions
- Future Tasks

General Objectives

- Investigate the Inlet Geometry Effects on Two-Phase Air and High Viscosity Oil (181 cP-587 cP) for Horizontal Pipe
  - Flow Pattern
  - Slug Characteristics

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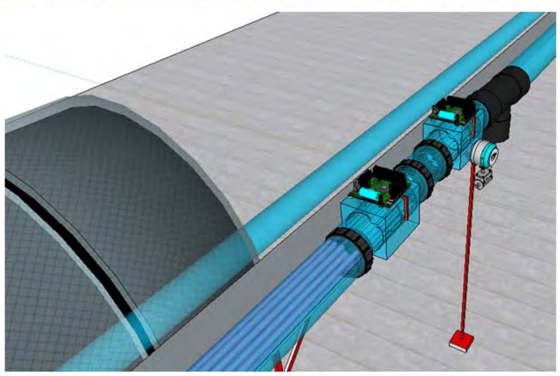
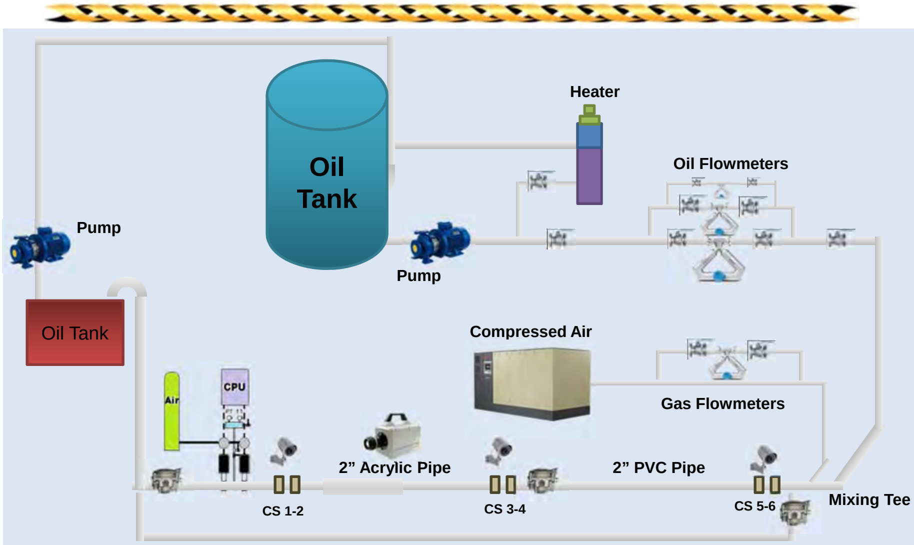


Experimental Program

Experimental Facility

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

Experimental Facility …



Test Oil Characteristics

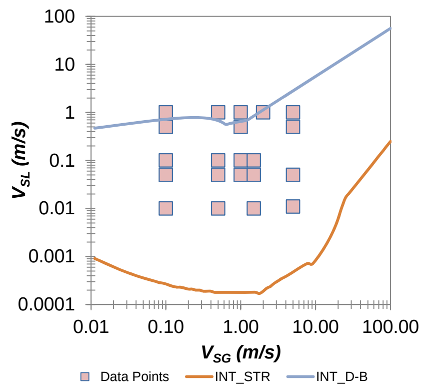
- Test Liquid: Citgo Sentry 220 Oil
  - Gravity: 27.6 °API
  - Viscosity: 220 cP @ 40 °C
  - Density: 889 kg/m3 @ 15.6 °C
  - Surface Tension: 0.02976 N/m
- Test Gas: Air

Experimental Matrix

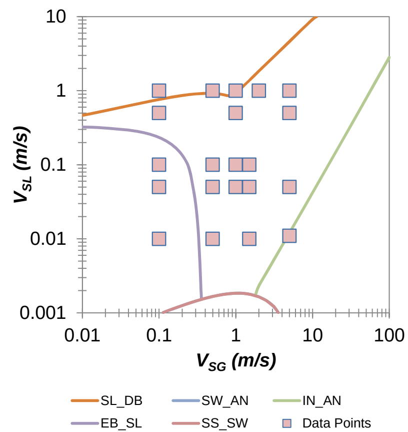
- Based on Gokcal (2008) Experimental Matrix
- Superficial Liquid Velocity
  - 0.01 – 1.0 m/s
- Superficial Gas Velocity
  - 0.1 – 5.0 m/s
- Mixture Reynolds Number
  - 10 – 450
- Inclination
  - Horizontal

Experimental Matrix …

Flow Pattern Map for 587 cP Oil (TUFFP Unified Model)



Flow Pattern Map 587 cP Oil (Barnea Model)



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Inlet Configurations

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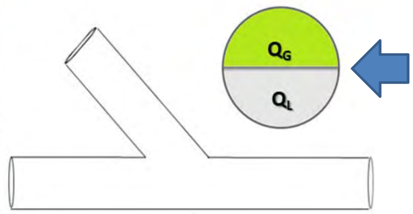
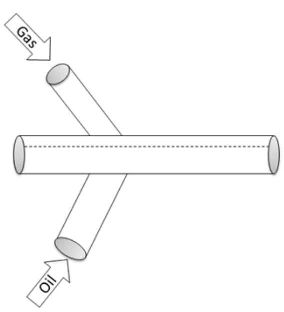
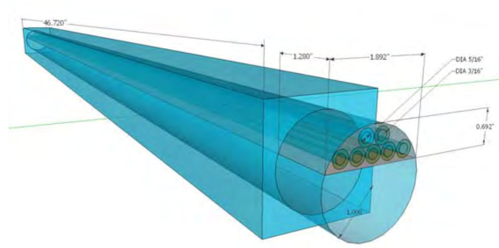
Inlet 1 “Y” Type



Steel Plate

Inlet 2 “2-Y” Type





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Data Analysis Methodology

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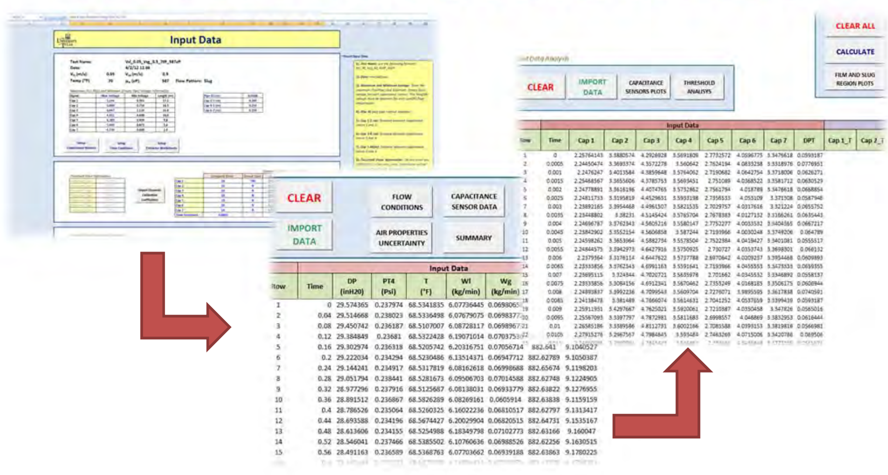
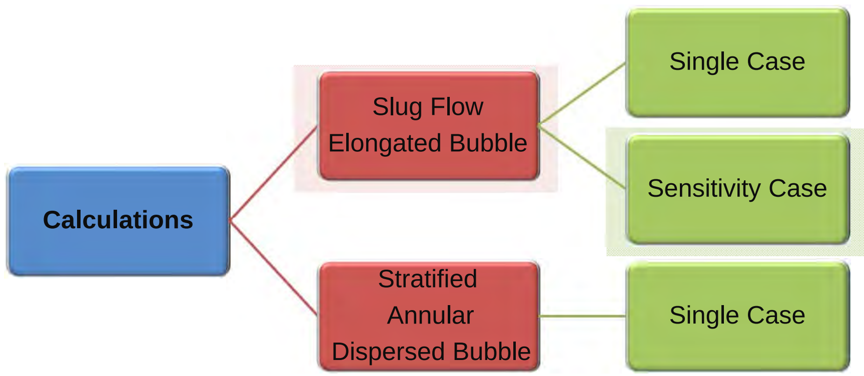
Input Data
Quality Validation and Setup



Calculations



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

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}
  - $L_{slug\_max\_CC}$, $L_{slug\_max\_FT}$
  - $L_{slug\_min\_CC}$, $L_{slug\_min\_FT}$

30

Threshold Values

Min ≤ Threshold ≤ Max

(Monte Carlo)

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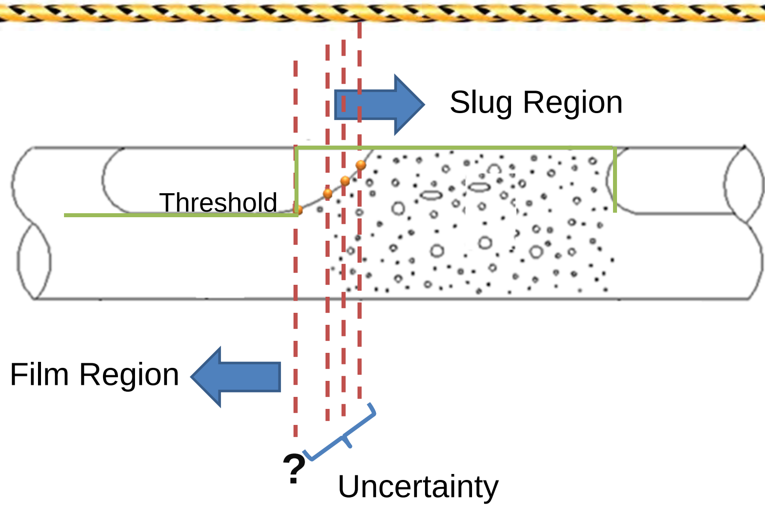
Threshold Value Selection



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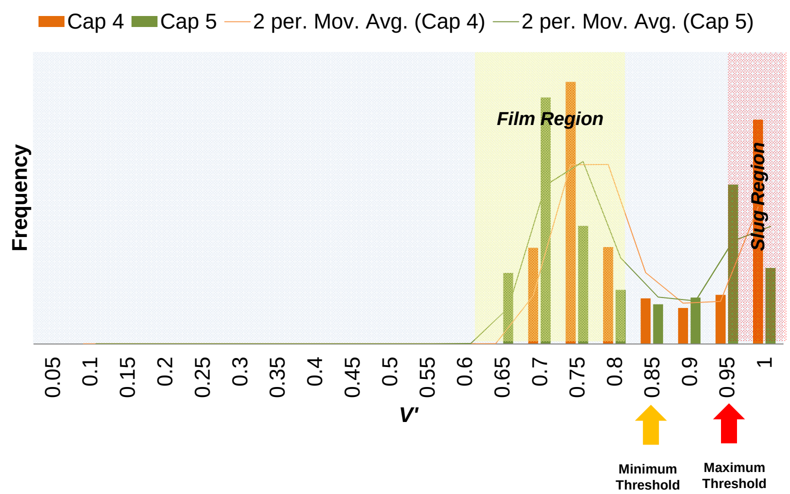
Threshold Value Selection



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Experimental Results

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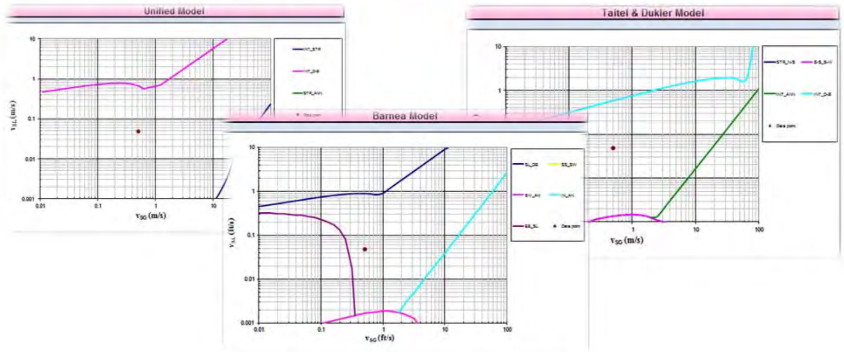

Flow Pattern

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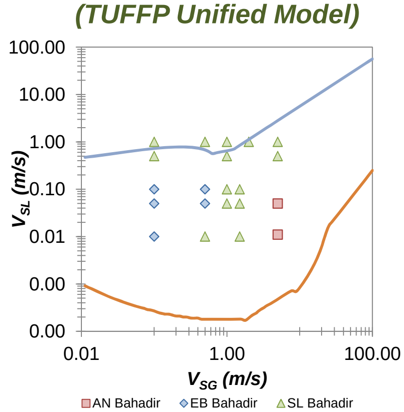
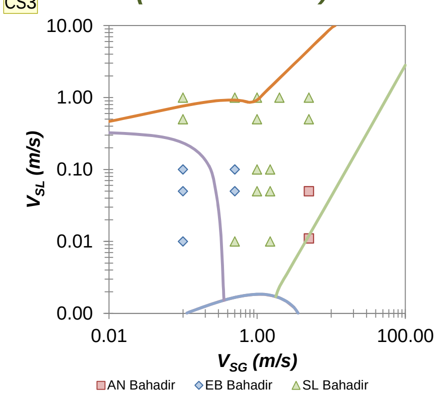
Gokcal's Results (2005)

Flow Pattern Map 587 cP Oil (TUFFP Unified Model)



Flow Pattern Map 587 cP Oil (Barnea Model)

CS3



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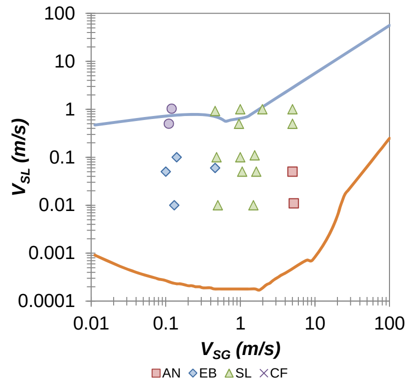
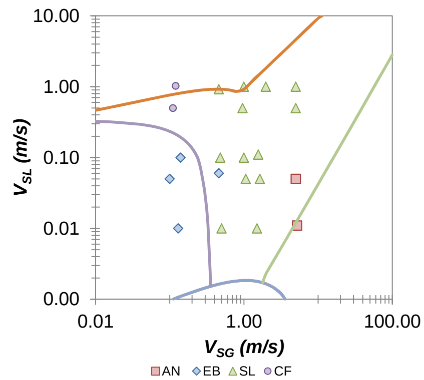
Inlet 1

Flow Pattern Map 587 cP Oil (TUFFP Unified Model)



Flow Pattern Map 587 cP Oil (Barnea Model)



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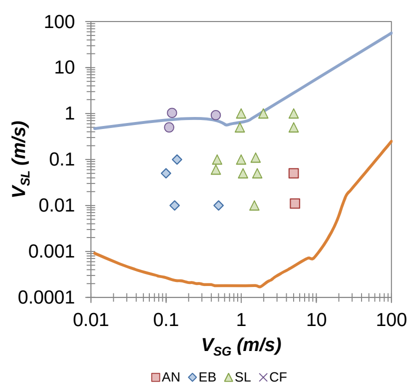
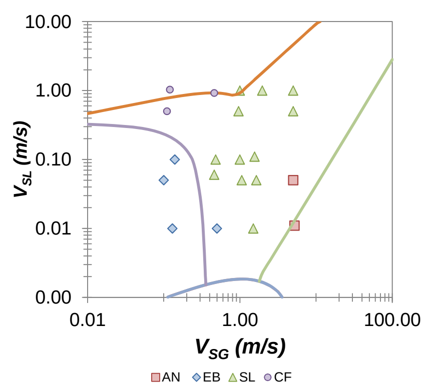
Inlet 2

Flow Pattern Map 587 cP Oil (TUFFP Unified Model)



Flow Pattern Map 587 cP Oil (Barnea Model)



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Inlet Effect on Flow Pattern

- Experimental Observations Indicates that the Flow Pattern Map for 587 cP is not Affected by Inlet Geometry Configuration

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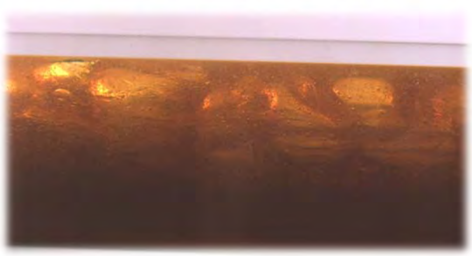
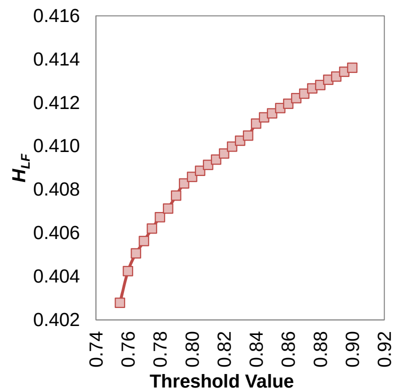


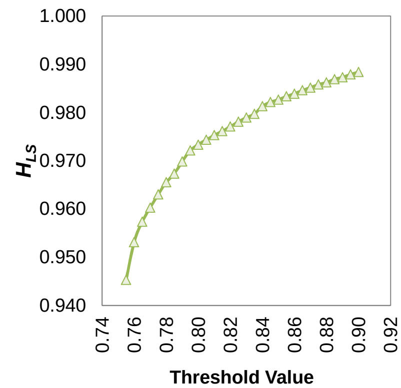
Threshold Value Effect on Slug Characterization

Holdup

*Capacitance Sensor 2. **Threshold Value Effect on Film Region Liquid Holdup***



*Capacitance Sensor 2. **Threshold Value Effect on Slug Region Liquid Holdup***



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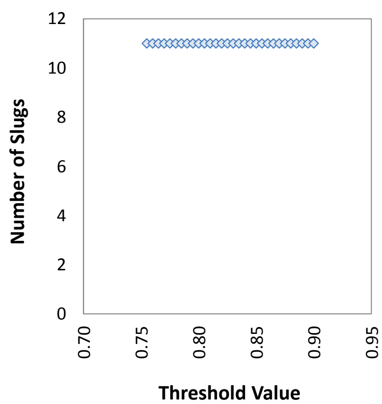
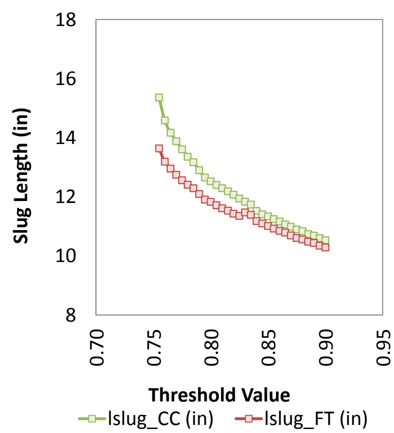
Number of Slugs and Slug Length

*Capacitance Sensor 2. **Threshold Value Effect on Slug Number***



*Capacitance Sensor 2. **Threshold Value Effect on Slug Length***



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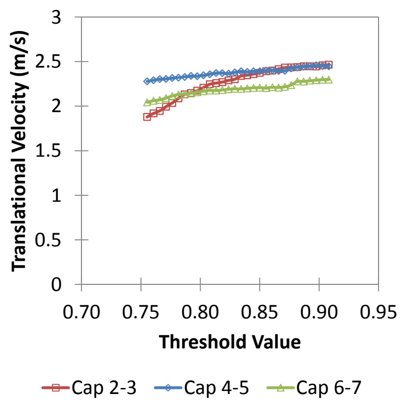
Translational Velocity

Time of Flight Approach



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Findings

- Monte Carlo Analysis Indicates
  - ***Film and Slug Liquid Holdups are Affected by TV***
    - ***H_{LF} Uncertainty Range ± 0.01***
    - ***H_{LS} Uncertainty Range ± 0.05***
  - ***Slug Length is Significantly Affected by TV***
    - ***TV Increases -> Slug Length Decreases***
  - ***Slug Number is not Affected by TV***

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Findings …

- ***Cross Correlation Approach to Calculate Translational Velocity is Independent of TV Making This Approach More Suitable for Translational Velocity Calculation***
- ***Cross Correlation and Time of Flight Approaches Tend to Be Equal for the Highest Threshold Values***

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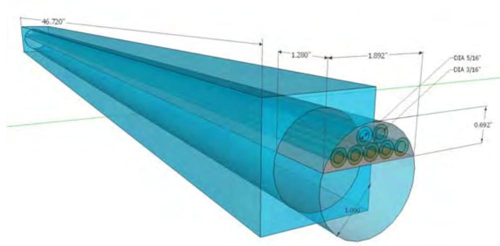

Inlet Geometry Effect on Slug Characterization

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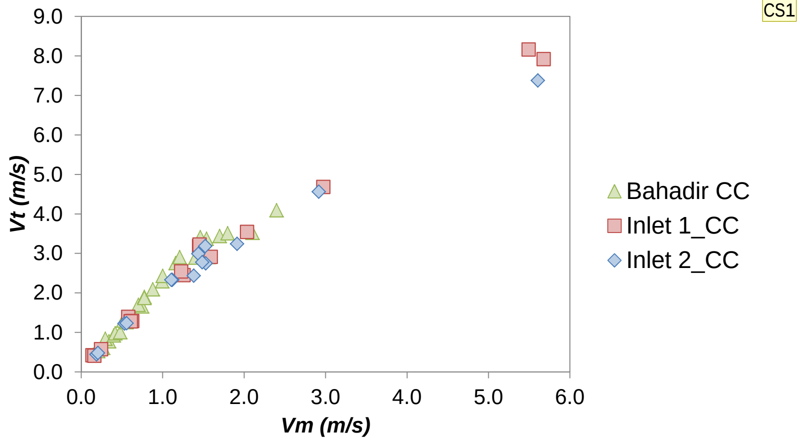
Mixture Velocity vs. Translational Velocity …

Cross-Correlation Methodology

CS1



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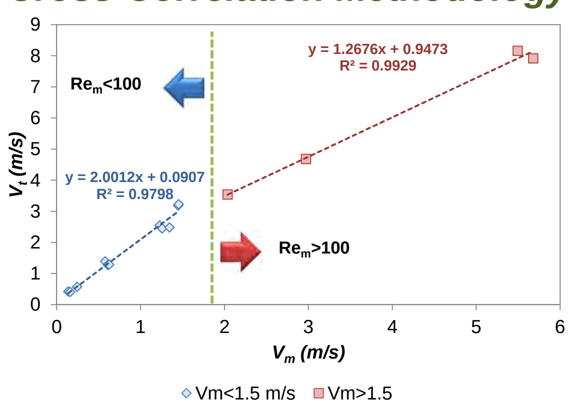
Mixture Velocity vs. Translational Velocity …

Cross-Correlation Methodology



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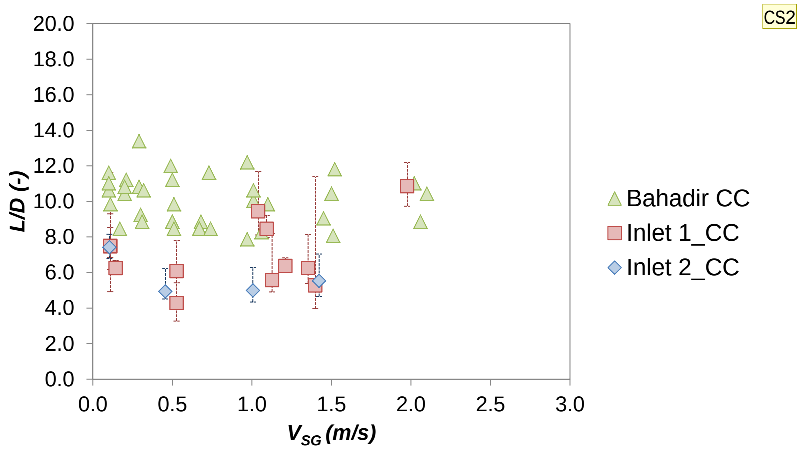
Slug Length



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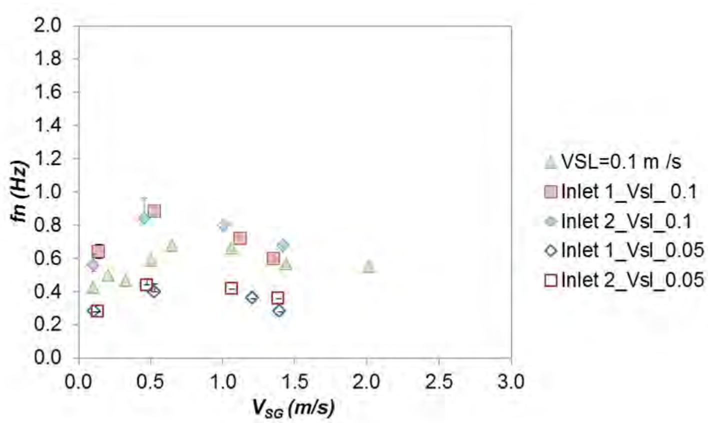
Slug Frequency



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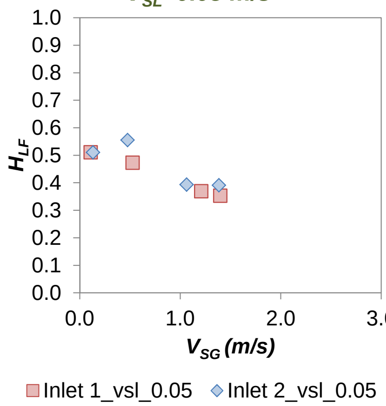
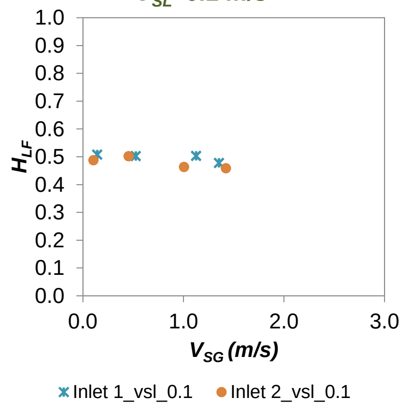
Liquid Holdup in Film Region

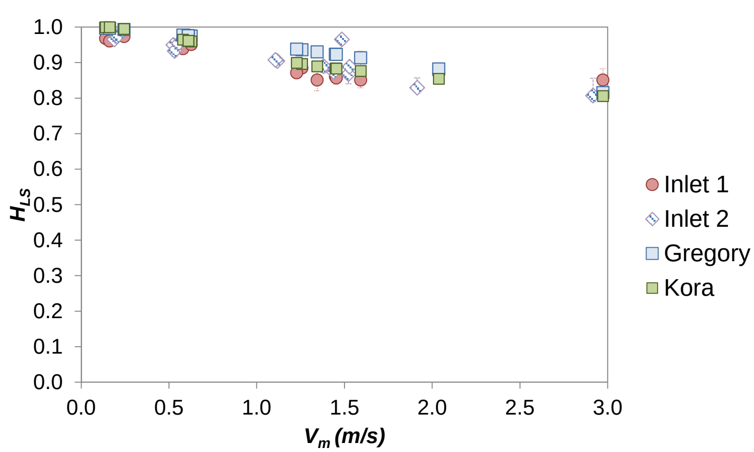
Effect of Inlet Geometry for a V_{SL}=0.05 m/s



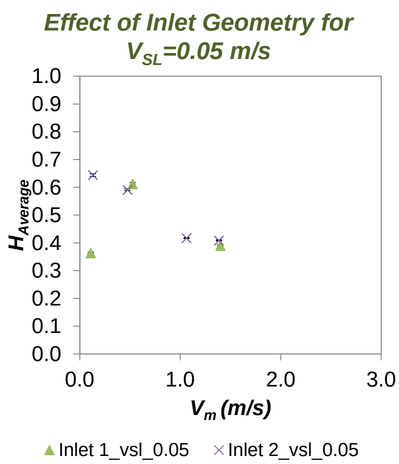
Effect of Inlet Geometry for a V_{SL}=0.1 m/s

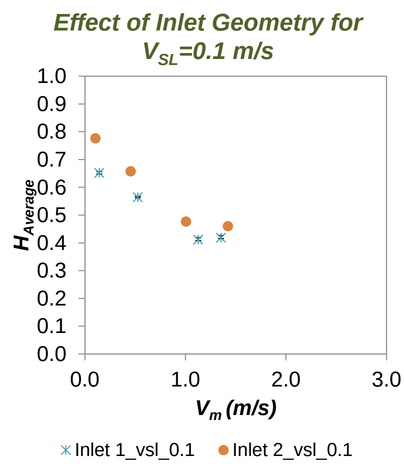


Liquid Holdup in Slug Region



Average Liquid Holdup





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Inlet Geometry Effect on Slug Characterization

- **Translational Velocity (V_t)**
  - ***Translational Velocity for Inlets 1 and 2 are Significantly Similar and in Agreement with Gokcal's Results***
  - ***V_t vs V_m Curve Presents Two Different Slopes***
    - ***V_m < 1.5 m/s -> m≈2.0***
    - ***V_m > 1.5 m/s -> m≈1.2***
- **Slug Length (L_s)**
  - ***L_s Obtained with Inlets 1 and 2 are Significantly Similar***
  - ***L_s is Sensitive to Selected Threshold Value***
  - ***Average L_s Obtained with Inlets 1 and 2 Differ from Gokcal's Results***

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Inlet Geometry Effect on Slug Characterization

- *Gokcal → Laser Sensor & Constant TV*
- *Brito → Capacitance Sensor & TV Sensitivity*

- Slug Frequency (F_n)
  - *F_n Obtained with Inlets 1 and 2 are Significantly Similar*
  - *F_n Obtained with Inlets 1 and 2 for a V_{SL}=0.1 m/s are in Agreement with Gokcal's Results*
- Liquid Holdup in Film Region (H_{LF})
  - H_{LF} *decreases When V_{SG} increases*
  - H_{LF} *Obtained with Inlets 1 and 2 are Significantly Similar*

Inlet Geometry Effect on Slug Characterization

- Liquid Holdup in Slug Region (H_{LS})
  - *Decreases when V_m Increases*
  - *Obtained with Inlets 1 and 2 are Significantly Similar*
  - *In Agreement with Gregory and Kora (2010) Correlations and Nulan (1999) Observations*
- Average Liquid Holdup ($H_{LAverage}$)
  - *Decreases for a Constant V_{SL} When Mixture Velocity Increases*
  - *Obtained with Inlets 1 and 2 are Significantly Similar*

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Flow Development

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Flow Loop Sections

Inlet Section	Middle Section	Test Section
2 Ring CS 1 SC	2 Ring CS 1 SC	2 Ring CS 1 TW CS 2 SC 1 HSC

Inlet 1 vs. Inlet 2

Temp=70 °F, μ_o=587 cP V_{SL}=0.1 m/s , V_{SG}=0.5 m/s

Inlet 1	*Inlet 2. Middle Section*
V_{sl}= 0.1 m/s, V_{sg}= 0.5 m/s	*V_{sl}= 0.5 m/s, V_{sg}= 1.0 m/s*

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Inlet 1.Temp=70 °F, μ_o=587 cP V_{SL}=0.1 m/s , V_{SG}=0.5 m/s

Video

Inlet Section

Middle Section

Test Section

Top View

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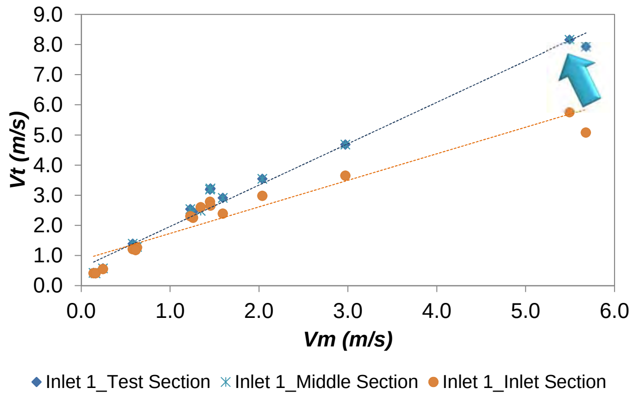
Inlet 1. Mixture Velocity vs. Translational Velocity



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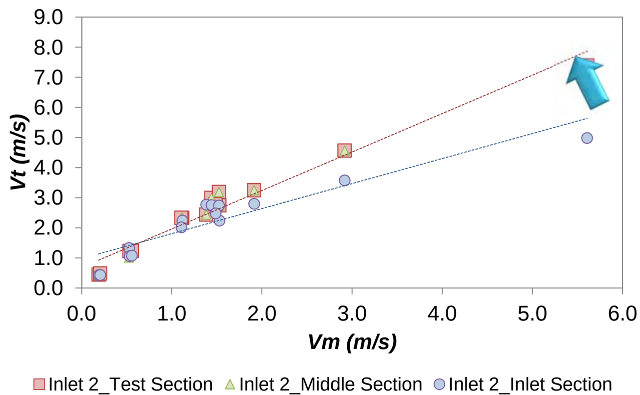
Inlet 2. Mixture Velocity vs. Translational Velocity



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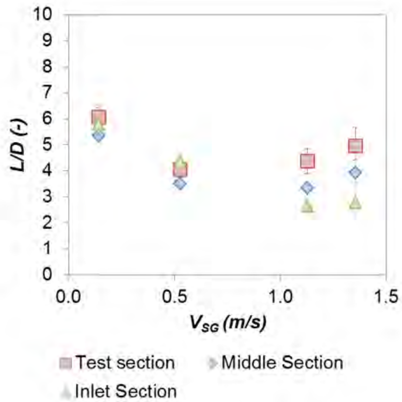
Slug Length

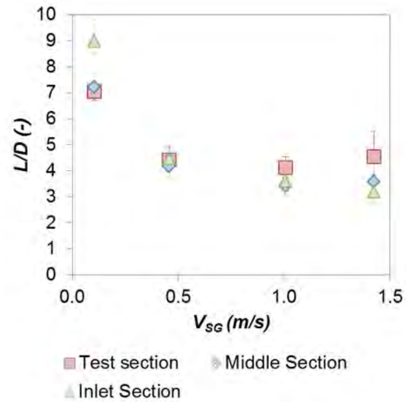
Inlet 1. Slug Length Evolution

v_{SL}=0.1 m/s



Inlet 2. Slug Length Evolution

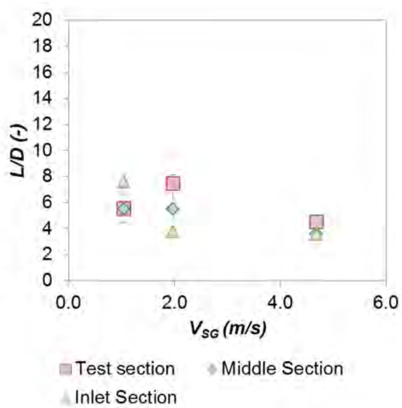
v_{SL}=0.1 m/s



Slug Length

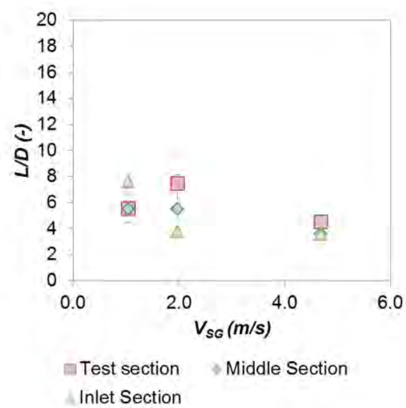
Inlet 1. Slug Length Evolution

v_{SL}=1.0 m/s



Inlet 2. Slug Length Evolution

v_{SL}=1.0 m/s



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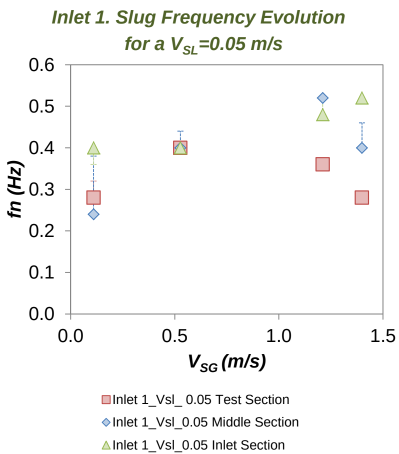
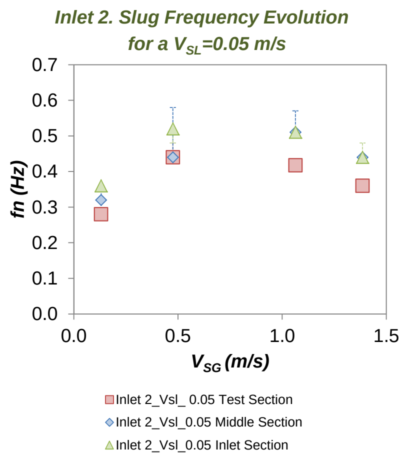
Slug Frequency





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Flow Development

- Translational Velocity (V_t)
  - *Translational Velocity Increases from Inlet to Middle Section and Then Remains Constant*
  - *This Indicates Fully Developed Flow*
- Slug Length (L_s)
  - *Minimum Slug Length Selected Was 2D*
  - *L_s Tends to*
    - *Remain Constant From Inlet to Test Section for v_{SG}<2 m/s*
    - *Be Slightly Higher at Test Section for v_{SG}=2 m/s*
    - *Remain Constant from Inlet to Test Section for v_{SG}>2 m/s*

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Flow Development …

- **Liquid Holdup**
  - ***This Parameter Was Not Calculated Because Dynamic Calibration Was Applied Just at Test Section***

Conclusions

- **Inlet Geometry Does Not Affect Experimental Results Obtained at Test Section**
- **For Both Inlet, It Can Be Concluded that Flow is Fully Developed Based On**
  - ***Translational Velocity Remains Constant from Middle Section to Test Section***
  - ***Slug Length Tends to***
    - ***Remain Constant From Inlet to Test Section for v_{SG}<2 m/s***
    - ***Be Slightly Higher at Test Section for v_{SG}=2 m/s***
    - ***Remain Constant From Inlet to Test Section for v_{SG}>2 m/s***

Future Tasks

- Evaluate Front and Back Velocity Information to Validate Fully Developed Conditions
- Data Analysis for 181 cP and Perform Comparison with Highest Oil Viscosity Case

Thanks …

Questions

Inlet Geometry Effects on Two-Phase High Viscosity Oil-Gas Flow in Horizontal Pipes

Rosmer Brito

Project Completion Dates

Data Analysis for μ_{oil}= 181 cP (70 °F) .... April 2011
Write Report .... May 2012

Objective

Investigate the inlet geometry effects on two-phase air and high viscosity oil (181 cP - 587 cP) for a horizontal pipe.

Introduction

The effect of highly viscous oils in two phase flow has been studied by TUFFP in the recent years. These studies have been restricted to horizontal and near horizontal pipes (±2°) and viscosities varying from 181 cP to 587 cP. The High Viscosity Oil/Gas Two-Phase Flow Loop facility consists of 50.8 ID and 18.9 m pipe.

The effects of the inlet geometry on two-phase flow of high oil viscosity and gas are studied experimentally. Two inlet geometry configurations are tested. A data analysis methodology is proposed to determine the slug characteristics and uncertainty in each of the measured parameters. In addition, flow development is evaluated using six capacitance sensors by performing slug characterization calculations at three different points along the flow loop.

Activities Summary

Since the last advisory board meeting, several activities have been carried out for this project. The most important achievements are presented in the following sections.

Experimental Program Definition

The experiments were performed using air and mineral oil as the two phases. A 18.9-m long and 50.8 mm ID horizontal pipe has been utilized. Two oil viscosity values have been considered, namely, 181 cP (100 °F) and 587 cP (70 °F). The superficial liquid velocities vary from 0.01m/s to 1.7 m/s, and the superficial gas velocities vary from 0 to 5 m/s. These result in mixture Reynolds numbers varying from 10 to 450. This experimental matrix is a simplification of the experimental matrix proposed by Gokcal (2005).

Seven capacitance sensors are installed along the flow loop, two at the entrance, two in the middle, and three in the test section of the flow loop. The main purpose of these sensors is to analyze the evolution of the slug characteristics as well as the average liquid holdup. Four high definition cameras are installed along the flow loop, one at the entrance, one in the middle and two in the test section. The video recordings are utilized to identify the flow pattern in each section and its evolution trough the flow loop. Additionally, a high speed video camera is installed in the test section.

Two different inlet geometry configurations are used. The first is a *“Y”* type mixing tee (Inlet 1), with inside diameter of 50.8 mm and a length of 0.21 m. length. A steel plate is located parallel to the flow in the middle of the pipe to separate the gas and liquid phases. The second one is an acrylic *“Y-2”* type mixing tee (Inlet 2) with an inside diameter of 50.8 mm and a length of 1.22 m. An acrylic plate is located at one quarter of the pipe diameter with respect to the top separating the gas and liquid phases. Gas phase is injected through the top branch and liquid through the bottom. In addition, gas phase flows through seven capillary tubes to avoid any flow rotation. This inlet has been design to promote stratified flow in the inlet region avoiding premature slug formation that may affect the experimental observations.

Data Analysis Methodology

An excel macro is developed to process the time traces from sensors and verify its quality through an uncertainty analysis. This excel macro calculates the average, standard deviation and uncertainty of the all measured and estimated parameters. The considered parameters are pressure gradient, liquid temperature, mass flow rate, fluid properties (density and viscosity), superficial velocities, mixture velocity, mixture Reynolds number, average liquid holdup, liquid holdups in the slug and film regions, number of slugs, slug frequency, translational velocity, and slug length.

For each capacitance sensor, the slug characterization is performed by selecting a threshold value to identify the slug region (voltage > threshold) and film region (voltage < threshold).

A dimensionless voltage histogram is plotted to facilitate the determination of all possible threshold values. The threshold should be between the maximum possible holdup value for the film region and the minimum possible holdup value for the slug region. Considering that all possible threshold values are equally likely, a Monte Carlo analysis is carried out to analyze the effect of this parameter on slug estimated characteristics.

The application of the threshold value generates a vector (ν) indicating the film region (zeros) and slug region (ones). This vector of zeros and ones is used to calculate the slug number, slug frequency and translational velocity. Two techniques are used to calculate the translational velocity, namely, cross-correlation and time of flight. As two different translational velocities are obtained for each data point, two slug lengths are reported for each capacitance sensor.

This methodology allows the estimation of the P05, P50, and P95 for the slug characteristic parameters, and the uncertainty range for each parameter can be determined with the upper value (P95) minus the average value (P50) and the average value (P50) minus the lower value (P05). These values define the error bars values for each parameter.

In addition, a flow development study is performed comparing the data obtained from the seven capacitance sensors. The evolution of slug flow parameters along the flow loop is used to determine whether the flow is fully developed.

Experimental Results for μ_{oil}=587 cP (70 °F)

The following section presents the experimental results, observations, and conclusions obtained for an oil viscosity of 587 cP (70 °F).

Flow Pattern

Inlet 1 experimental observations are compared with the flow pattern map reported by Gokcal (2005). Most of the flow patterns are in agreement with Gokcal (2005) observations with the exception of the highest superficial liquid velocity (v_{SL}=1.0 m/s) and lowest superficial gas velocities (v_{SG}=0.1 m/s and 0.5 m/s). For this case, the flow pattern differs from typical slug flow configuration. The elongated gas bubble behind the liquid slug penetrates into the liquid without pushing the liquid ahead of it as a plug.

Inlet 1 and 2 flow pattern observations are compared indicating that the flow pattern map for 587 cP is not affected by the inlet geometry configuration.

Threshold Value Effect

The sensitivities performed for the threshold values (*TV*) for each capacitance sensor show a similar trend for all the flow conditions covered in this study. The Monte Carlo analysis, applied to determine the effect of *TV* selection, indicates that the film and slug regions are slightly affected by the threshold value. The estimated uncertainties for liquid holdup in the film and slug region are ± 0.01 and ± 0.05, respectively. Number of slugs is not affected by the *TV* selection, while slug length is significantly affected. When the *TV* increases, the slug length decreases owing to the additional film region. Cross-Correlation approach to calculate translational velocity is independent of *TV*, making this approach more suitable for the translational velocity calculation. Finally, slug lengths obtained with Cross-Correlation and Flying Time tends to be equal for the highest threshold values.

Inlet Geometry Effect on Slug Characterization

<u>Translational Velocity</u>

The translational velocity, v_t, is directly proportional to the mixture velocity, v_m. Two different regions are identified for this parameter: $v_m<1.5$ *m/s* ($Re_{mix}<100$) and $v_m>1.5$ *m/s* ($Re_{mix}>100$) corresponding to a slope of 2.0 and 1.2, respectively, on a v_t vs. v_m plot.

The experimental results obtained for Inlet 1 and 2 are in agreement with Gokcal (2008) indicating that the inlet geometrical configuration does not affect the translational velocity.

<u>Slug Length</u>

Dimensionless slug length *(L/D)* vs. superficial gas velocity, v_{SG}, is plotted for the different flow conditions and both inlets. Plots indicate that the inlet geometry configuration does not affect the slug length. As shown in the error bars reported in this plot, threshold value has an important effect on the estimated slug length. Average dimensionless slug lengths obtained for Inlets 1 and 2 differ from Gokcal (2008) results. This can be explained by the fact the Gokcal (2008) used laser sensors and different data analysis algorithm.

<u>Slug Frequency</u>

Slug frequency, f_n, for constant superficial liquid velocities of 0.1 and 0.05 m/s, indicates that the inlet geometry does not affect this parameter. In addition, the experimental results for Inlets 1 and 2 are compared with Gokcal (2008) results showing a good agreement.

<u>Liquid Holdup in Film Region</u>

For a constant superficial liquid velocity, the liquid holdup in the film region tends to decrease when the superficial gas velocity increases. This behavior is observed for both inlet configurations indicating that the inlet geometry does not affect the liquid holdup in the film region.

Liquid Holdup in Slug Region

Liquid holdup in the slug region decreases when mixture velocity increases owing to the increase in momentum exchange between liquid slug and film regions, which promotes gas entrainment. For both inlet configurations, the same behavior and values are observed concluding that the inlet geometry configuration does not affect the liquid holdup in the slug region.

In addition, the obtained liquid holdups are compared with Gregory (1978) and Kora (2010) models showing good agreement with the experimental results and corroborating that the slug liquid holdup is not strongly affected by the liquid viscosity.

Average Liquid Holdup

Average liquid holdup for a constant superficial liquid velocity decreases when the superficial gas velocity increases. For both inlet configurations similar trends and values are obtained indicating that the inlet geometry configuration does not affect the average liquid holdup.

Flow Development

The flow development from the inlet to the middle section is studied using six capacitance sensors. The obtained results are discussed in the flowing sections.

Translational Velocity

The translational velocity increases from the inlet to the middle section, and then remains constant from the middle section to the test section. This indicates that fully develop flow is achieved after the middle section.

Slug Length

The slug length tends to remain constant from inlet to test section for $v_{SG}<2$ m/s and $v_{SG}>2$ m/s. For $v_{SG}=2$ m/s, the slug length in the test section is found to be slightly higher at test section than the middle section.

Slug Frequency

For Inlet 1, no clear trend in the slug frequency from the inlet to the test section is observed. On the other hand, for the Inlet 2, the slug frequency decreases from the inlet to the test sections, this coincides with the increase of the slug length from the inlet to the test section. When the slug length increases over the same period of time, the number of slugs decreases.

Findings

It can be concluded that the inlet geometrical configuration does not significantly affect the experimental results obtained in the test section. In addition, the flow at the test section can be considered developed.

Future Tasks

This data analysis procedure will be repeated for the data obtained for an oil viscosity of 181 cP and the results will be compared with the results of high viscosity case presented above. The fully developed conditions will also be investigated by comparing the back and front velocities of slugs for both viscosities.

References

(1) Kora, C., "Effect of High Oil Viscosity on Slug Liquid Holdup in Horizontal Pipes," M.S. Thesis, The University of Tulsa, OK, 2010.

(2) Shoham, O., "Mechanistic Modeling of Gas-Liquid Two-Phase Flow in Pipes," Society of Petroleum Engineers, 2005.

(3) Gokcal, B., Wang, Q., Zhang, H. Q., and Sarica, C.: “Effects of High Oil Viscosity on Oil-Gas Flow Behavior in Horizontal Pipes,” SPE 102727, Presented at the 2006 SPE ATCE, San Antonio, TX, September 24 – 27.

(4) Al-safran, E.: "An Experimental Study of Two-Phase Flow in a Hilly-Terrain Pipeline," Master Thesis. The University of Tulsa. (1999).

(5) Gokcal, B., Al-Sarkhi, A. S., Sarica, C., and Al-Safran, M. E.: "Prediction of Slug Frequency for High-Viscosity Oils in Horizontal Pipes," SPE Projects, Facilities & Construction, vol. 5. (2010).

Fluid Flow Projects

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

Rosmer Brito

Advisory Board Meeting, April 25, 2012

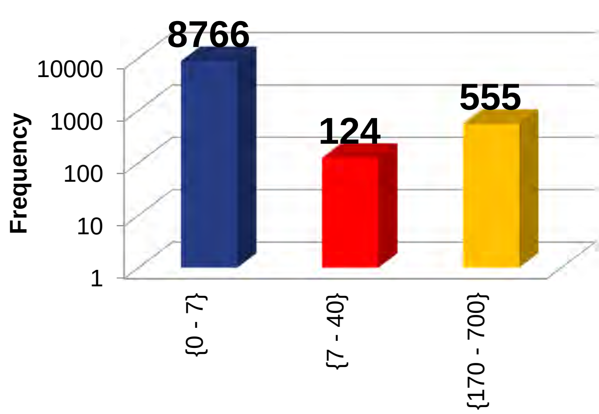
Outline

- Objective
- Justification
- Experimental Program
- Experimental Matrix
- Activities Since ABM-Fall-2011
- Short Term Future Tasks

General Objectives

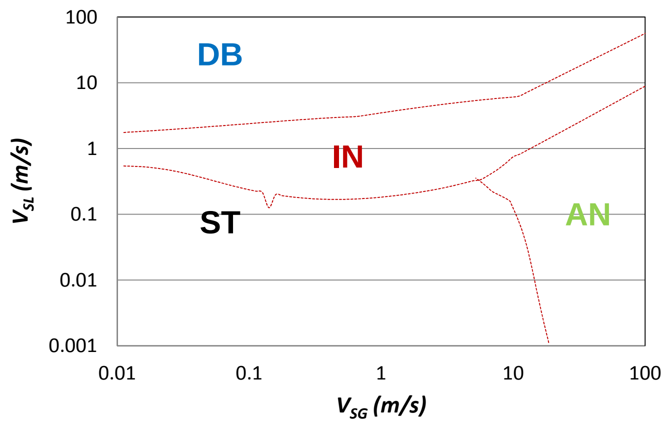
- Experimental and Modeling Study of Oil-Gas Two Phase Flow to Investigate the Effects of Medium Viscosity Oil (33 cP - 129 cP)
  - Flow Pattern
  - Pressure Drop
  - Liquid Holdup
  - Slug Characteristics

Justification



Pereyra et al.

Justification …



Flow Pattern Map for μ_L=1cp
Unified Model

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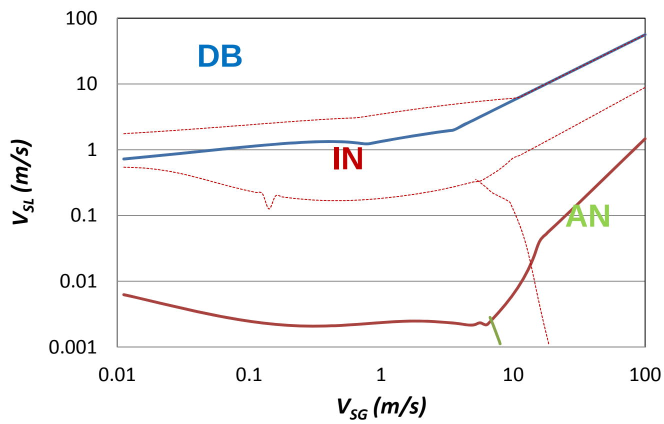
Justification …



Flow Pattern Map Comparison for Liquid Viscosities of 129 cP and 1cP Using Unified Model

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Experimental Facility

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

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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

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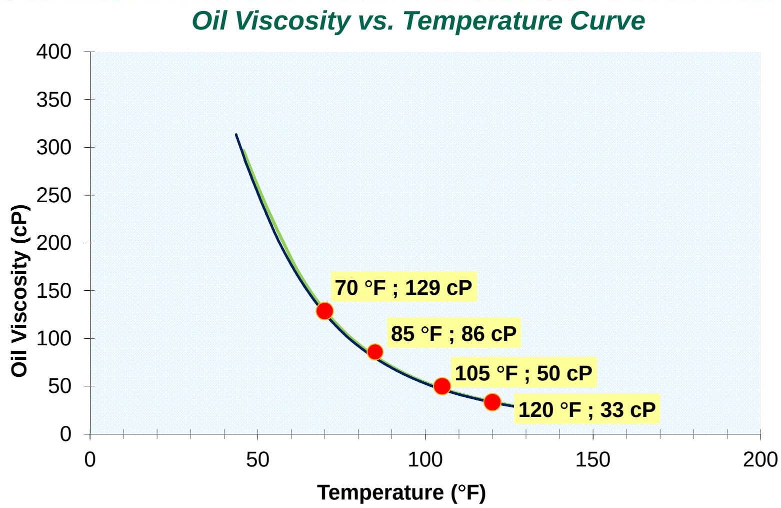
Test Oil Characteristics …

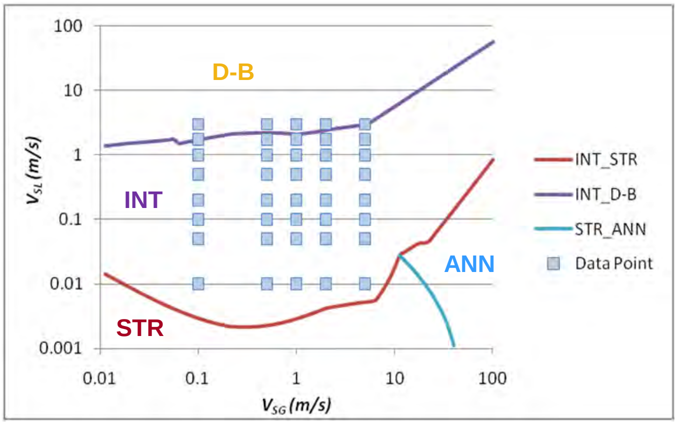


Experimental Matrix

- Superficial Liquid Velocity
  - 0.01 – 3 m/s
- Superficial Gas Velocity
  - 0.1 – 5 m/s
- Inclination
  - Horizontal

Experimental Matrix …

Flow Pattern Map for μ_o=33 cP Using TUFFP Unified Model



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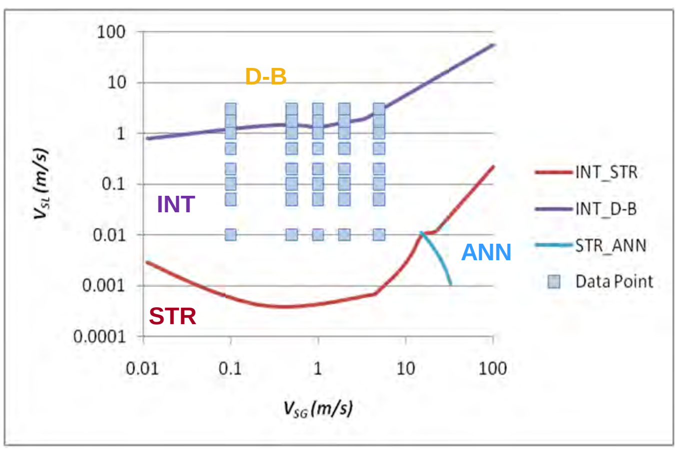
Experimental Matrix …

Flow Pattern Map for μ_o=129 cP Using TUFFP Unified Model



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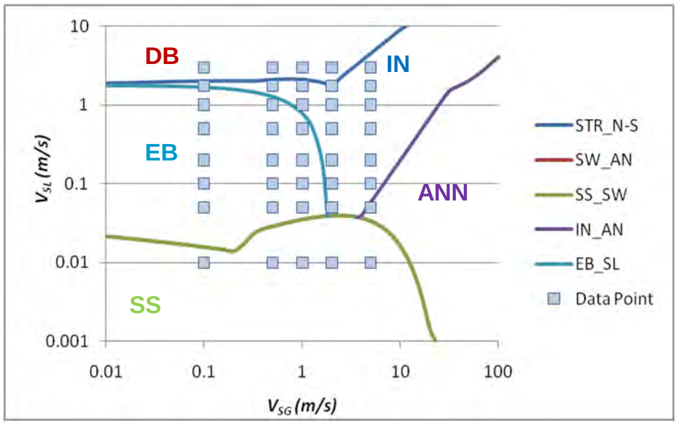
Experimental Matrix …

Flow Pattern Map for μ_o=33 cP Using Barnea Model



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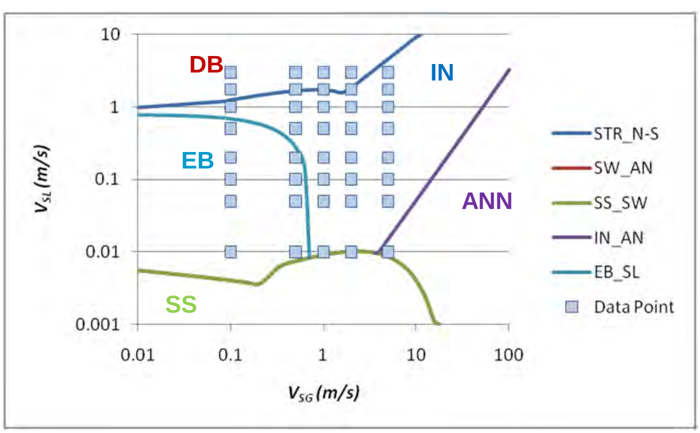
Experimental Matrix …

Flow Pattern Map for μ_o=129 cP Using Barnea Model



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Activities Since ABM-Fall-2011

- Selection of the Capacitance Sensor Type for the Holdup Measurement
  - Two-Wire Capacitance Sensor
    - Linear Relationship Between Output Voltage and Liquid Holdup
    - Temperature Compensation is not Required (Static Conditions)
    - In-Place Static Calibration Will be Carried Out
    - Dynamic Calibration for Each Fluid Temperature will be Performed in both Film and Slug Regions

Activities Since ABM-Fall-2011…

- Oil Replacement
  - Mineral Oil Citgo 220 was Removed
  - Tanks and Flow Loop were Cleaned to Charge with the Mineral Oil DN-20
  - Oil Viscosity was Validated Running Experiments Under Single and Laminar Flow Condition

Future Tasks

Experimental Program Execution for Medium Oil Viscosity	May-2012
Data Analysis	Jun- 2012
Model Verification or Develop New Ones (if Necessary)	Jul-2012
Write Thesis	Aug-2012

Thanks …

Questions

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

Rosmer Brito

Project Completion Dates

Experimental Program Execution for Medium Oil Viscosity May2012
Data Analysis .... July 2012
Model Verification or Develop New Ones (if Necessary) .... July 2012
Final Report (Thesis) …………………………………………………………………….......................... July 2012

Objective

Perform an experimental and modeling study of oil-gas two phase flow in horizontal pipe to investigate the effects of medium viscosity oil (33 cP < μ_O < 129 cP) on two-phase flow parameters such as flow pattern, pressure drop, liquid holdup, and slug characteristics.

Introduction

Previous experimental studies show different behavior between low viscosity oils (20 cP < μ_O) and high viscosity oils (μ_O > 200 cP) for two-phase gas-liquid flow. Only few experimental studies for medium oil viscosity (20 cP < μ_O < 200 cP) have been published in the literature. Thus, there is a need for experimental investigation of medium viscosities in order to characterize the two-phase flow behavior for the entire range of possible viscosities. Furthermore, current two-phase flow models are based on experimental data with low and high viscosity liquids. Therefore, existing mechanistic models need to be verified or improved with medium liquid viscosity experimental results.

Activities Summary

Since the last Advisory Board meeting, several activities have been carried out for this project. The most important achievements are presented in the following sections.

Capacitance Sensor Section

Based on a rigorous evaluation to determine the most accurate and reliable capacitance sensor to measure the liquid holdup the two-wire capacitance sensor was selected as the instrument to perform the holdup measurements and slug characterization if slug flow is observed.

Facility Modifications

The following facility modifications were completed in preparation for the experimental program.

Capacitance Sensor

Six two-wire capacitance sensors are installed along the flow loop, two at the entrance, two in the middle and two at the actual test section of the flow loop. The main purpose of these sensors is to analyze the evolution of the slug characteristics as well as the average liquid holdup.

The new capacitance sensors can now be statically calibrated in-place. Dynamic calibration will be performed for the temperatures of 70 °F, 85 °F, 105 °F and 120 °F, with the corresponding viscosities of 129 cP, 86 cP, 50 cP and 33 cP, respectively.

Oil Change

The previous high viscosity oil (Citgo 220) was removed, and the facility was cleaned to charge the tanks and flow loop with the new mineral oil DN-20.

Inlet Selection

The newly tested inlet geometry will be used in this study.

Project Plan

The project plan is divided into experimental program and modeling.

Experimental Program

The experiments will be run using air and mineral oil in a 50.8 mm ID horizontal pipe. The oil viscosity varies from 33 to 129 cP. The range of superficial liquid and gas velocity are 0.01 m/s to 3 m/s and 0 to 5 m/s, respectively.

Modeling

The experimental results will be used to validate the performance of existing flow pattern, pressure gradient and holdup prediction models. If the performance analysis indicates a poor performance of the existing models, new models or closure relationships will be developed.

Fluid Flow Projects

Characterization of High Viscosity Slug Flow in Horizontal Pipes

Eissa Al-safran (KU/KOC)

Advisory Board Meeting, April 25th, 2012

Outline

- Introduction
- Objective
- Physical and Empirical Modeling of Slug Liquid Holdup
- Analysis of Slug Flow Characteristics Interaction
- Future Work

Introduction

- How Accurate OLGA to Predict dp/dL and Average HL for High Viscosity (90 mPa.s) Horizontal Slug Flow?
  - OLGA 6.1.2 Point Model Overpredicts dp/dL 60-80%
  - OLGA 6.1.2 Point Model Underpredicts Average HL 25-30%
  - OLGA Slug Tracking Model: 30-40% Overprediction in dp/dL and 20% Underprediction in HL

(Smith et al. 2011, BHRG Conference)

Introduction . . .

- Slug Flow Characteristics are Critical in Design and Operation of Multiphase Systems
- Interrelationships 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

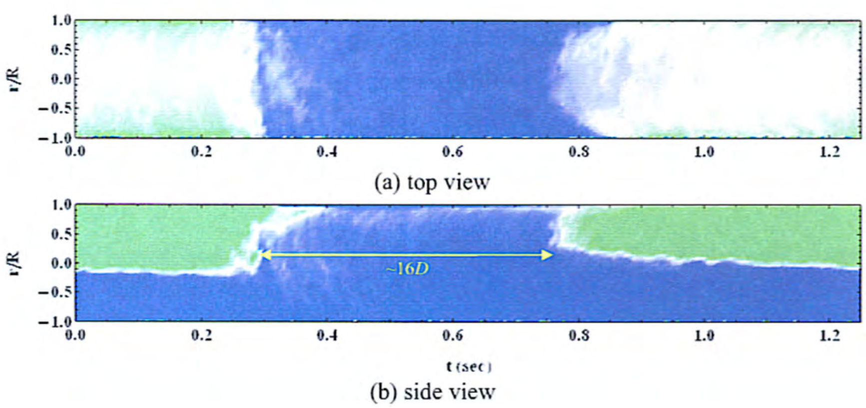
- Understand and Model High Viscosity Effect on Slug Liquid Holdup in Horizontal Pipes
- Develop a Physical Model to Explain Slug Flow Characteristics Interaction under the Condition of High Viscosity Flow

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 . . .

- X-Ray CT Image



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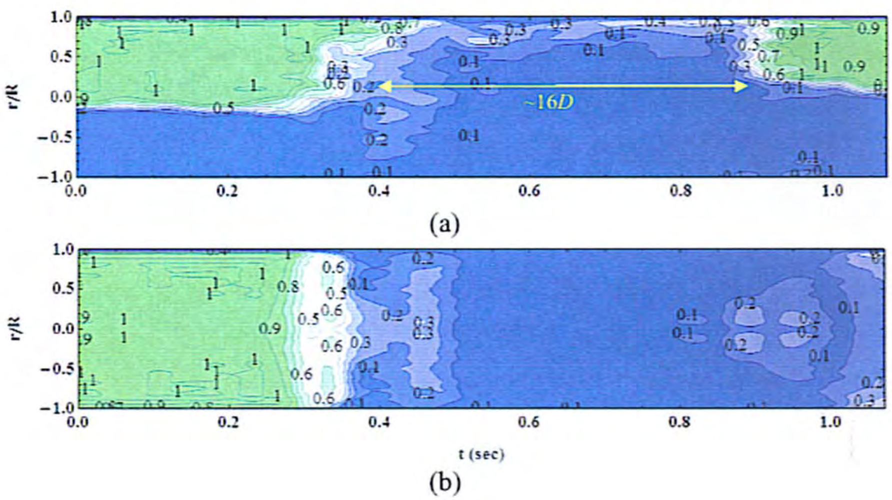
Slug Liquid Holdup . . .



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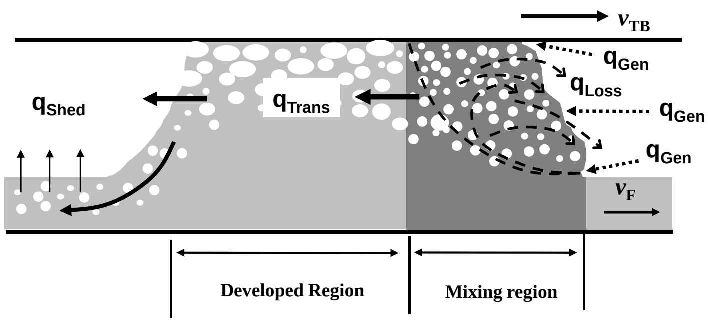
Slug Liquid Holdup . . .

- Gas Entrainment and Transport in Low Liquid Viscosity Slug



$$q_{Gen} - q_{Loss} = q_{Trans} = q_{Shed}$$

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

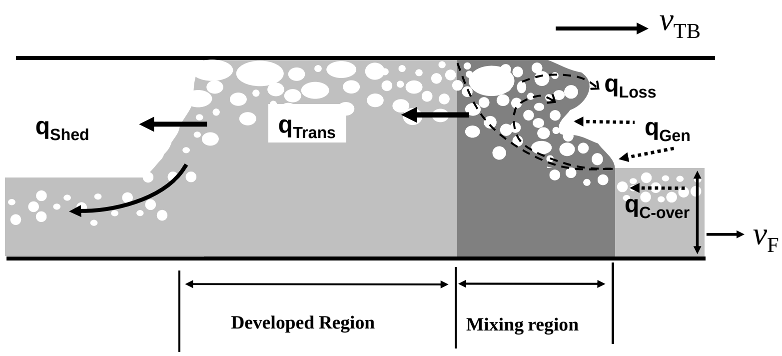
Slug Liquid Holdup . . .

- 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 . . .



$$q_{C-over} + q_{Gen} - q_{Loss} = q_{Trans} = q_{Shed}$$

Slug Liquid Holdup . . .

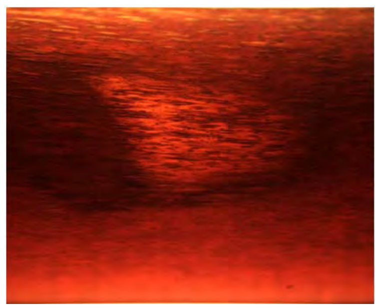
- Slug Front Entrainment Behavior (v_{SL}=0.01 m/s, v_{Sg}=1.5 m/s)

μ=0.590 Pa.s

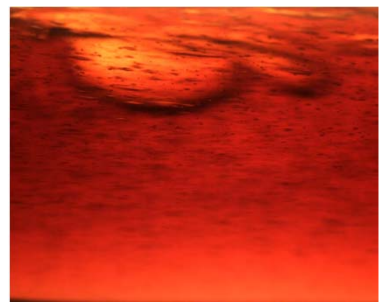
μ=0.182 Pa.s

Slug Liquid Holdup . . .

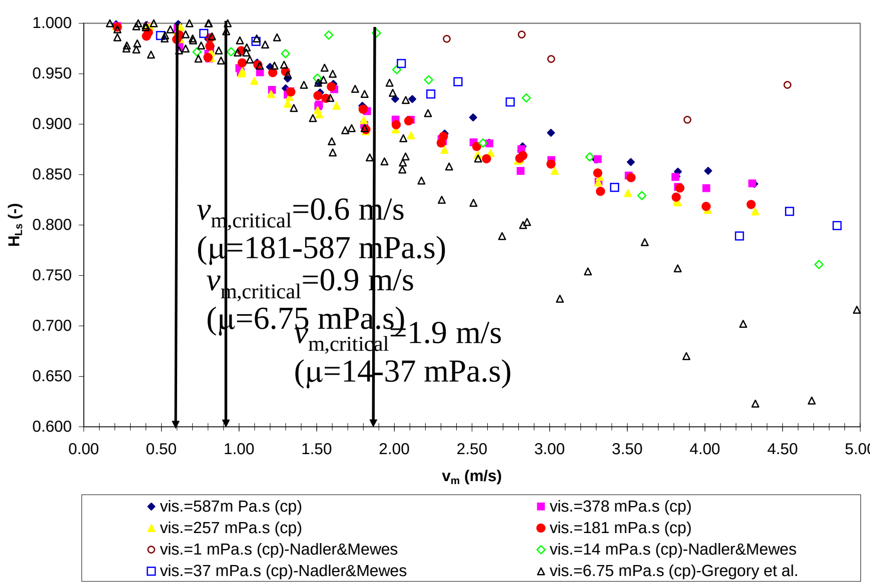
- Entrained Large Bubbles (v_m=1.5 m/s)



μ=0.590 Pa.s



μ=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

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Slug Liquid Holdup . . .

- Medium Viscosity Oil
  - Moderate Aeration Critical Mixture Velocity (v_m=1.9 m/s)
- High Viscosity Oil
  - Lower Aeration Critical Mixture Velocity (v_m=0.6 m/s)
- Slug Liquid Holdup Matches Beyond Aeration Critical Velocity for Medium and High Viscosity Oils

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Modeling Slug Liquid Holdup

- **Ceyda *et al.* (2010)**

$$N_{Fr} = \frac{v_m}{(gd)^{0.5}}\sqrt{\frac{\rho_L}{\rho_L - \rho_g}} \qquad N_\mu = \frac{v_m \mu_L}{gd^2(\rho_L - \rho_g)}$$

$$H_{Ls} = 1.012\, e^{(-0.085\, F_r N_\mu^{0.2})}$$ For $0.15 < N_{Fr}N_\mu^{0.2} < 1.5$

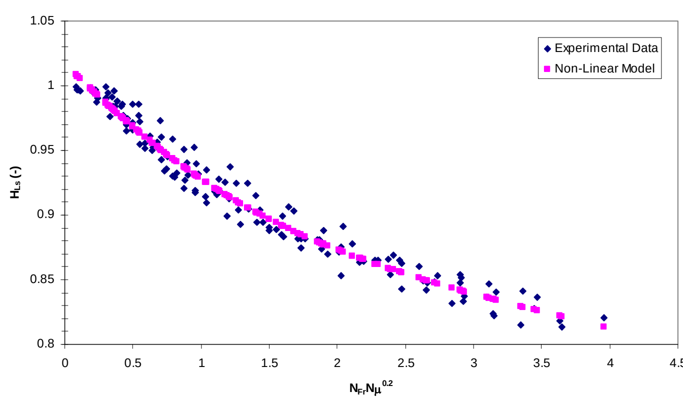
$$H_{Ls} = 0.9473\, e^{(-0.041\, F_r N_\mu^{0.2})}$$ For $N_{Fr}N_\mu^{0.2} \geq 1.5$

$$H_{Ls} = 1.0$$ For $N_{Fr}N_\mu^{0.2} \leq 0.15$

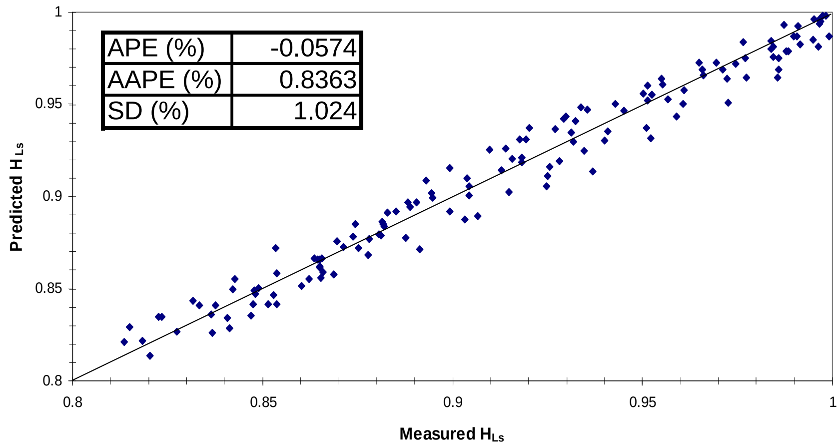
Modeling Slug Liquid Holdup . . .

- **Non-Linear Modeling**

$$H_{Ls} = 0.85 - 0.075\left(N_{Fr}N_\mu^{0.2} - 0.89\right) + 0.057\left[\left(N_{Fr}N_\mu^{0.2} - 0.89\right)^2 + 2.3\right]^{0.5}$$



Modeling Slug Liquid Holdup . . .



Modeling Slug Liquid Holdup . . .

$$SSE = \sum_{i=1}^{n} (H_{Ls\,i} - \hat{H}_{Ls\,i})^2 \qquad MSE = \hat{\sigma} = \frac{\sum_{i=1}^{n} (H_{Ls\,i} - \hat{H}_{Ls\,i})^2}{n-1}$$

$$SSR = \sum_{i=1}^{n} (\hat{H}_{Ls\,i} - \overline{H}_{Ls})^2 \qquad SST = SSE + SSR$$

$$R^2 = \frac{SSR}{SST} = \frac{\sum_{i=1}^{n} (\hat{H}_{Ls\,i} - \overline{H}_{Ls})^2}{\sum_{i=1}^{n} (H_{Ls\,i} - \overline{H}_{Ls})^2}$$

Slug 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

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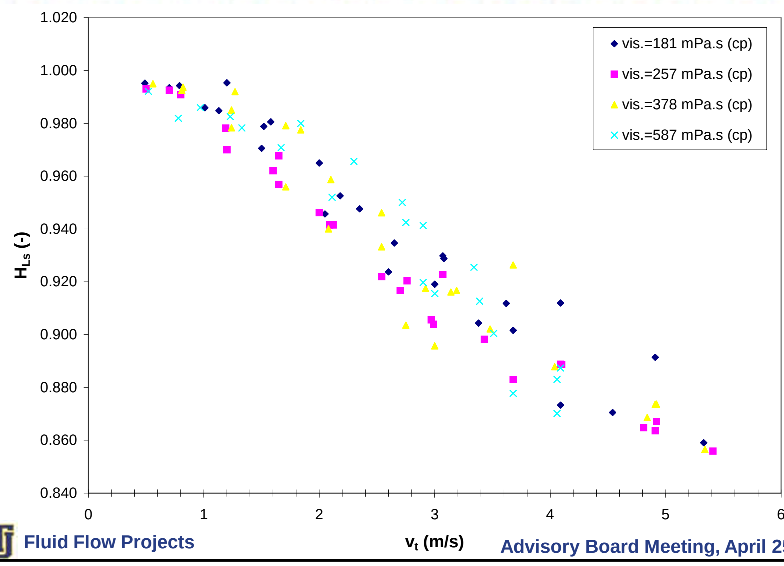
Slug Characteristics Interaction . . .



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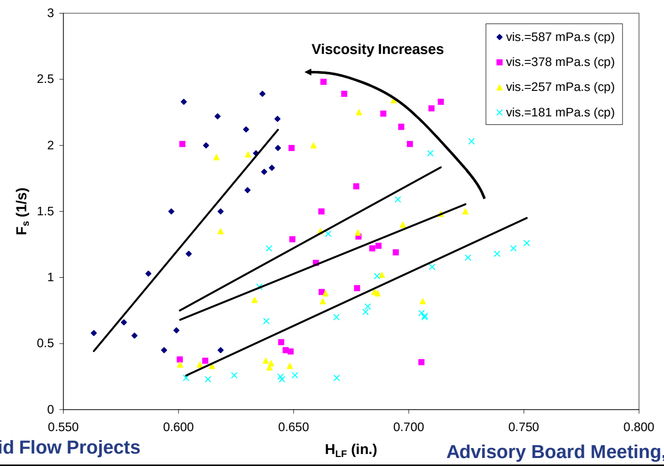
Slug Characteristics Interaction . . .

- Slug Frequency is Proportional to Film Thickness and Liquid Viscosity



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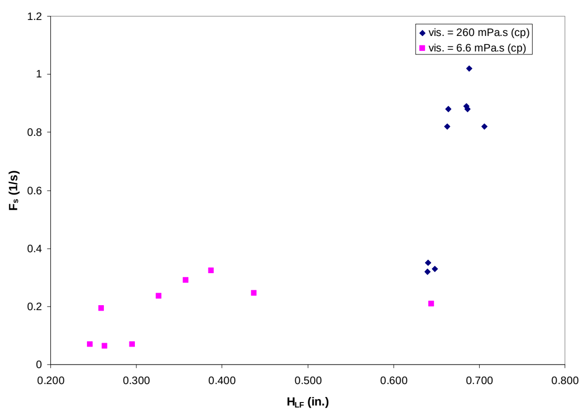
Slug Characteristics Interaction . . .

- Kokal (1987) Light Oil and Gokcal (2008) High Viscosity Oil



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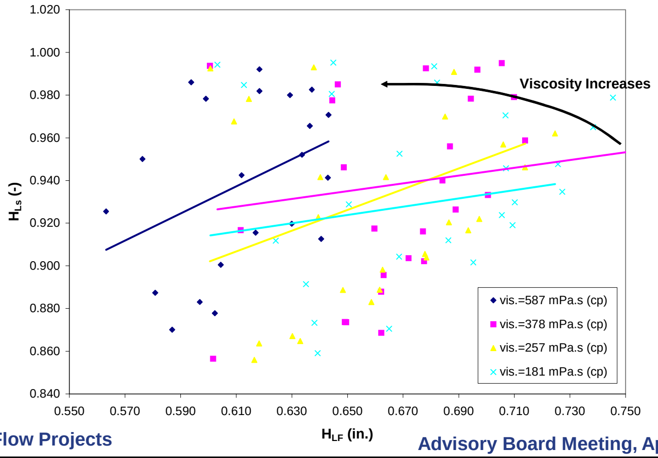
Slug Characteristics Interaction . . .

- Slug Liquid Holdup is Proportional to Film Thickness and Liquid Viscosity



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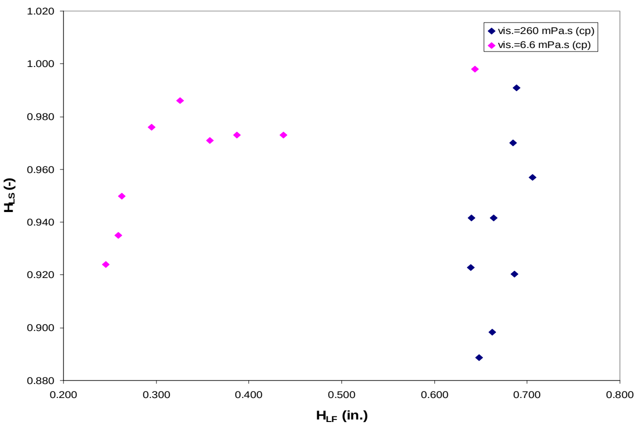
Slug Characteristics Interaction . . .

- Kokal (1987) Light Oil and Gokcal (2008) High Viscosity Oil



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Future Work

- Slug Liquid Holdup Model Validation and Comparison
- Investigate High Viscosity Slug Characteristics Interactions and their Effect on Flow Behavior
- Develop Physical Model for High Viscosity Slug Flow Characteristics

Characterization of High Viscosity Slug Flow in Horizontal Pipes

Eissa Al-safran

Project Completion Dates

Literature Review .... Completed
Slug Liquid Holdup Physical Modeling .... Completed
Data Analysis .... Ongoing
Modeling .... Ongoing
Model validation and comparison .... April 2013
Final Report .... April 2013

Objectives

The objectives of this project are two fold:

1. To understand and model the effect of high viscosity liquid on slug liquid holdup in horizontal pipes.
2. To develop a physical model to explain the interaction among all slug flow characteristics (holdup, length, frequency and velocity) under the condition of high viscosity liquid in horizontal pipes.

Introduction

Gas-liquid two-phase flow in pipes occurs at production and transportation facilities. Slug flow, the most common flow pattern in horizontal and near horizontal flows, is described by alternating liquid slugs and gas intervals. Slug liquid holdup is the liquid fraction in the slug body and is required for the closure of all slug flow mechanistic models. Several empirical and mechanistic correlations were developed to predict slug liquid holdup. However, none of which is applicable under high liquid viscosity conditions. In continuation of recent TUFFP efforts to investigate viscosity effect on slug liquid holdup, this study is carried out to thoroughly understand and physically/mathematically model this phenomenon (objective 1). In addition, TUFFP was recently involved in several studies to investigate individual slug flow characteristics in horizontal pipes by Gokcal *et al*. (2008, 2009), Al-Safran *et al*. (2011), Kora *et al*. (2010). However, the physical interaction among these slug flow characteristics is poorly understood and was not the focus of any of these studies. Therefore, the second objective of this study aims at a comprehensive understanding of slug flow behavior and characteristics under high viscosity conditions.

Activities Summary

Several tasks have been completed in terms of the first and second objectives of this study.

Physical Modeling

The basis of a physical model of slug liquid holdup is founded according to our previous understanding of slug liquid holdup and the observed structure of slug flow under high viscosity condition. These bases are as follows.

1. Low gas entrainment at slug front due to low turbulence intensity and circulation/vortex motion.
2. Slug front folding entrainment mechanism entraining large bubbles with high rise velocity in mixing zone resulting in higher loss rate into Taylor bubble tail.
3. Gas carryover to slug body by aerated liquid layer due to high retention time and short film.
4. Thick liquid film in Taylor bubble region resulting in high Taylor bubble velocity and low entrainment rate.
5. Low bubble fragmentation in slug front resulting in large mean bubble diameter in slug body accumulating at upper pipe wall increasing shedding rate.

Data Analysis

Experimental slug liquid holdup data of light and medium oils from the literature (Gregory *et al*., 1978 and Nadler and Mewes, 1994) was compared with high viscosity oil acquired at TUFFP which revealed several observations. Below, the most two important observations are listed.

1. High viscosity data, counter intuitively, showed a lower critical mixture velocity to aerate slug than lower viscosity data. This observation is explained by the aerated liquid film scooped by slug and by the slug front folding entrainment mechanism which entrains bubble under low slug velocity.
2. Beyond the critical slug mixture velocity, low viscosity oil data showed lower slug liquid holdup; while high viscosity oil data showed a

higher slug liquid holdup. However, water data showed higher slug liquid holdup than all other data indicating the effect of surface tension on slug liquid holdup.

Modeling

A robust non-linear model is developed in this study to predict slug liquid holdup as a function of dimensionless numbers used in Al-Safran *et al*. (2011), Kora *et al*. (2010) and Gokcal *et al*. (2009) high viscosity slug flow characteristics studies. The final form of the proposed non-linear model is as follows.

$$H_{Ls} = 0.85 - 0.075\left(N_{Fr}N_{\mu}^{0.2} - 0.89\right) + 0.057\sqrt{\left(N_{Fr}N_{\mu}^{0.2} - 0.89\right)^2 + 2.27}$$

The model was validated with the measured slug liquid holdup and showed 0.836% absolute average percent error and 1.024% standard deviation. A detail uncertainty analysis and further validation and comparison of the model will be a near future task.

Slug Flow Characteristics Interaction

Preliminary data analysis revealed that the slug front and liquid film relative velocity plays a major role in the bubble entrainment phenomenon in slug front and a further subsequent slug flow characteristics such as slug length. Inverse proportionality of slug front velocity with slug liquid holdup explains the high slug liquid holdup in high viscosity oil since slug front (translational) velocity is reduced under high viscosity conditions (Gokcal, 2008). Furthermore, the analysis of the liquid film in Taylor bubble region revealed its significant effect to other slug flow characteristics. For example, data revealed that liquid film height has a direct proportional effect on slug frequency. This relationship increases with the increase of liquid viscosity as shown in the comparison between Gokcal (2008) and Kokal (1987) data for the same flow condition. Furthermore, a positive significant correlation between the liquid film height and slug liquid holdup was observed by comparing 260 mPa.s and 6.6 mPa.s liquid viscosity data for the same flow condition. This positive correlation increases as liquid viscosity increases indicating its importance in high viscosity slug flow.

Future work

The following are among the future tasks of this project.

1. To complete the physical modeling of both slug liquid holdup and slug flow characteristics interaction under high viscosity condition.
2. To carry out uncertainty analysis, validation and comparison studies of the proposed high viscosity slug liquid holdup model.
3. To develop a comprehensive phenomenological understanding of liquid viscosity effect on slug flow characteristics to be the basis for a future mechanistic modeling.

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Fluid Flow Projects

Experiments of High-Viscosity Oil/Gas Slug Flow in Upward Vertical Pipes

Yue Lin

Outline

- Introduction
- Objectives
- Literature Review
- Research Plan
- Future Tasks
- Schedule

Introduction

- Available Multiphase Flow Models Developed for Low Viscosity Liquids
- Few Studies of Liquid Viscosity Effect on Slug Characteristics
- Slug Flow Dominant Flow Pattern for High-Viscosity Oil/Gas Flow

Objectives

- Experimental Study of High-Viscosity Oil/Gas Slug Flow in Upward Vertical Pipe
  - Slug Liquid Holdup
  - Slug Frequency
  - Slug Length
  - Translational Velocity

Literature Review

- Effect of Liquid Viscosity on Slug Flow Characteristics
  - Rosa *et al.* (2004)
    - 1 cP $\leq \mu_L \leq$ 27 cP
    - Average Slug Length and Bubble Length Decreased with Increasing Liquid Viscosity
    - Bubble Front Velocity and Slug Frequency Increased with Increasing Liquid Viscosity
  - Gokcal *et al.* (2008)
    - 181 cP $\leq \mu_O \leq$ 587 cP
    - Slug Length Decreased with Increasing Liquid Viscosity

Literature Review …

- Kora *et al.* (2010)
  - 181 cP $\leq \mu_L \leq$ 587 cP
  - Slug Liquid Holdup Decreased with Increasing Superficial Gas Velocity

Literature Review …

- **Jeyachandra *et al.* (2011)**
  - 181 cP ≤ μ_L ≤ 587 cP
  - Approximately 2-14*D* for Upward Inclined Flow
  - Translational Velocity Increases with Increasing Mixture Velocity, Decreases with Increasing Liquid Viscosity

Literature Review Summary

- Limited Experimental Data of High Viscosity Oil/Gas Slug Flow
- No Experimental Data on Slug Characteristics for High-Viscosity Oil in Vertical Flow

Research Plan

- Experimental
  - Facility
  - Instrumentation
    - Quick-Closing Valve System
  - Test Fluids
  - Test Range

Experimental Facility

- 2-in. ID TUFFP Facility for Gas/Oil/Water Flow
  - Test Section
    - Two 21.2-m (69.3-ft) Steel Pipes Connected with U-shaped Bend
  - Metering Section
  - Storage Tanks
  - Heating System
  - Separator

Experimental Facility …

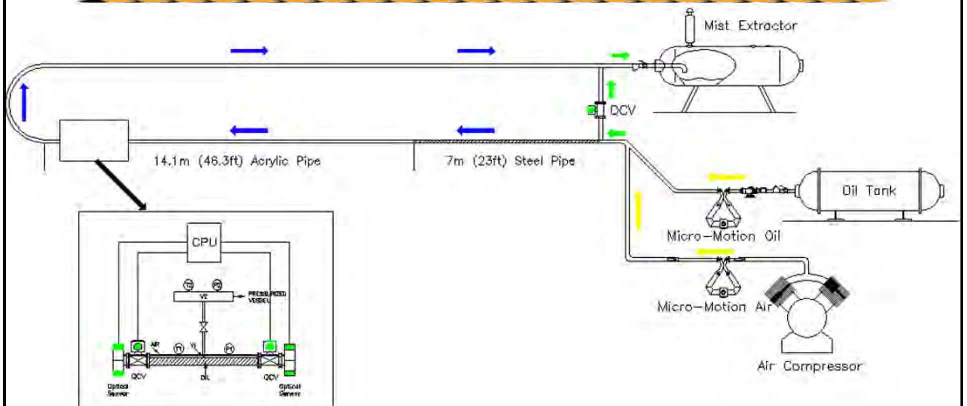
Experimental Facility …

- **Test Facility**
  - **Facility in Operating Condition**
  - **Modifications Needed**

Experimental Facility …

- **Modifications**
  - **Test Section: 7-m (23-ft) Steel Pipe and 14.1-m (46.3- ft) Acrylic Pipe**
    - **For Visual Observation of Flow Behavior**
  - **Several Instruments Needed**

Experimental Facility…



Schematic of Facility

Instrumentation

- Quick-Closing Valves
  - Slug Liquid Holdup
  - Average Holdup
- Visualization Box
  - Reduce Image Distortion
- High Speed Video Camera
  - Record Flow Pattern

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Instrumentation …

- Optical Sensors
  - Distinguish Slug Body from Bubble Region
- Dynamic Pressure Transducer
  - Measure Pressure Gradient
- Capacitance Sensors
  - Measure Slug Characteristics
  - Liquid Holdup

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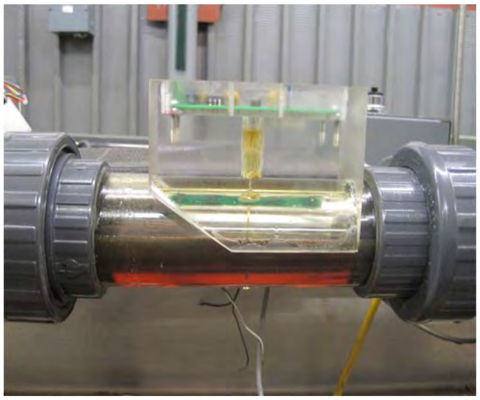
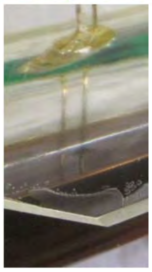
Capacitance Sensor



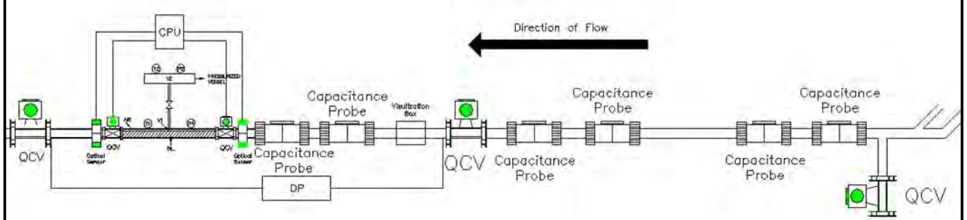


Capacitance Sensor …

- Provide Information about Slug Characteristics
  - Slug Liquid Holdup
  - Slug Frequency
  - Slug Length
  - Translational Velocity

Test Section

Horizontal View



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Quick-Closing Valve System

- Challenges
  - Slug Length
  - Velocity of Slugs
  - Automatic Closing

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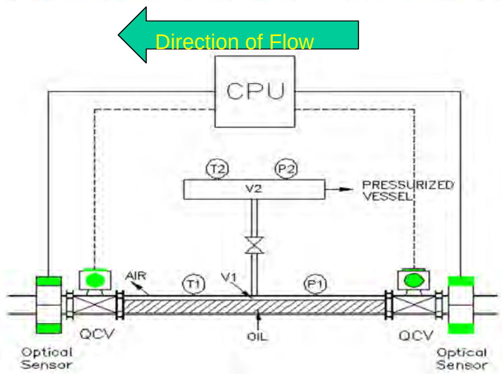
Quick-Closing Valve System …

- Two Quick-Closing Valves
  - Distance between Two Valves: 4 in.
- Two Optical Sensors
  - Detect Slug
  - Ensure Capturing Representative Portion of Slug Body

Quick-Closing Valve System …

- Pressurized Vessel
  - Connect to Trap Section to Equalize Pressure
- Two Pressure Transducers
- Two Temperature Transducers

Quick-Closing Valve System …



$$Vo = \frac{\frac{P_e(V_1+V_2)}{z_e T_e} - \frac{P_1 V_1}{z_1 T_1} - \frac{P_2 V_2}{z_2 T_2}}{\frac{P_e}{z_e T_e} - \frac{P_1}{z_1 T_1}}$$

V1 – Total Volume of Trap Section

V2 - Total Volume of Pressurized Vessel

Test Fluids

- **Test Liquid: Lubsoil ND 50 Base Oil**
  - **Viscosity:** 1000 cP @ 60° F
  - **Density:** 884.4 kg/m3 @ standard condition
  - **Gravity:** 28.5 ° API
  - **Pour Point:** 5 ° F
  - **Flash Point:** 510 ° F
  - **Surface Tension:** 35.75 dynes/cm @ 67.6° F
- **Test Gas: Air**

Test Fluids …

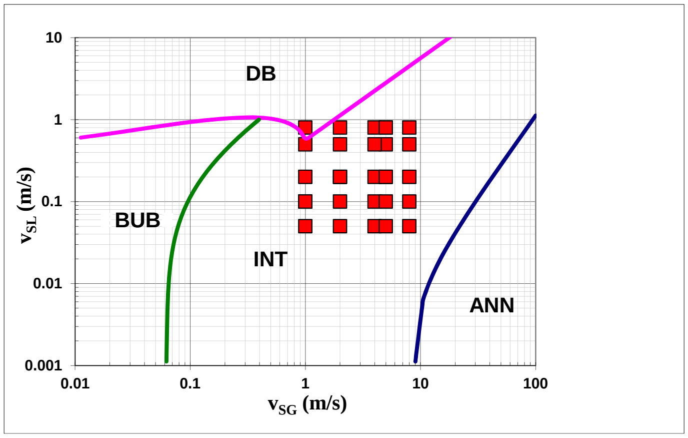
- Viscosity Range

Temperature	Dead Oil
80°F	452 cP
100°F	237 cP

Test Range

- Superficial Liquid Velocity
  - 0.05 – 0.8 m/s
- Superficial Gas Velocity
  - 0.5 – 8 m/s
- Temperatures
  - 26.7 – 37.8 °C (80 – 100 °F)
  - 452 – 237 cP
- Inclination
  - Upward Vertical

Test Range ...



Test Matrix on Vertical Flow Pattern Map Predicted by TUFFP Unified Model

Future Tasks

- Facility Modifications
  - Calibration of Capacitance Sensors
- Conduct Experiments
- Analyze Acquired Data
  - Compare Data with Existing Models
- Develop or Improve Closure Relationships

Schedule

Literature Review	Completed
Facility Modifications	Aug. 2012
Experimental Program	Nov. 2012
Model Improvement	Jan. 2013
Final Report	Apr. 2013

Questions

Experiments of High-viscosity Oil/Gas Slug Flow in Upward Vertical Pipes

Yue Lin

Project Completion Dates

Literature Review....................Completed
Facility Modifications....................August 2012
Experimental Program....................November 2012
Model Verification....................January 2013
Final Report....................April 2013

Objectives

Perform an experimental and modeling study of high-viscosity oil/gas slug flow in upward vertical pipe to investigate the effects of high oil viscosity on slug characteristics.

Introduction

In the petroleum industry, slug flow is a complex and dominant flow pattern for high-viscosity oil/gas flow in horizontal and vertical pipes. Although high-viscosity oil/gas slug flows in horizontal and near-horizontal pipes have been studied recently, slug characteristics for high-viscosity oil/gas flow in vertical pipes are still not well understood. Only few experimental studies for high-viscosity oil/gas flow in vertical pipes have been published recently in the literature showing different behaviors as compare with low viscosity case. Especially, there are no experimental data on slug characteristics for high-viscosity oil/gas flow in vertical pipes. Thus, there is a need of experimental investigation. Furthermore, current two-phase flow models for vertical flow are based on experimental data with low viscosity liquids. These models need to be verified and modified if required for high liquid viscosity conditions.

Activities Summary

This section describes the most relevant activities and results carried out during this period.

Literature Review

Effect of Liquid Viscosity on Slug Flow Behavior

Rosa and Netto (2004) studied the influence of liquid viscosity on gas/liquid structures of horizontal slug flow. Air and glycerin (27 cP) were the test fluids. They concluded that the average slug, bubble length and coalescence rate decreased with increasing liquid viscosity. The bubble front velocity and slug frequency increased with an increase of the liquid viscosity.

Effect of Liquid Viscosity on Slug Length

Al-Safran *et al.* (2005) proposed a probabilistic model for fully developed slug-length distribution in a horizontal pipeline. Two empirical relationships for slug length average and standard deviation were developed. The slug length standard deviation is related to film liquid holdup which in previous studies has been found to be strongly dependent on the liquid viscosity.

Gokcal (2008) experimentally showed that average slug length decreases with increasing liquid viscosity for horizontal pipes. Further analysis of slug length data has continued as part of high viscosity oil studies in TUFFP.

Jeyachandra *et al.* (2011) studied the effects of high oil viscosity on slug length in near horizontal flows. The viscosity range was from 181 to 587 cP. It was confirmed that slug length decreased with increasing liquid viscosity. Taitel *et al.* (1980) and Barnea and Brauner (1985) proposed a minimum liquid slug length of 32*D* for horizontal flow. It was found that slug lengths are much shorter than 32*D* and are approximately 2-18*D* for downward inclined flow and 2-14*D* for upward inclined flow.

Effect of Liquid Viscosity on Slug Liquid Holdup

Kora *et al.* (2010) investigated the effects of high oil viscosity on slug liquid holdup in horizontal flows. The viscosity range was from 181 to 587 cP. Within this viscosity range, no significant change in slug liquid holdup was observed with increasing oil viscosity.

Effect of Liquid Viscosity on Translational Velocity

Slug translational velocity is one of the key closure relationships in the mechanistic modeling of two phase flow. Jeyachandra *et al.* (2011) investigated the effects of high oil viscosity on translational velocity in near horizontal flows. Translational velocity increases with increasing mixture velocity.

The previous literature review shows that several experimental and modeling studies indicated that liquid viscosity has a significant effect on slug characteristics, but there is no experimental study on slug characteristics for high-viscosity oil/gas flow in vertical pipes. Thus, there is a need of experimental investigation to develop a better model for slug characteristics.

Experimental Study

Experimental Facility Design

The experimental work will be conducted using the TUFFP gas/oil/water flow loop located at the University of Tulsa North Campus Research Complex. The gas/oil/water facility was previously used by Atmaca (2007) for characterization of oil/water flow in inclined pipes. The facility consists of a closed circuit loop with storage tanks, progressive cavity pumps, and heat exchangers, metering sections, filters, test section and separator. The test section is attached to an inclinable boom that can be raised to upward vertical position. The original gas/oil/water flow loop consisted of two 21.1-m (69.3-ft) long runs connected with a U-shaped bend to reduce the disturbance to the flow pattern due to a sharp turn.

An acrylic pipe section and instrumentations will be added in the test section to measure and observe slug characteristics. The test section is designed as a 50.8-mm (2-in.) ID 21.1-m (69.3-ft) long pipe consisting of a 7-m (23-ft) steel pipe section and a 14.1-m (46.3-ft) transparent acrylic pipe section. The transparent acrylic pipe section is used to observe the flow behavior visually. It is connected to a 21.1-m (69.3-ft) long, 50.8-mm (2-in.) ID return pipe which is set parallel to the test section at the same height. The instruments are mounted on the acrylic pipe section for detailed measurements of the slug flow characteristics.

Test Fluids

The fluids used in the experiments are mineral oil ND 50 and compressed air. Lubsoil ND 50 is selected due to its high viscosity and Newtonian behavior in the testing range.

Test Range

The experiments will be run using air and mineral oil as the two phases in a 50.8 mm ID vertical pipe. The oil viscosity range will be from 237 to 452 cP corresponding to the two different temperatures: 80 and 100 °F. The superficial liquid velocity will vary from 0.05 to 0.8 m/s. The superficial gas velocity will vary from 0.5 to 8 m/s.

Instrumentation and Data Acquisition

Capacitance Sensor

Capacitance sensor works on the principle of difference in dielectric values between two different phases. The new design of the capacitance sensor provides more detailed information across the slug body. The sensor consists of two parallel copper wires positioned perpendicular to the flow with a distance 0.25 in, an electronic circuit to filter, amplify and convert the measured capacitance to a voltage.

Six capacitance sensors will be installed in the test section; two at the entrance, two at the middle and two toward the end of the acrylic section. They are used to analyze the evolution of the slug characteristics as well as the average liquid holdup.

Optical Sensors

The optical sensors are used for new quick-closing valve system and work based on the light intensity principle. The light reflects/refracts from the oil or the gas phase. This information is converted to a voltage signal which indicates the slug region crossing the sensor. Two optical sensors are mounted in the test section to distinguish slug body from elongated bubble and trigger the close of the quick-closing valves to capture a specific portion of slug body.

Quick-Closing Valve System

A new quick-closing valve system is designed and constructed for the measurement of slug liquid holdup. It consists of one pressurized vessel, two optical sensors, two quick-closing valves, two pressure transducers and two temperature transducers. Gokcal (2008) observed that the slug length of high-viscosity oil/air flow is roughly 8-13*D* in horizontal flow. For QCV system used by Brito (2012), the distance between two quick-closing valves was determined as 4-8*D*. Generally, the slug length in vertical flow is about half of that in horizontal flow. Therefore, the QCV distance for vertical flow is set as 4 in. to assure that only the slug region can be captured. An optical sensor is placed before the first valve in order to distinguish slug body from the bubble region. The other optical sensor is placed after the second valve. When the second optical sensor detects the slug front, the signals from the two sensors will be transmitted to CPU, closing the quick-closing valves capturing a representative portion of slug body. When capturing, a by-pass valve is opened simultaneously to direct the flow from the inlet of the test section to the outlet of the return pipe. By using a high speed camera, proper calibration of the system is required to assure that the correct slug portion is captured.

After liquid slug is trapped by two QCVs, $P1$, $P2$ and $T1$, $T2$ can be recorded from the pressure and temperature transducer located at the test section and pressurized vessel. Then, the connecting valve between the test section and pressurized vessel will be opened to equalize the pressure between them.

Equalized pressure *Pe* and temperature *Te* will be recorded at this time. Then the slug liquid holdup is related to the pressure change of gas by using gas law principles. Proper calibration of the system will carried out to ensure accurate liquid holdup measurements.

Near Future Work

- Completion of facility modifications
- Calibration of capacitance sensors
- Quick-closing valve system calibration
- Conduct experiments
- Analyses of experimental measurements and observations
- Compare experimental data with existing model

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Fluid Flow Projects

Effect of High Oil Viscosity on Two-Phase Oil-Gas Flow Behavior in Vertical and Highly Deviated Pipes

Feras Alruhaimani

Advisory Board Meeting, April 25, 2012

Outline

- Objectives
- Introduction
- Literature Review
- Project Plan
  - Static Experiments
  - Dynamic Experiments
- Projected Time Line

Objectives

- Conduct Experimental and Modeling Study on High Oil Viscosity (>180 cP) Two-phase Flow in Vertical and Highly Deviated Pipes
- Improve Existing Closure Relationships Used in Predicting Two-phase Flow Parameters in Mechanistic Models

Introduction

- Most Two-phase Flow Models are Based on Experimental Low Oil Viscosity Data (μ_O < 20 cP)
- Increase Demand from High Viscosity Reservoirs
- TUFFP Experimental Studies on High Oil Viscosity (μ_O >180 cP) for Flow in Horizontal and Slightly Inclined Pipes

Literature Review

- Gokcal (2005)
  - Horizontal Pipe
  - Significant Effect on Flow Behavior
  - Performance of Models are Not Satisfactory
  - As Oil Viscosity Increases
    - Pressure Gradient Increases
    - Slug Frequency Increases
    - Slug Length Decreases
    - No Significant Change in Liquid Holdup

Literature Review …

- Gokcal (2008)
  - Horizontal Pipe
  - New Drift Velocity and Translation Velocity Model
  - New Closure Relationship for Slug Frequency

Literature Review …

- Kora (2010)
  - Horizontal Pipes
  - Gregory *et al.* (1978) Correlation & Zhang *et al.* (2003) Model Give Best Predictions
  - New Correlation Developed
  - As Oil Viscosity Increases
    - Amount of Small Entrained Bubbles Increases
    - No Significant Change in Liquid Holdup
    - Slight Increase in Film Height

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Literature Review …

- Jeyachandra (2011)
  - Inclined Pipes (- 2^o and +2^o)
  - TUFFP Unified Model Give the Best Flow Pattern Prediction
  - As Oil Viscosity Increases
    - No Significant Change in Average Liquid Holdup or Slug Liquid Holdup
    - Pressure Gradient Increases
    - Slug Frequency Increases
    - Slug Length Decreases

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Literature Review …

- Schmidt, Giesbrecht, and van der Geld (2008)
  - Upward Vertical Flow with High Viscosity Liquid
  - Used Visual Observations and γ-ray Densitometry
  - Measured Flow Pattern and Void Fraction Distribution
  - Presented a New Correlation for Average Void Fraction

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Literature Review …

- Viana, Pardo, Yanez, Trallero & Joseph (2003)
  - Used a Syringe to Inject Bubbles into Down Facing Cup to Get Desired Bubble Size
  - Water and Oil with Viscosities of 0.48, 1.3 & 3.9 Pa.s
  - Velocity Measured by High Speed Video Camera
  - Correlation for the Rise Velocity of Long Gas Bubble in Round Pipes

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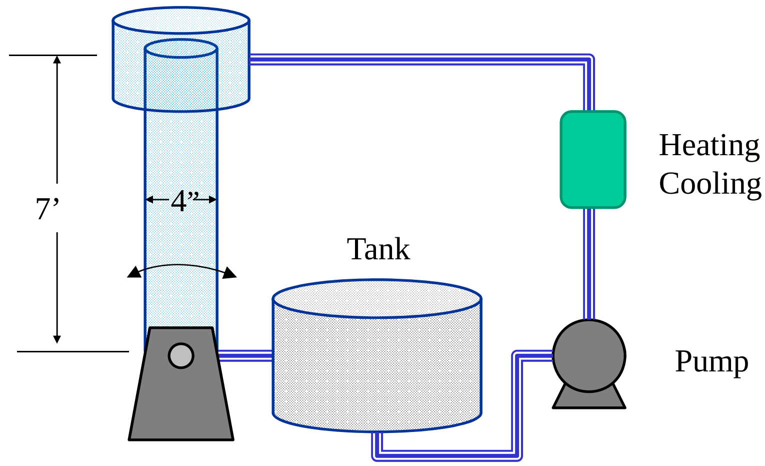
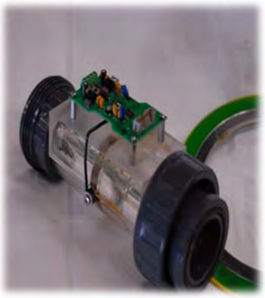
Static Experiments



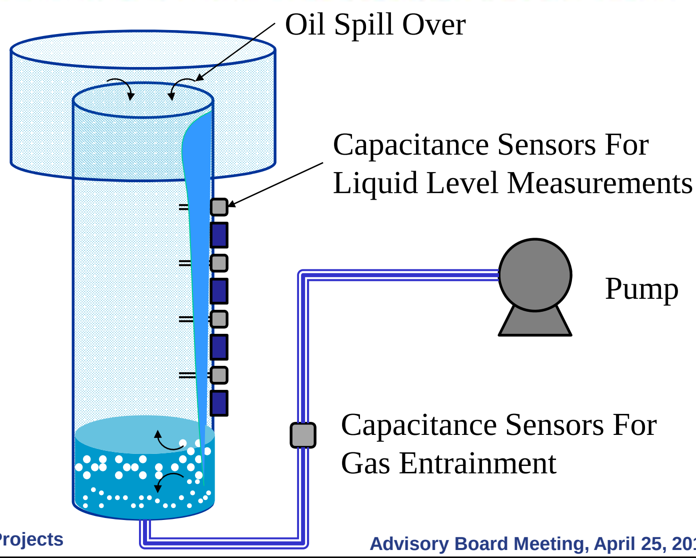
Static Experiments …



Portable Doppler Ultrasonic Flow Meters

Capacitance Sensor

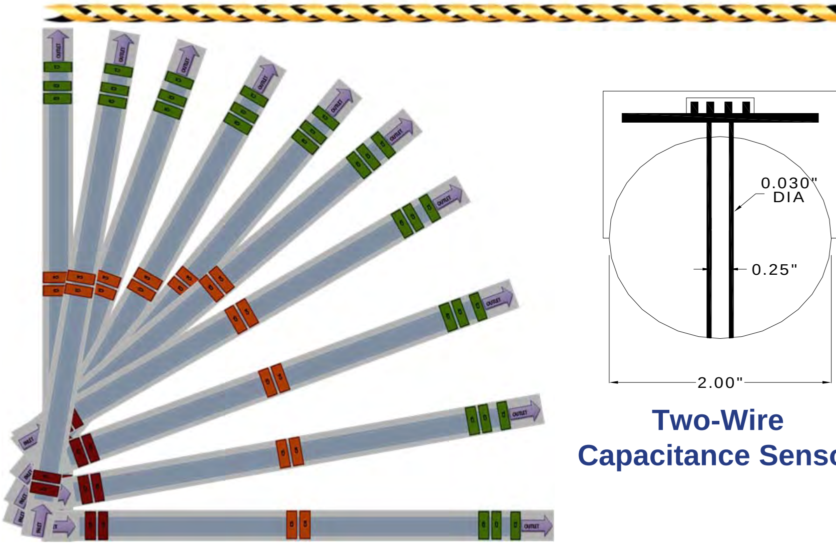
Static Experiments …



Dynamic Experiments …

- Available 2” 3 Phase Facility

Dynamic Experiments



Two-Wire Capacitance Sensor

Dynamic Experiments …

- Experimental Matrix
  - Viscosity
    - 181 – 587 cP
  - Inclination
    - Vertical
    - Highly Deviated (90° to 75°)
  - Superficial Liquid Velocity
    - 0.1 – 3 m/s
  - Superficial Gas Velocity
    - 0.1 – 5 m/s

Dynamic Experiments …

- Two Phase Flow Parameters
  - Flow Pattern
  - Pressure Drop
  - Liquid Holdup
  - Slug Characteristics
    - Slug Length
    - Slug Frequency
    - Translation Velocity
    - Film Thickness
    - Gas Entrainment

Projected Time Line

Literature Review	Ongoing
Static Experiments	Fall 2012
Dynamic Experiments	Fall 2013
Final Report	Spring 2014

Questions
&
Comments

Effect of High Oil Viscosity on Two-Phase Oil-Gas Flow Behavior in Vertical and Highly Deviated Pipes

Feras Alruhaimani

Project Completion Dates

Literature Review .... Ongoing
Static Experiments .... Fall 2012
Dynamic Experiments .... Fall 2013
Final Report .... Spring 2014

Objective

The objective of this study is to conduct experimental and modeling study on oil-gas two phase flow using high oil viscosity (μ_O >180 cP) in vertical and highly deviated pipes. Acquired data will be used to verify and improve the closure relationships used for the existing mechanistic models.

Introduction

With the continuous need of hydrocarbon resources and decline in light oil reserves, heavy oils became a very important source of hydrocarbons. Most two-phase flow models in literature were based on experimental data using low viscosity oils (μ_O < 20 cP). Therefore, studies for the effect of high oil viscosity on two-phase flow parameters are necessary to verify the ability of available mechanistic models with high viscosity oil.

TUFFP conducted several experimental studies on two-phase gas-liquid flow using high oil viscosity (μ_O > 180 cP) for horizontal and slightly inclined pipes (±2^o). These studies investigated the effect of high viscosity oil on two phase flow parameters like flow pattern, pressure drop, liquid holdup, and slug characteristics. The results from these studies were used to improve existing mechanistic models for high oil viscosity multiphase flow.

This study is a continuation of the high oil viscosity efforts initiated by TUFFP, and is focused on the effect of high liquid viscosity on vertical and highly deviated gas liquid two phase flow.

Literature Review

Gokcal (2005) studied the effect of high oil viscosity on two-phase oil-gas flow behavior in horizontal pipes. His study showed that high liquid viscosity has significant effect in flow behavior showing that existing mechanistic models were not suitable for these conditions. Gokcal observed that the pressure gradient increased with liquid viscosity. No significant effect of high viscosity on liquid holdup was observed. Slug frequency increased, and the slug length decreased with increasing liquid viscosity.

Later, Gokcal (2008) presents a detailed study on slug flow in horizontal pipes. In addition, to his first study, he experimentally observed a significant dependency of drift velocity on liquid viscosity. A new drift velocity model for high viscosity oils was developed. A closure model for upward inclined pipe was proposed by combining available horizontal and vertical drift flux models. Final model presented a good agreement with his experimental results and the published data. A new slug frequency closure model was also developed. The model gave good predictions for laminar flow region.

Kora (2010) studied the effect of high oil viscosity on slug liquid holdup in horizontal pipes. Her study showed presence of large and small entrained bubbles in the liquid slug, and large bubbles were observed for mixture velocities from 0.6 to 3.5 m/s. A decrease in the amount of small entrained bubbles was visually observed with decreasing oil viscosity. Gregory *et al.* (1978) correlation and Zhang *et al.* (2003) model gave the best predictions at all viscosities. All available correlations showed a good agreement with the measured slug liquid holdup data for mixture velocities lower than 2 m/s. Therefore, a new correlation for slug liquid holdup was developed as a function of liquid viscosity based on experimental data of the study.

Jayachandra (2011) studied the effect of pipe inclination on flow characteristics of high viscosity oil-gas two-phase flow. His study was carried out for upward (+2^o) and downward (-2^o) flows. Pressure drop, liquid holdup, flow pattern and slug characteristics were reported in his study.

Schmidt *et al*. (2008) measured the flow pattern and void fraction distribution in vertical gas-liquid upward flow in vertical pipes. They considered liquid viscosities up to 7 Pa s. In their study, γ-ray densitometry was utilized to measure the void fraction and flow pattern was determined by visual observations. Based on their results, authors proposed new correlations for the average void fraction.

Viana, Pardo, Yanez, Trallero and Joseph (2003) conducted a study on the rise velocity of a large bubble in a vertical round pipe. They used an acrylic box that contains a syringe to inject bubbles into a down facing cup traping the bubble until the desired Taylor bubble size is achieved. Then, the cup was turned up to release the bubble. Four liquids considered were water, and oil with viscosities 0.48, 1.3 & 3.9 Pa s. Bubble rise velocity was measured by high speed video. Based on their results, they presented a universal correlation for the rise velocity of long bubbles in round pipes.

As can be seen in the literature review, there is a lack of experimental and theoretical studies on gas and highly viscous liquid two phase flow for vertical and highly deviated pipes.

Project Plan

The project plan is divided into two parts; in the first part, the static slug experiments will be carried out, while in the second part an available experimental facility will be utilized to characterize dynamic slugs.

Static Experiments

Static experiments will be run using air and oil as two phases in a pipe for vertical and highly deviated configurations (90^o to 75^o). The experimental apparatus consist of a circular pipe where the oil will be introduced from the top of the pipe. Falling film thicknesses will be measured by capacitance sensors and the velocity will be recorded by an ultrasonic flow meter (omega FD613 series). This flow meter utilizes a non-invasive clamp-on transducer which is placed on the outside of a pipe. The FD613 Series utilizes two piezoelectric crystals contained within one transducer to emit ultrasonic energy into the fluid stream and one receiver which reflects off discontinuities (suspended particles or entrained gases) within the moving liquid. Fluid velocity is estimated by the delay time between the emitted and acquired signal.

High speed video recording will be utilized to analyze the wall jet occurring at the bottom of the pipe. This jet is generated by the interaction of falling film with the bottom liquid. This phenomenon is the responsible of gas entrainment into the liquid slug. A capacitance sensor will be connected at the drain pipes to measure the amount of entrained gas.

This experimental setup will allow improvements of the understanding of the falling film and gas entrainment under slugging conditions. Data will be utilized to improve or generate new closure relationships for these conditions.

Dynamic Experiments

Dynamic experiments will be run using similar measurements techniques as in the static experiments Air and mineral oil as the two phases in a vertical and highly deviated pipe (90^o to 75^o) will be considered. The oil viscosity will vary from 181 to 587 cP. The range of superficial liquid and gas velocities are 0.1 to 3 m/s and 0 to 5 m/s, respectively.

Similar experimental setup as implemented by Brito (2011) will be considered. Three stations of capacitance sensors will be installed at the entrance, middle and test section regions. Each station comprise of two capacitance sensors for slug characteristic such as translational velocity, slug length, slug frequency, slug liquid holdup and film thickness.

The experimental results will be used to validate the performance of existing models to estimate two-phase gas-liquid flow parameters. If the existing models show poor performance, new closure relationships will be developed.

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Fluid Flow Projects

Liquid Loading of Gas Wells

Ge (Max) Yuan

Advisory Board Meeting , April 25, 2012

Outline

- Objectives
- Literature Review
- Experimental Program
- Experimental Results
- Model Comparison
- Conclusion
- Recommendations

Objectives

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

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Literature Review

- Mechanisms of Liquid Loading
  - Droplet Flow Reversal
  - Liquid Film Flow Reversal
- Effect of Well Deviation on Liquid Loading

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Effect of Well Deviation

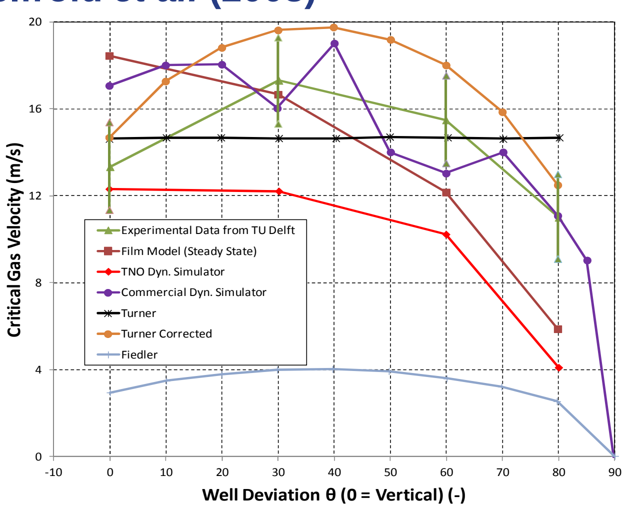
- **Belfroid *et al.* (2008)**
  - Corrected Turner's Expression

$$M_{g,min} = 3.1A\sqrt{\rho_g}\left(g\sigma\left[\rho_L - \rho_g\right]\right)^{0.25} \frac{\left[sin 1.7\alpha\right]^{0.38}}{0.74}$$

Referred As TNO-Shell Correlation

Effect of Well Deviation …

- **Belfroid *et al.* (2008)**



Literature Summary

- Mechanism in Debate
- Limited Experimental Data About Well Deviation Effect

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Experimental Program

- 3 inch Multiphase Flow Loop

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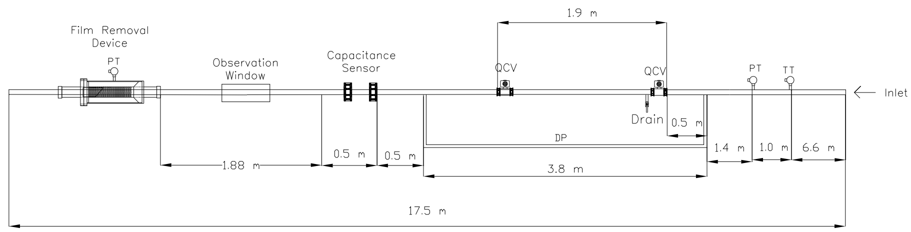
Experimental Program

- Test Section Design



- Test Fluids
  - Gas – Air
  - Liquid – Tap Water

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Experimental Program …

- Test Ranges
  - Superficial Gas Velocity:
    10 to 35 m/s
  - Superficial Liquid Velocity :
    0.005, 0.01, 0.02, 0.05 and 0.1 m/s
  - Well Deviation:
    0º, 15º, 30º, 60º

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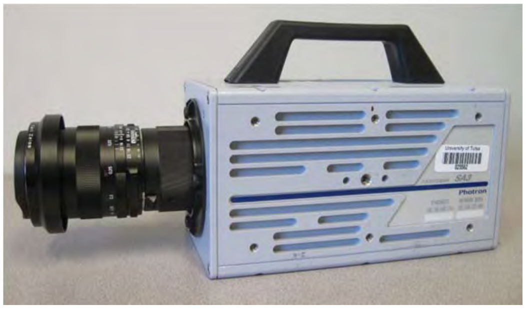
Instrumentation

- Pressure and Temperature: PTs and DPs and TTs
- Holdup: Quick Closing Valves
- High Speed Camera



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Experimental Results

- Testing Results
  - Vertical Wells
  - 15° Deviated Wells
  - 30° Deviated Wells
- Criteria of Liquid Loading
- Well Deviation Effect

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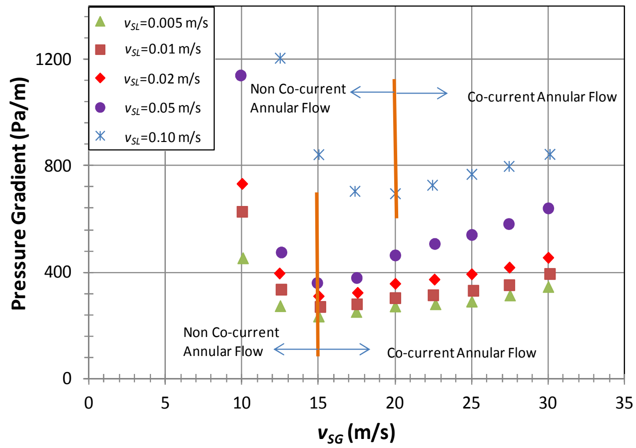
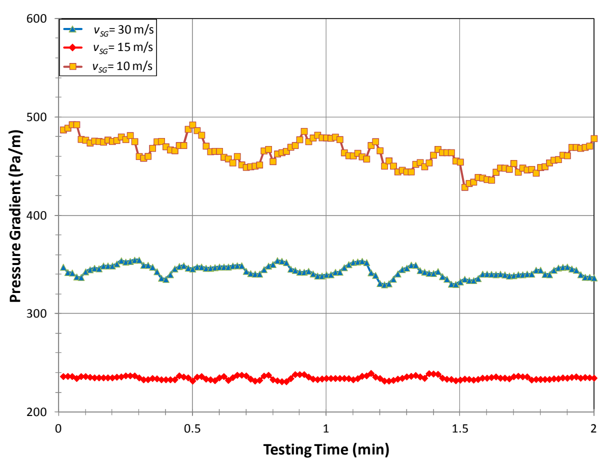
Vertical Wells

- Pressure Gradient



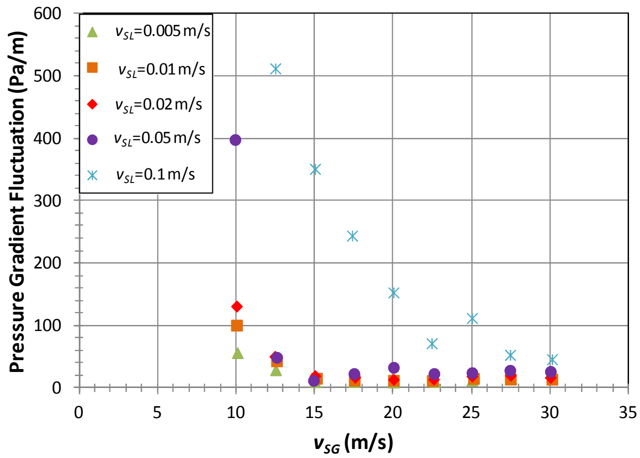
Vertical Wells …

- Pressure Gradient, v_{SL} = 0.005 m/s



Vertical Wells …

Pressure Gradient Fluctuation



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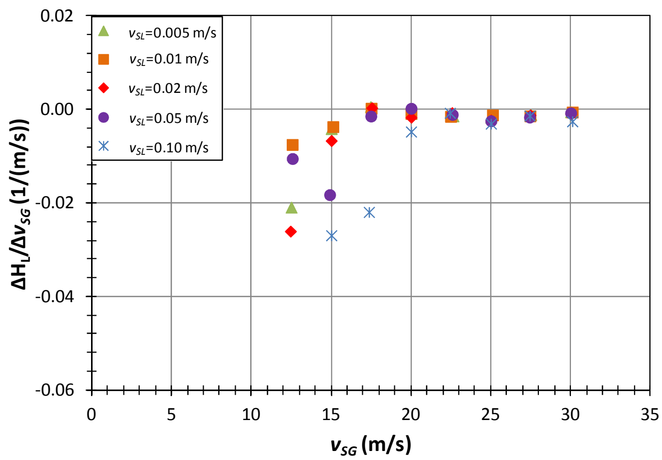
Vertical Wells …

Liquid Holdup



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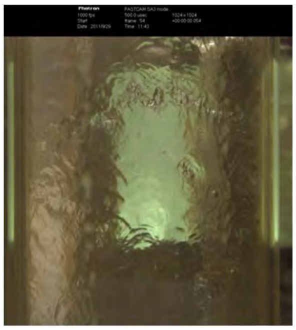
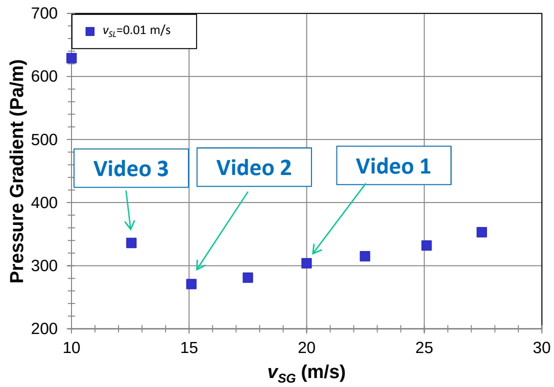
Vertical Wells …

- High Speed Videos

Video 1

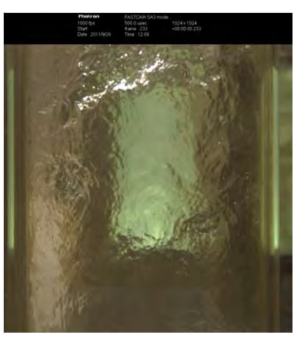


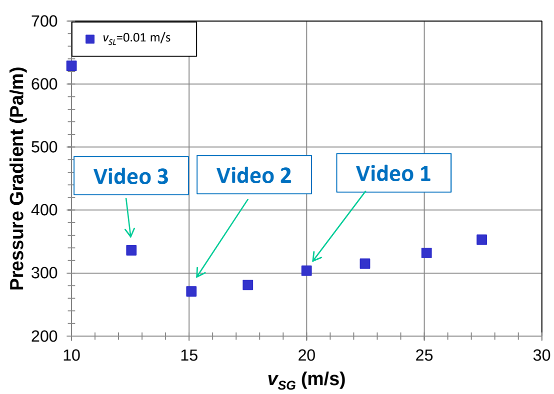


Vertical Wells …

- High Speed Videos

Video 2

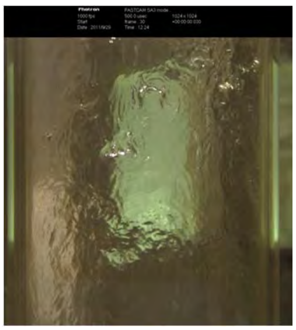


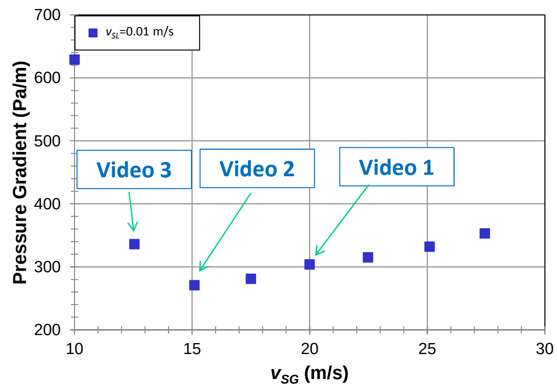


Vertical Wells …

High Speed Videos

Video 3





Vertical Wells …

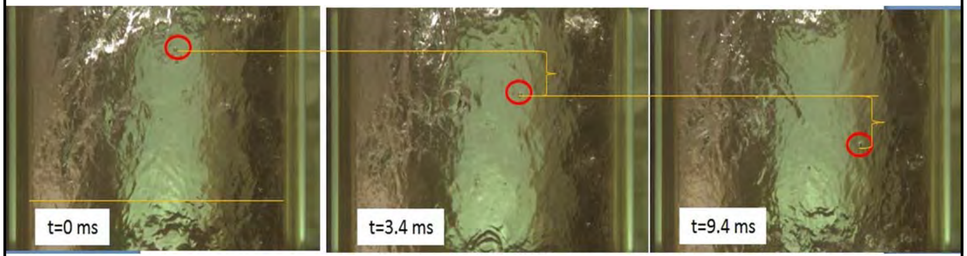
Images Analysis 1

Condition 1: v_{SL}=0.01 m/s, v_{SG}= 20 m/s, Well Deviation= 0°

Average Bubble Velocity = 1.9 m/s

Vertical Wells …

- Images Analysis 2



Condition 2: v_{SL}=0.01 m/s, v_{SG}= 15 m/s, Well Deviation= 0°

Average Bubble Velocity = -2.7 m/s

Vertical Wells …

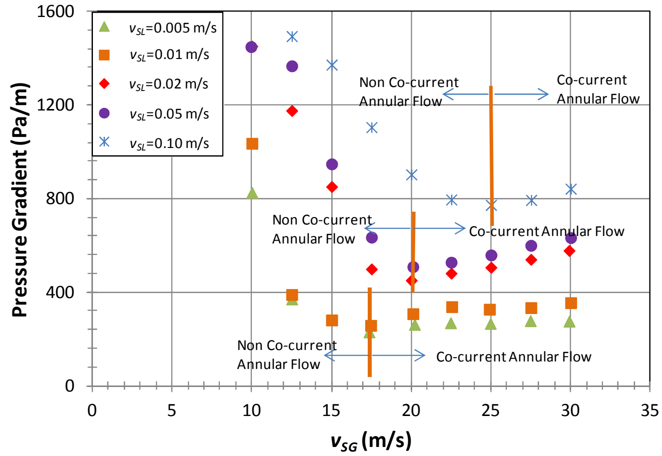
- Images Analysis 3

Condition 3: v_{SL}=0.01 m/s, v_{SG}= 12.6 m/s, Well Deviation= 0°

Average Bubble Velocity = -4.6 m/s

15° Deviated Wells

- Pressure Gradient



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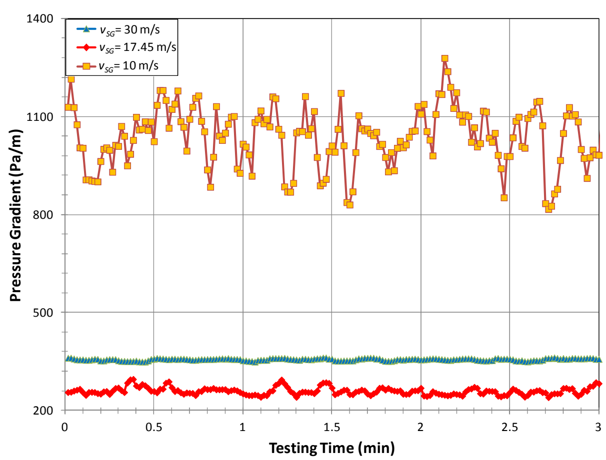
15° Deviated Wells …

- Pressure Gradient, v_{SL} = 0.01 m/s



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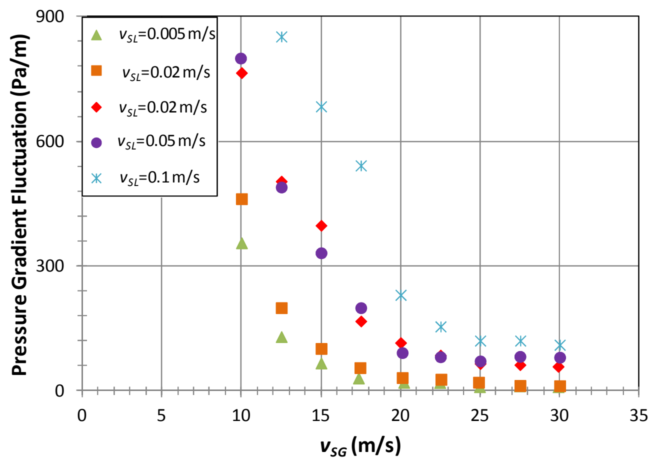
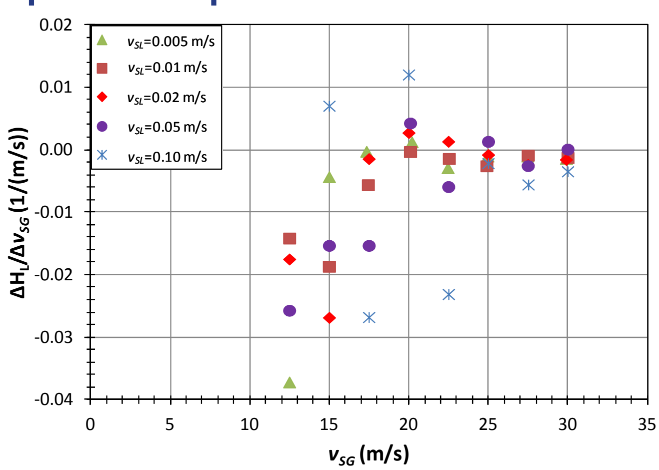
15° Deviated Wells …

- Pressure Gradient Fluctuation



15° Deviated Wells …

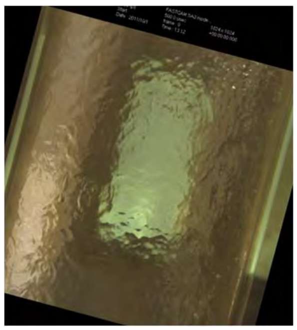
- Liquid Holdup

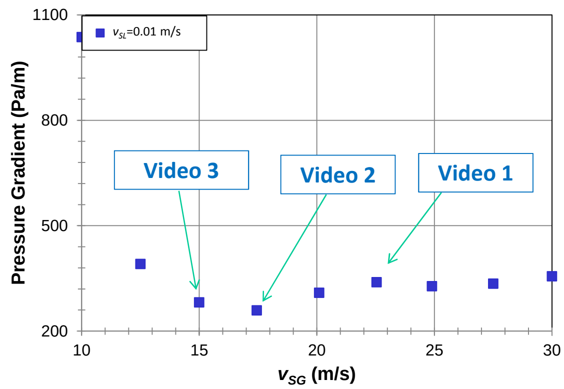


15° Deviated Wells …

High Speed Videos

Video 1





Fluid Flow Projects

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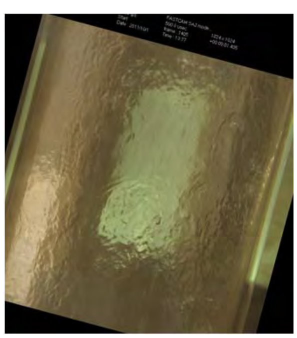
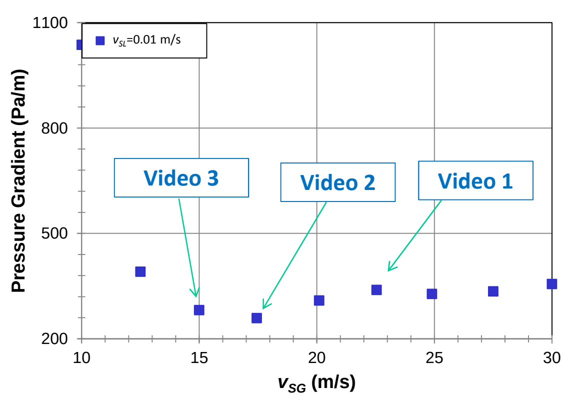
15° Deviated Wells …

High Speed Videos

Video 2





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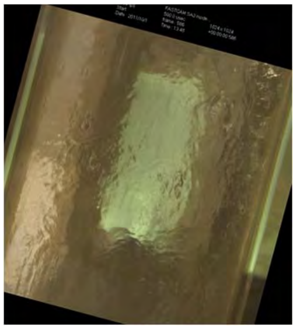
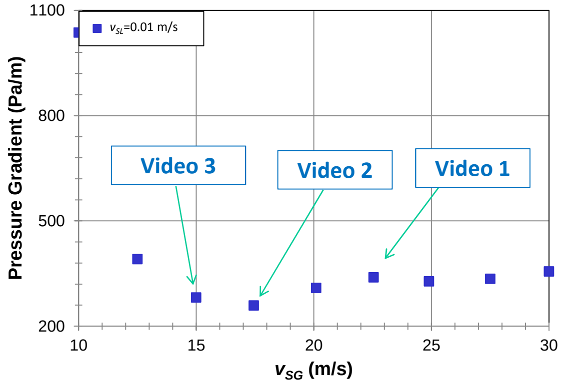
15° Deviated Wells …

- **High Speed Videos**

Video 3





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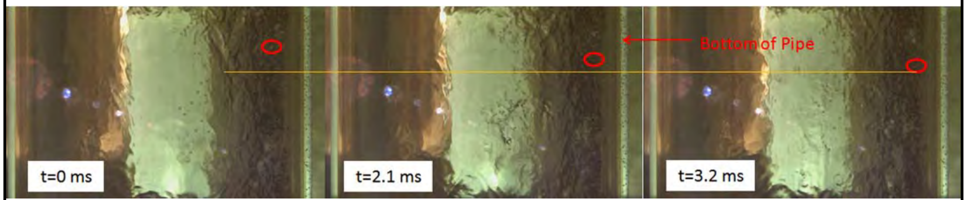
15° Deviated Wells …

- **Images Analysis**



Condition 2: v_{SL}=0.01 m/s, v_{SG}= 17.45 m/s, Well Deviation= 15°

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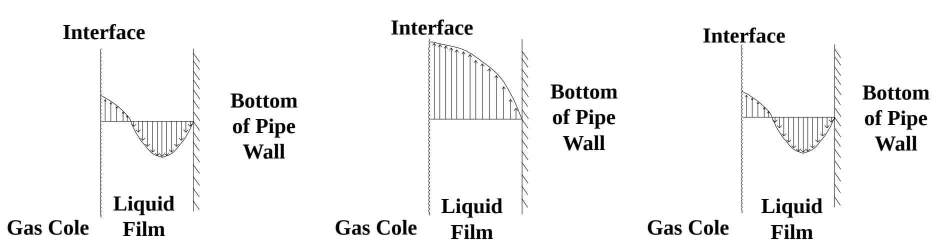
15° Deviated Wells …

- Images Analysis

Condition 3: v_{SL}=0.01 m/s, v_{SG}= 15 m/s, Well Deviation= 15°

15° Deviated Wells …

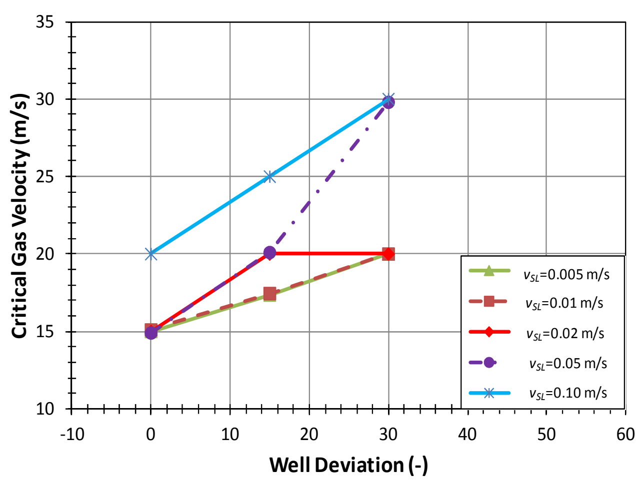
- Schematic of Velocity Profile Within Liquid Film for Condition 3



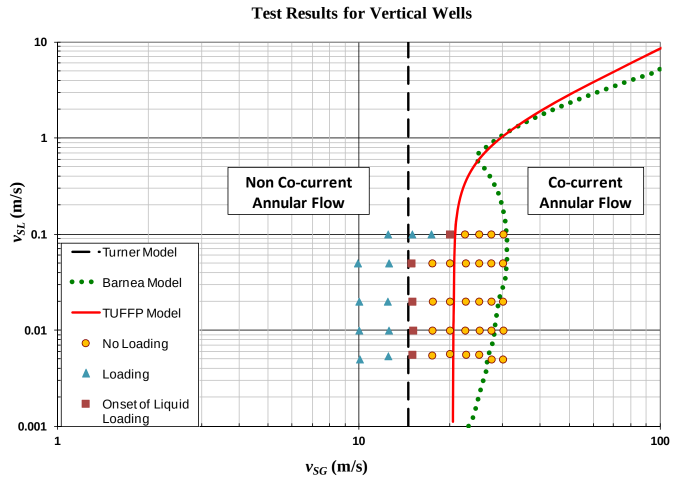
Criteria of Liquid Loading

- Vertical Wells
  - Film Flow Reversal
  - Flow Pattern Changes to Partially Co-Current Annular Flow
- Deviated Wells
  - Film at the Bottom Flows Downward Continuously
  - Flow Pattern Changes to Wavy-Annular Flow

Well Deviation Effect



Model Comparison – Critical Velocity



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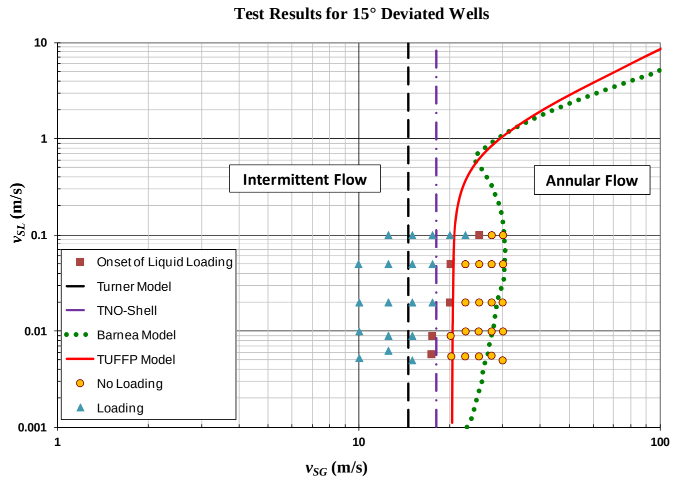
Model Comparison – Critical Velocity …



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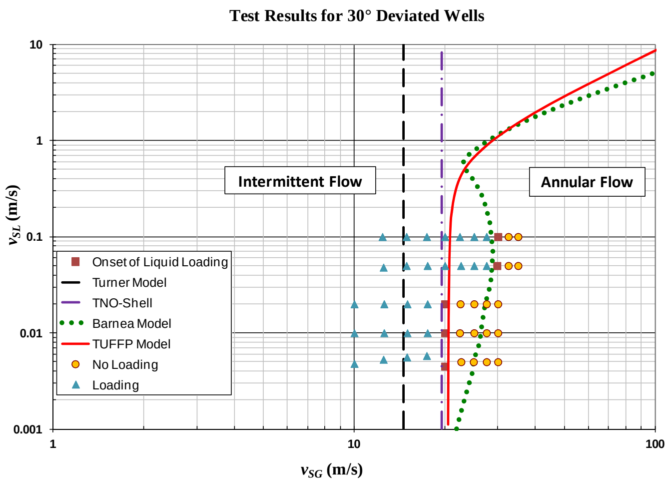
Model Comparison – Critical Velocity …



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Conclusions

- For Vertical Wells
  - Droplets Flowing Upward with Gas Core Even Though Liquid Loading Occurs
  - Loading is Controlled by Film Flow Reversal and Flow Pattern Transition from Fully Co-Current Annular Flow to Partially Co-Current Annular Flow
  - Turner's Model Predicts Well

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Conclusions …

- For Deviated Wells
  - Liquid Film at Bottom of the Pipe Flows Downward Continuously
  - Flow Pattern Changes from Annular Flow to Wavy-Annular Flow

Conclusions …

- In Well Deviation Range of 0° to 30°, Critical Velocity Increases as Well Deviation Increases
- Liquid Amount Effect on Critical Gas Velocity
- Critical Gas Velocity can be Identified by Minimum Pressure Gradient Analysis
- DP and H_L Predicted by TUFFP Unified Model Lies in 50% Error Range

Recommendations

- Conduct Experiments at More Well Deviations
- Reduce Gas Velocity Interval
- Add Film Thickness Measurement
- Improve Holdup Measurement
- Allow Sufficient Time Before Taking Data
- Develop a Mechanistic Model Considering Liquid Film Flow Reversal Mechanisms

Questions/Comments

Liquid Loading from Gas Wells (completed)

Ge (Max) Yuan

Project Completion Dates

Literature Review .... Completed
Experimental Testing .... Completed
Data Analysis .... Completed
Model Comparison .... Completed
Final Report .... Completed

Objectives

The main objectives of this study are:

- Explore the mechanisms controlling the onset of liquid loading, and
- Investigate the effect of well deviation on liquid loading process.

Introduction

As natural gas is produced from a reservoir, the simultaneous flow of gas with liquid hydrocarbons and/or water is a common occurrence in both onshore and offshore production systems. Liquid loading in the wellbore has been recognized as one of the most challenging problems in gas production. During the early time of the production, natural gas carries liquid as mist flow. Before loading conditions, the reservoir pressure is sufficient to transport the liquid phase to the surface along with the gas phase. As the gas well matures, the reservoir pressure decreases and gas flow velocity drops. When the gas velocity becomes lower than a critical value, the liquid falls back and the flow pattern changes from annular flow to slug flow. As liquid loading progresses, the accumulation of liquid increases the bottom-hole pressure reducing the gas production rate. Then, the flow pattern may change to slug flow and eventually the well can no longer produce.

Literature Review

Several methods have been developed to solve the liquid loading problem; such as down-hole pumping to produce water, velocity string to increase gas velocity, and foam assisted lift to reduce the elevation losses. Although several efforts have been made to model the liquid loading process of gas wells, experimental data are very limited. Field data from Turner (1969), Coleman (1991) and Veeken (2009) are the only available data to validate the existent models.

The first method to estimate the critical gas velocity has been proposed by Turner *et al.* (1969). This method considers a balance between the upward drag and downward gravity forces on the largest possible liquid droplet. The maximum Weber number determines the largest possible droplet size. The so-called Turner expression for liquid loading includes a 20% upward adjustment to best-fit field data. The Turner method has been widely used in the industry for decades because it only requires fluid properties at wellhead conditions.

There is no satisfactory model to predict the critical velocity for inclined wells. Girija's (2006) study the transitional region from slug to Annular Flow. In this region, gas flows upward in the central core of the conduit, while the liquid film flows around the walls of the conduit. Moreover, two zones are observed in the test section owing to the effect of gravity. In the lower zone, the liquid film is thick, and its direction of flow oscillates between upward and downward. In the upper part of the loop, the film is thinner and the direction of flow is downward. The lower zone generates large quantities of liquid droplets which are lifted to the upper zone in the test section, where they coalesce on the walls and flow downward until they meet the thicker film of the lower zone. Thus, the flow regimes in the loop consist of a lower zone with a gas core and annular film from which droplets are transported upward, and an upper coalescing zone in which droplets strike the wall of the loop and flow downward. There is a distinct interface between the lower zone and the upper zone.

Experimental Facility

The 76.2-mm (3-in.) diameter multiphase flow facility of the Tulsa University Fluid Flow Projects (TUFFP) with a total length of 17.5 m has been modified for this project. The facility is capable of being inclined from horizontal to vertical. Pressure and temperature transducers are placed near the test section to obtain fluid properties and other flowing characteristics. Compressed air and Tulsa city tap water will be used in this study.

Instrumentation and Data Acquisition

There are two major sections in the flow loop, namely, quick-closing valve and flow visualization section. Absolute inlet pressure and differential pressure are acquired. Liquid holdup is measured by trapping the fluid in the quick-closing valve section.

High speed camera is used to observe the flow phenomena.

Experimental Program

In this study, experiments were conducted at different flow conditions in terms of flow rates and inclination angle. Superficial water velocities range from 0.005 to 0.1 m/s. Superficial gas velocities range from 10 to 35 m/s. The test range covered the onset of liquid loading including the critical gas velocity. Experiments were conducted at well deviation of 0°, 25°, 30° and 45° from vertical. During one test run, liquid flow rate was kept constant while gas flow rate was decreased step by step from 35 m/s until liquid loading is observed.

Experimental Results

Based on visual observation and data analysis, the criteria for liquid loading were established as follows:

- For vertical pipes, liquid loading occurs when the liquid film flows downward and flow pattern changes from fully co-current annular flow to partially co-current annular flow.
- For deviated pipes, liquid loading occurs when the liquid film at the bottom of the pipe flows downward continuously and flow pattern changes from annular to wavy-annular flow.

In general, the critical gas velocity is defined as the minimum gas superficial velocity at which the liquid film is flowing upward continuously. This critical velocity also corresponds to the minimum pressure gradient and pressure fluctuation for constant liquid superficial velocity.

The critical gas velocity is affected by pipe deviation. The critical gas velocity increases as the well deviation increases in the range of 0° to 30°. For v_{SL} = 0.02 m/s, critical gas velocity increases as pipe deviation changes from 0° to 15° but no change has been observed between 15° and 30° inclination. These observations are in agreement to results reported by Westende (2008).

Model Comparisons

Experimental results are compared with predictions from different models including the TUFFP unified model. Flow pattern, pressure gradient and average liquid holdup data are the main two phase flow parameters compared in this study.

None of the models does show good agreement with the pressure drop and liquid holdup experimental data. The discrepancy of most of the data lies in the range of ±50%. Flow pattern observations have been compared against TUFFP unified model (Zhang *et al.*, 2003), Barnea (1987), Turner (1969) and TNO-Shell (Belfroid *et al.*, 2008) models. TNO-Shell correlation presents the best agreement against the acquired data.

Conclusions

Liquid loading mechanism differs for vertical wells and inclined wells. For vertical wells, the mechanisms controlling the onset of liquid loading are the liquid film flow reversal and flow pattern transition from fully co-current annular flow to partially co-current annular flow. For inclined wells, the mechanism controlling the onset of liquid loading is the liquid film at the bottom of the pipe flowing downward continuously, which promotes flow pattern transition from annular flow to wavy-annular flow

At the onset of liquid loading for both vertical and inclined wells, the total pressure gradient and pressure fluctuation reach a minimum value. For both vertical and inclined wells, the average liquid holdup has a sharp increase near the onset of liquid loading. This slope change starts at slightly higher gas superficial velocities than the corresponding liquid loading onset for all inclination angles.

The critical gas velocity is affected by the deviation angle. For low superficial liquid velocity ($v_{SL} \leq$ 0.05 m/s), critical gas velocity increases as deviation increases. At higher superficial liquid velocity (v_{SL} = 0.1 m/s), the critical gas velocity first increases and then decreases.

Recommendations

It is recommended that experiments should be carried out at more well deviation angles. Moreover, gas velocity should be reduced in smaller intervals to get more accurate critical gas velocity. Film thickness measurement is strongly recommended. Liquid holdup can be measured at multiple locations. Sufficient time should be given to reach steady state before acquiring data.

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Fluid Flow Projects

Liquid Loading of Gas Wells (Current Study)

Mujgan Guner

Advisory Board Meeting, April 25, 2012

Outline

- Objective
- Introduction
- Literature Review
- Experimental Program
- Instrumentation
- Wave Characteristic Analysis
- CFD Modeling
- Near Future Tasks

Objective

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

Introduction

- Liquid Loading is Inability of Produced Gas to Carry Produced Liquids
- Liquid Loading Mechanisms
  - The Main Reason is Still in Debate
    - Liquid Droplet Fall Back
    - Liquid Film Reversal

Literature Review

- Yuan (2011)
  - Exploratory Experiments for Investigation of Pressure Gradient and Observation of Film Reversal
  - Inclination Effects on Film Reversal
  - Liquid Loading Tends to be Observed at Higher Gas Velocity as Liquid Velocity Increases
    - Current Models do not Predict This Behavior Correctly

Literature Review

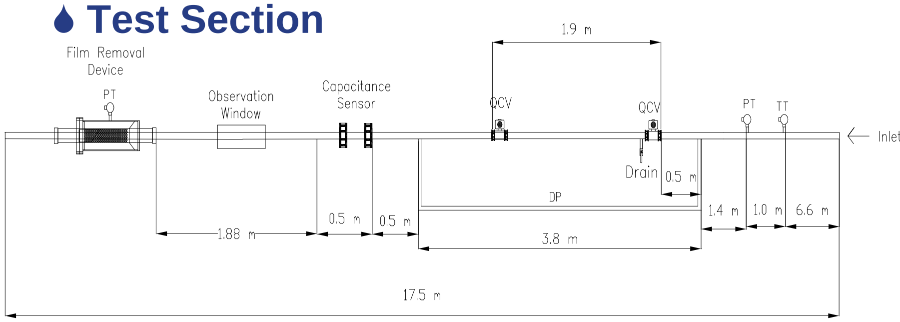
- Sawai *et al.* (2003)
  - Gas – Liquid Interfacial Structure and Pressure Drop Characteristics of Churn Flow
  - Experimental Study
    - Air – Water as Testing Fluids
    - 1 in. ID Pipe in Vertical Configuration
    - Gas – Liquid Interface is Investigated by Conductance Probes
    - Wave Celerity and Pressure Gradient

Experimental Program

- Experimental Study of Film Reversal Mechanisms in Annular Flow
  - Effects of Inclination for Angles Between 90° – 60°
  - Film Flow Mechanisms
  - Investigation of Flow in Gas Core
  - Observation of Flow Development for Loading and Unloading Conditions
  - Wave Characteristics

Experimental Program…

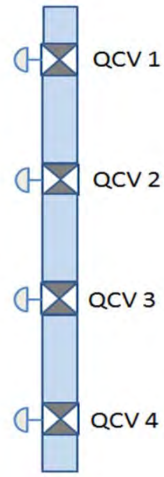
- Test Section



- Testing Fluids
  - Air – Tap Water

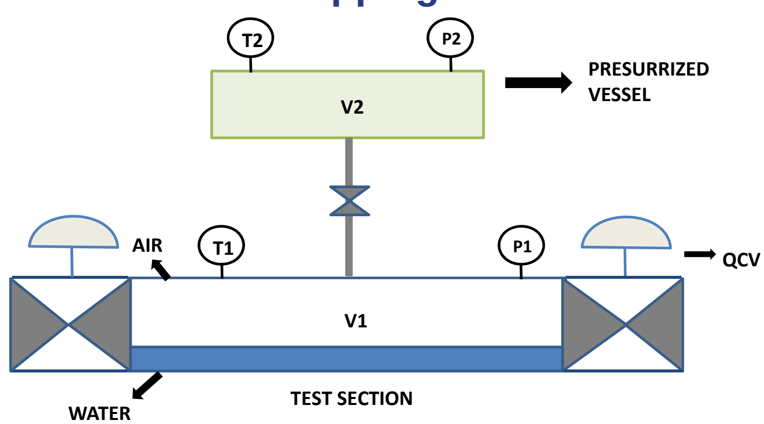
Instrumentation

- Investigation of Holdup
  - Three Trapping Sections
  - Special Design to Increase Accuracy and Decrease Operation Time



Instrumentation …

- Schematic of Trapping Section



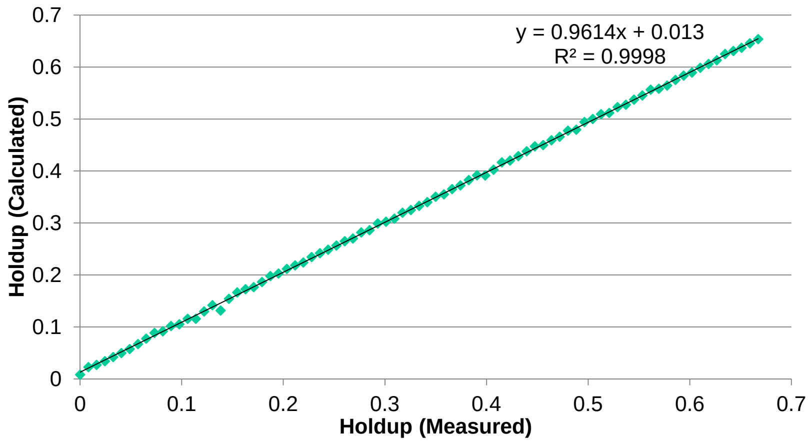
Instrumentation …

$$V_w = \frac{\frac{P_F(V_1+V_2)}{z_F T_F} - \frac{P_1 V_1}{z_1 T_1} - \frac{P_2 V_2}{z_2 T_2}}{\frac{P_F}{z_F T_F} - \frac{P_1}{z_1 T_1}}$$

$$H_L = \frac{V_w}{V_1}$$

Instrumentation …

- Holdup Calibration Curve

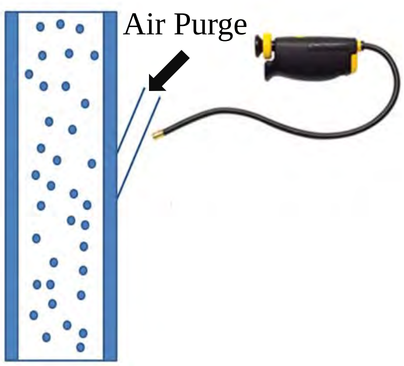


Instrumentation …

- Flow Pattern Observation
  - Flow Pattern Evaluation Videos from the Bottom of the Test Section to the Top by Utilizing Outdoor Surveillance Cameras
  - High Speed Camera Will be Connected to the Test Section

Instrumentation …

- Visual Observation
  - Boroscope
    - Boroscope Will be Utilized to Observe the Droplet Flow Direction



Instrumentation …

- Film Flow Direction
  - Wall Shear Stress Sensor
    - Wall Shear Stress Measurement
    - Near Wall Flow Direction Indicator
    - Commercial Device for Direct Wall Shear Stress Measurement Lenterra RealShear™ F - Series

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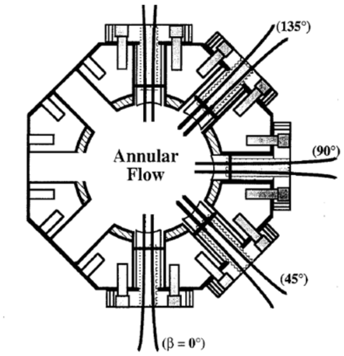
Instrumentation …

- Capacitance Sensor
  - Wave Characteristics



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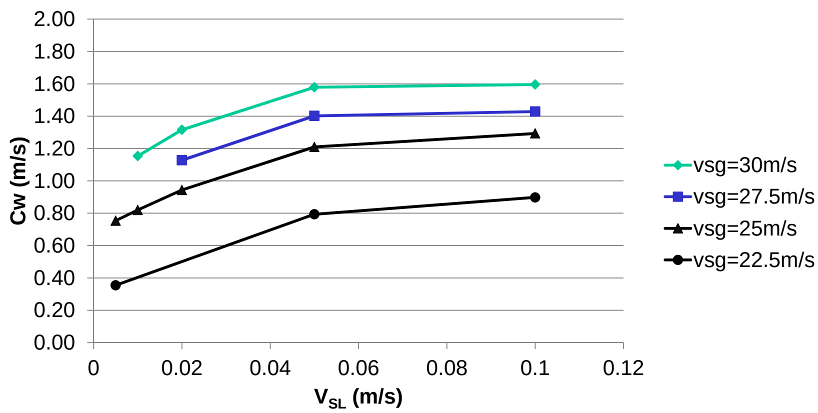
Wave Characteristic Analysis

- Raw Capacitance Sensor Data Collected by Yuan (2011)
- Data Analysis with MATLAB Cross Correlation and Related Algorithms
- Wave Celerity Investigated for Different V_{SL} and V_{SG} for Vertical and Inclined Cases
- Initial Investigation of Capacitance Sensors
- Necessary Sensor Modification Will be Implemented

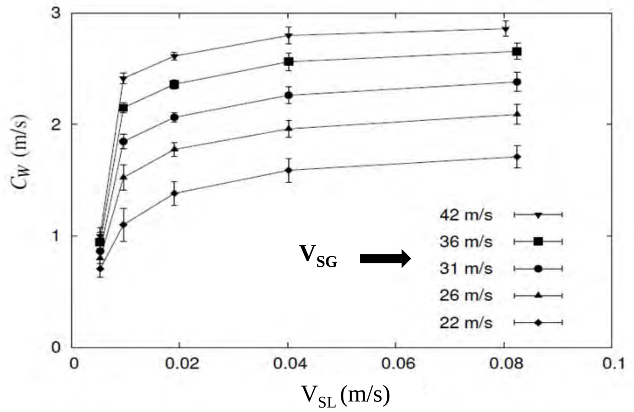
Wave Characteristic Analysis …

- Wave Celerity vs. V_{SL} (90°)



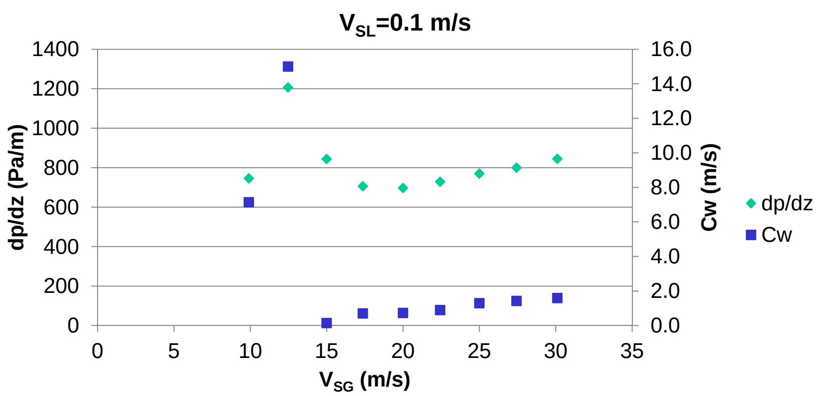
Wave Characteristic Analysis …

- **Belt (2007)**
  - **Wave Celerity vs. V_{SL} (90°)**



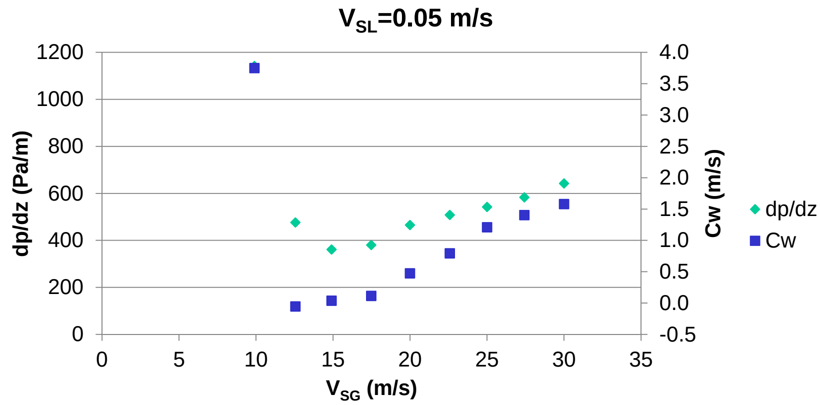
Wave Characteristic Analysis …

- **Wave Celerity vs. V_{SG} (90°)**



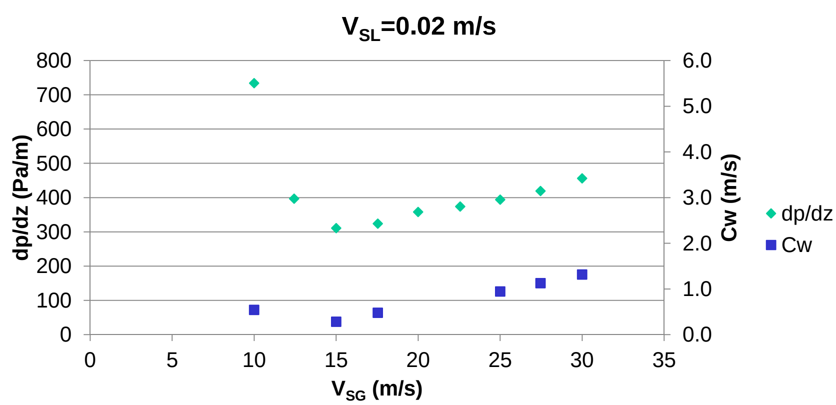
Wave Characteristic Analysis …

Wave Celerity vs. V_{SG} (90°)



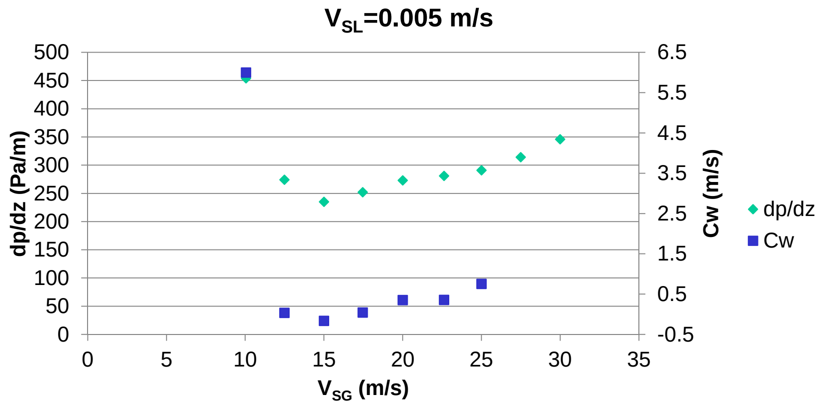
Wave Characteristic Analysis …

Wave Celerity vs. V_{SG} (90°)



Wave Characteristic Analysis …

- Wave Celerity vs. V_{SG} (90°)



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Wave Characteristic Analysis …

- Conclusions
  - Wave Celerity Increases with Superficial Liquid Velocity
  - Wave Celerity Shows a Parallel Trend to Pressure Gradient and Reaches Zero When Minimum Pressure Gradient is Attained
  - Capacitance Probes
    - Will be Located Closer
    - Will be Modified for Inclined Tests

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CFD Modeling

- CFD Modeling of the Vertical 2-phase Air-Water Flow by Using the Same Conditions of Zabaras (1986) and Yuan (2011) Experimental Data to Estimate
  - Velocity Distribution
  - Wall Shear Stress Distribution

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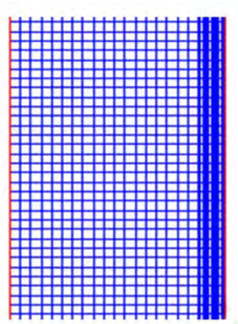
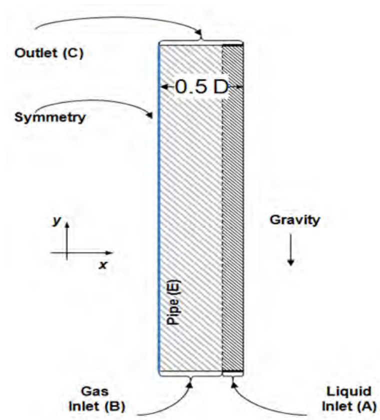
CFD Modeling …

- Geometry and Mesh for CFD Modeling Modeling





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Near Future Tasks

Literature Review	Ongoing
Instrumentation	May 2012
CFD Modeling	August 2012
Experimentation	August 2012
Data Analysis	September 2012
Modeling	November 2012
Final Report	December 2012

Questions & Comments

Fluid Flow Projects
Advisory Board Meeting, April 25, 2012

Liquid Loading of Gas Wells (Current Study)

Mujgan Guner

Project Completion Dates

Literature Review .... Ongoing
Instrumentation .... May 2012
Experimentation .... August 2012
CFD Modeling .... August 2012
Data Analysis and Model Comparison .... October 2012
Final Report .... December 2012

Objectives

The main objective of this study is to explore mechanisms controlling onset of liquid loading in vertical and inclined pipe configurations.

Introduction

Liquid loading of a gas well is the inability of the gas to remove the liquids from the well. Liquid loading in gas wells have been recognized one of the most important problems in gas production. For normally operated wells, gas flow rate is high enough to carry the liquid mixture to the surface. However, as the gas well becomes mature, gas phase is unable to drag the liquid phase to the surface. At this stage, liquid starts to accumulate in the well and eventually block further gas production. Therefore, it is essential to investigate the liquid loading mechanisms, in order to predict and avoid its occurrence.

Several studies address the liquid loading in gas wells based on two mechanisms. The first one assumes that the liquid loading occurs due to the falling of the droplets, which are unable to be effectively carried by gas phase. The second mechanism is based on the reversal of the film velocity profile. In this study, mainly, the reversal effect will be studied. Droplet formation and transport in loading and unloading conditions will be observed to determine the relationship between the two loading mechanism.

Activities Summary

Main activities have been carried out during this period, namely, literature review, facility modification and instrumentation, capacitance sensor data analysis and CFD modeling conceptualization. A summary of each particular activity are presented next.

Literature Review

Yuan (2011) conducted an experimental study of liquid loading of gas wells. Liquid loading and well deviation effects were investigated. Holdup and pressure gradient were measured, and critical gas velocity of liquid loading was determined by high speed videos. Superficial gas velocity corresponding to minimum pressure gradient coincides with the onset of liquid loading. Yuan (2011) observed that liquid loading tends to occur at higher gas velocities as the superficial liquid velocity increases. This phenomenon cannot be predicted by all the existent models.

Sawai *et al.* (2004) investigated gas liquid interfacial structure and pressure drop characteristics of churn flow. The experiments were conducted in 1-in. ID vertical pipe. Pressure gradient and wave velocity were obtained in slug, slug-churn, churn and annular flow regions. Average liquid holdup and wave velocity data were obtained by using several conductance probes. Pressure gradient and wave velocity curves were divided into negative slope and positive slope sections. A simple predictive method for frictional pressure gradient for churn and annular regions was developed.

Instrumentation

Current instrumentation will be updated for the parameters to be investigated by adding new measurement devices to the existing facility.

Average liquid holdup will be measured by using quick closing valves (QCV). A multiple QCV configuration will be implemented. There will be three successive trapping sections, namely, entrance, developing and test sections. This arrangement allows the analysis of the liquid holdup evolution along the system. Each QCV section will be connected to a pressurized vessel and the average holdup will be correlated to the pressure change of gas by using real gas law principles. A calibration curve was generated allowing the determination of liquid holdup at any given condition. This new design will improve the accuracy of holdup measurement and decrease the operation time.

Wave characteristics will be investigated by using capacitance probes. Existing probes will be improved by using preliminary data analysis from initial experiments. Probes will be located closer than the initial distance to compensate the low wave celerity observed in Yuan (2011) conditions. A couple of additional capacitance probes will be constructed to investigate lower superficial liquid velocities with shorter inserts.

Six low speed video cameras will be added to record lateral and bottom videos at the entrance, developing and test sections. These videos will be utilized for qualitative flow behavior evaluation in different sections of the pipe.

A boroscope will be introduced through a temporary tubular insert to the periphery of the pipe. The lens of the boroscope will be cleaned with an air purge. This setup will be utilized to investigate the flow direction of liquid droplets in loading condition.

A Lenterra RealShear™ F-Series wall shear stress sensor will be installed. This probe will be attached to the pipe surface to obtain wall shear stress values. Additionally, the sign of the wall shear stress will indicate the film flow direction and magnitude can be utilized to tune the CFD models.

Data Analysis

Capacitance probe data acquired by Yuan (2011) were analyzed. Wave celerity curves were constructed with respect to superficial gas and liquid velocities. Signal processing algorithm was implemented in MATLAB. Trends obtained were also compared with previous studies to collaborate the consistency of the results. For unloading conditions, plots indicate that wave celerity increases as superficial liquid velocity increases. For gas velocities close to or lower than critical gas velocity a not clear trend is observed owing to the oscillating nature of the flow.

CFD Modeling

CFD modeling can be utilized to estimate the velocity profile in unloading conditions. The Volume of Fluid (VOF) model implemented in Fluent will be utilized to simulate two phase air-water flow in vertical pipes. The geometry will be constructed based on the test section and the mesh size will be finer close to the pipe wall (liquid region), while coarser in through the center of the pipe. For initial simulation runs, data from Yuan (2011) and Zabaras (1986) will be utilized.

Future Work

- Calibration and verification of new instrumentation (May 2012)
- Facility modification (May 2012)
- Start experimental work (June 2012)

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Fluid Flow Projects

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

Wei Zheng

Advisory Board Meeting, April 25, 2012

Outline

- Comments from Fall ABM 2011
- Objective
- Model Development
- Program Implementation
- Preliminary Evaluation
- Project Schedule

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Comments from Fall ABM 2011

- Mack Shippen, Schlumberger
  - Two-Phase and Three-Phase Heat Transfer Comparison
  - Joule Thomson Effects
- Taras Makogon, BP
  - Modify Mixture Temperature with Mass Fraction

Comments from Fall ABM 2011

- Hans I. Eikum, Galp Energia
  - Temperature Profile Comparison with PIPESIM, OLGA

Objective

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

Model Development

- 1^{st} Approach – Oil/Water Mixture
- Preliminary Test of 1^{st} Approach
- 2^{nd} Approach – Oil/Water Separated
- Model Modification

Model Modification

- **Mixture Temperature**
  - **Based on Mass Fraction and Heat Capacity**

$$T_M = \frac{T_{Oil} + T_W + T_C}{3}$$

$$\Downarrow$$

$$T_M = \frac{\rho_C A_C c_{PC} T_C + \rho_O A_O c_{PO} T_{Oil} + \rho_W A_W c_{PW} T_W}{\rho_C A_C c_{PC} + \rho_O A_O c_{PO} + \rho_W A_W c_{PW}}$$

Model Modification …

- **Assumptions for Energy Equation**
  - **Heat Loss between Oil/Water Layers Neglected**
  - **Heat Loss between Gas/Liquid Layers Considered**

Model Modification …

- Bubble or Dispersed Bubble Flow
- Annular Flow (*Modified*)
- Stratified Flow (*Modified*)
- Slug Flow

Annular Flow

- General Calculation Process
  - Energy Equation

$$(T_{F2} - T_{F1}) v_F H_{LF} A \rho_L c_{PL} = -q_F S_F dl - q_I S_I dl$$

$$(T_{C2} - T_{C1}) v_C (1 - H_{LF}) A \rho_C c_{PC} = q_I S_I dl$$

$$\Downarrow \quad \boxed{\frac{T_C - T_O}{T_F - T_O}}$$

$$\frac{\partial T}{\partial l} = \frac{4U_M (T_M - T_O)}{d_I (\rho_O c_{PO} v_{SO} + \rho_W c_{PW} v_{SW} + \rho_G c_{PG} v_{SG})}$$

Annular Flow …

- **Overall Heat Transfer Coefficient**
  - **Mixture Temperature: Arithmetic Average**

$$\boxed{T_M = \frac{T_C + T_F}{2}} \Rightarrow \quad U_M = \frac{q_F S_F + q_C S_C}{\pi d_I (T_M - T_O)} = \frac{U_F S_F + U_C S_C \dfrac{T_C - T_O}{T_F - T_O}}{\pi d_I \left(1 + \dfrac{T_C - T_O}{T_F - T_O}\right) \Big/ 2}$$

Annular Flow …

- **Overall Heat Transfer Coefficient**
  - **Mixture Temperature: Mass Fraction and Heat Capacity Based**

$$\boxed{T_M = \frac{\rho_C A_C c_{PC} T_C + \rho_F A_F c_{PC} T_F}{\rho_C A_C c_{PC} + \rho_F A_F c_{PL}}} \Rightarrow \quad U_M = \frac{q_F S_F + q_C S_C}{\pi d_I (T_M - T_O)} = \frac{U_F S_F + U_C S_C \dfrac{T_C - T_O}{T_F - T_O}}{\pi d_I \dfrac{\rho_C A_C c_{PC} \dfrac{T_C - T_O}{T_F - T_O} + \rho_F A_F c_{PF}}{\rho_C A_C c_{PC} + \rho_F A_F c_{PF}}}$$

Stratified Flow

- **General Calculation Process**
  - **Energy Equation**

$$(T_{C1}-T_{C2})\rho_C A v_{SC} c_{PC} = q_C S_C dl - q_I S_I dl$$

$$(T_{O1}-T_{O2})\rho_O A v_{SO} c_{PO} = q_O S_O dl + q_I S_I dl$$

$$(T_{W1}-T_{W2})\rho_W A v_{SW} c_{PW} = q_W S_W dl$$

$$\Downarrow \qquad \boxed{\frac{T_{Oil}-T_O}{T_C-T_O}} \qquad \boxed{\frac{T_W-T_O}{T_C-T_O}}$$

$$\frac{\partial T}{\partial l} = \frac{4U_M(T_M-T_O)}{d_I(\rho_O c_{PO} v_{SO} + \rho_W c_{PW} v_{SW} + \rho_G c_{PG} v_{SG})}$$

Stratified Flow …

- **Overall Heat Transfer Coefficient**
  - **Mixture Temperature: Arithmetic Average**

$$\boxed{T_M = \frac{T_{oil}+T_W+T_C}{3}}$$

$$\Downarrow$$

$$U_M = \frac{q_C S_C + q_O S_O + q_W S_W}{\pi d_I (T_M - T_O)}$$

$$= \frac{U_C S_C}{\pi d_I\left(\frac{1}{3B_1}+\frac{1}{3B_2}+\frac{1}{3}\right)} + \frac{U_O S_O}{\pi d_I\left(\frac{B_1}{3B_2}+\frac{1}{3}+\frac{B_1}{3}\right)} + \frac{U_W S_W}{\pi d_I\left(\frac{B_2}{3B_1}+\frac{1}{3}+\frac{B_2}{3}\right)}$$

Stratified Flow …

- Overall Heat Transfer Coefficient
  - Mixture Temperature: Mass Fraction and Heat Capacity Based

$$\boxed{T_M = \frac{\rho_C A_C c_{PC} T_C + \rho_O A_O c_{PO} T_{Oil} + \rho_W A_W c_{PW} T_W}{\rho_C A_C c_{PC} + \rho_O A_O c_{PO} + \rho_W A_W c_{PW}}}$$

$$\Downarrow$$

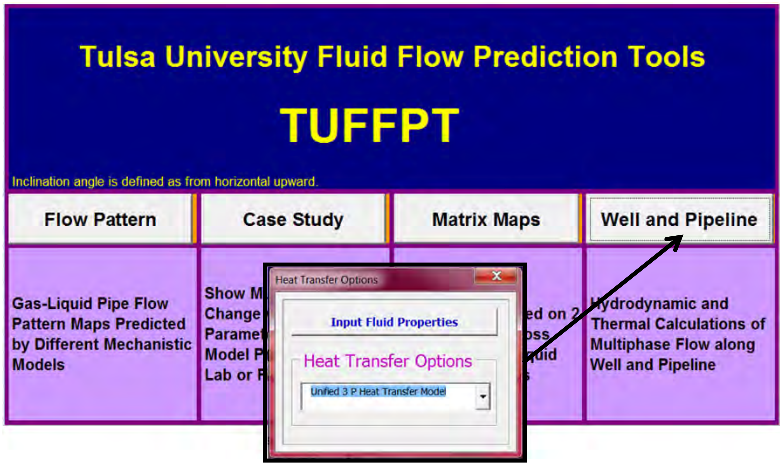
$$U_M = \frac{q_C S_C + q_O S_O + q_W S_W}{\pi d_I \left(T_M - T_O\right)}$$

$$= \frac{U_C S_C \left(T_C - T_O\right) + U_O S_O \left(T_{Oil} - T_O\right) + U_W S_W \left(T_W - T_O\right)}{\pi d_I \dfrac{\rho_C A_C c_{PC} \left(T_C - T_O\right) + \rho_O A_O c_{PO} \left(T_{Oil} - T_O\right) + \rho_W A_W c_{PW} \left(T_W - T_O\right)}{\rho_C A_C c_{PC} + \rho_O A_O c_{PO} + \rho_W A_W c_{PW}}}$$

Program Implementation

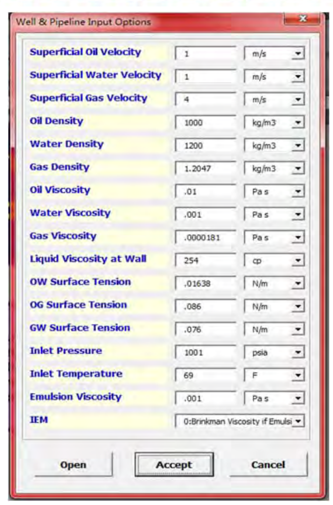
- User Interface Design
- Fortran Code
- Program Debugging

User Interface Design



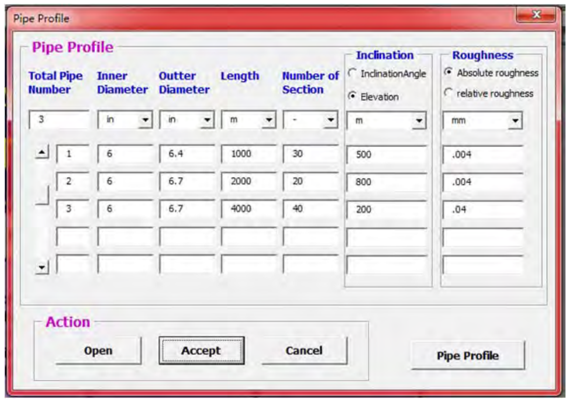
User Interface Design …

- Input Fluid Properties



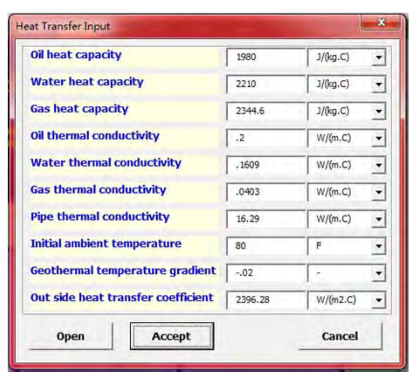
User Interface Design …

- Input Fluid Properties
- Input Pipe Profile



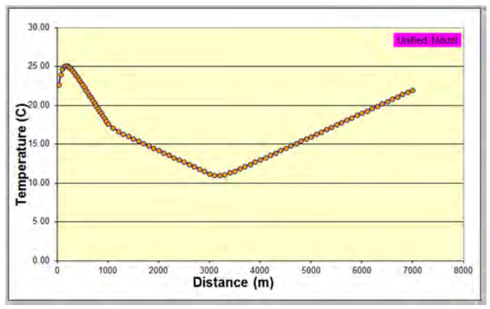
User Interface Design …

- Input Fluid Properties
- Input Pipe Profile
- Heat Transfer Input



User Interface Design …

- Input Fluid Properties
- Input Pipe Profile
- Heat Transfer Input
- Temperature Profile



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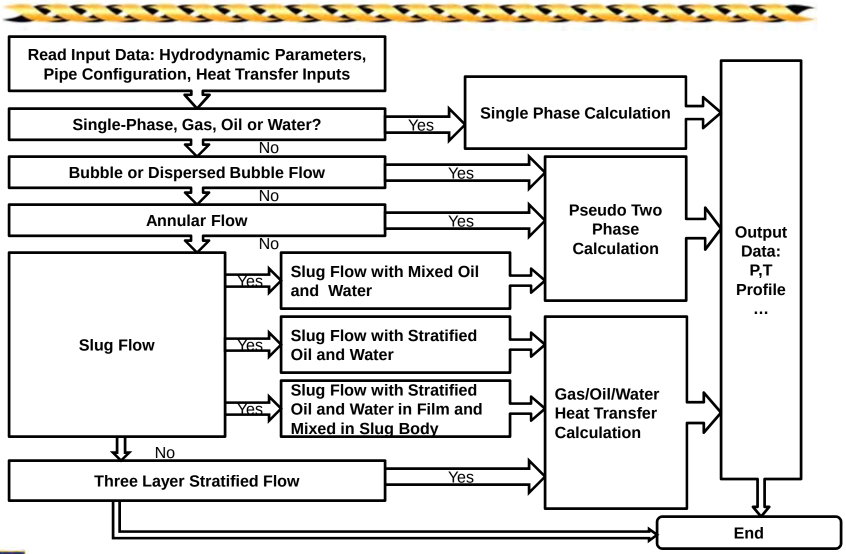
Fortran Code



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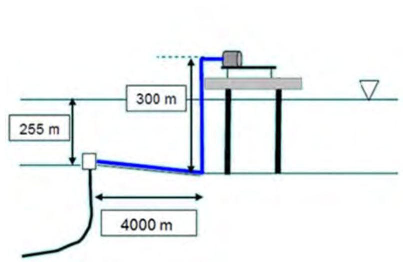
Preliminary Evaluation

- **Fluid**
  - Gas S.G.: 0.98
  - Oil S.G.: 0.83
  - Water S.G.: 1
  - GOR: 2
  - Water Cut: 0.5
  - API: 39°



Example Schematic

Preliminary Evaluation …

- **Pipe**
  - Steel Pipe
  - 6-in. I.D., 7-in. O.D., 4000 m Length
  - Roughness: 0.028 mm

Preliminary Evaluation …

- Other
  - Constant Inlet Pressure: 75 bara
  - Constant Wellhead T: 62 °C
  - Constant Ambient T: 6 °C
  - Constant Sea Current Velocity: 0.05 m/s

Preliminary Evaluation …

- Fluid Properties

Fluid Properties		
v_{SO}	2	m/s
v_{SW}	2	m/s
v_{SG}	4	m/s
ρ_O	1000	kg/m³
ρ_W	1200	Kg/m³
ρ_G	1.2	Kg/m³
μ_O	0.01	Pa·s
μ_W	0.001	Pa·s
μ_G	0.0000181	Pa·s
μ_{LW}	0.0254	Pa·s
σ_{OW}	0.01638	N/m
σ_{OG}	0.086	N/m
σ_{GW}	0.076	N/m
P_{in}	1087.78	Psia
T_{in}	62	°C
$\mu_{emulsion}$	0.001	Pa·s

Preliminary Evaluation …

- Fluid Properties
- Pipe Configuration

Total Pipe Number	Inner Diameter	Outer Diameter	Length	Number of Section	Elevation	Roughness
1	in	in	m	-	m	mm
1	0.1524	0.1778	4000	40	-15	0.028

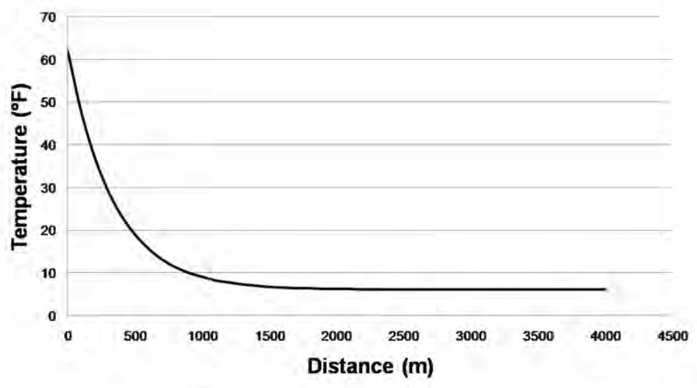
Preliminary Evaluation …

- Fluid Properties
- Pipe Configurations
- Heat Transfer

Heat Transfer Input		
cp_o	1884	J/(kg·°C)
cp_w	4187	J/(kg·°C)
cp_g	2303	J/(kg·°C)
K_o	0.138	W/(m·°C)
K_w	0.606	W/(m·°C)
K_g	0.035	W/(m·°C)
K_p	50	W/(m·°C)
T_{amb}	6	°C
T_{grad}	0	-
h_{out}	2396	W/(m²·°C)

Preliminary Evaluation …

- TUFFPT Result

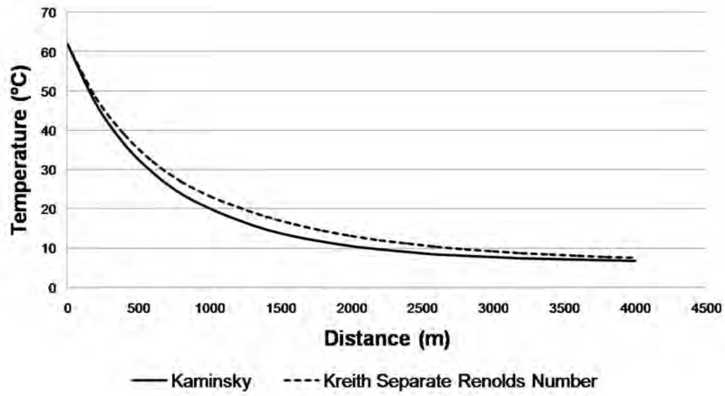


Preliminary Evaluation …

- PIPESIM Test
  - Black Oil Model
  - Flow Correlations
    - TUFFP Unified 2-phase v2007.1
  - Heat Transfer Options
    - Kaminsky
    - Kreith Separate Reynolds Number

Preliminary Evaluation …

- PIPESIM Test



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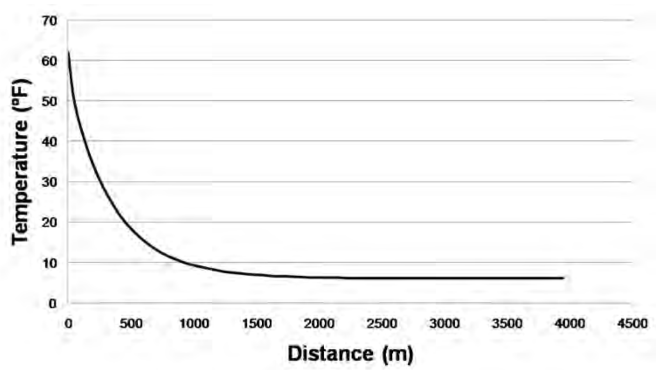
Preliminary Evaluation …

- OLGA 7 Test



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Preliminary Evaluation …

- Summaries
  - TUFFPT Predicts Well Compared to PIPESIM and OLGA
  - Program Implementation Completed
  - Experimental Evaluation Needed

Future Work

- Experimental Evaluation
- Sensitivity Analysis

Project Schedule

Literature Review	Complete
Model–1st Approach	Complete
Model– 2nd Approach	Complete
Program Implementation	Complete
Model Evaluation	Ongoing
Final Report	August 2012

Questions/Comments

?

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

Wei Zheng

Project Completion Dates

Literature Review .... Complete
Approach I – Pseudo Gas/Liquid Model .... Complete
Approach II – Gas/Oil/Water Model .... Complete
Program Implementation .... Ongoing
Model Evaluation .... Ongoing

Objectives

The main objective of this study is to develop a unified heat transfer model for gas/oil/water flow in pipes of all inclinations -90° to +90°. The model will be included in the TUFFP Excel VBA package for wellbore and pipeline thermal calculations.

Introduction

As offshore exploration is getting more active, long distance transportation of reservoir fluids under sea is required. As the prediction of pipeline temperature profile is crucial for flow assurance and production system design, it is important to accurately simulate the temperature to predict wax deposition and hydrate formation. For heavy oil, temperature has a significant effect on oil viscosity, which is one of the most important parameters to characterize the flow behavior.

Two approaches for the heat transfer model of gas/oil/water pipe flow are proposed. In the first approach, oil and water phases are combined into a pseudo single-phase. The three-phase outputs from the hydrodynamic calculation are converted into two-phase parameters to conduct temperature calculations. Zhang and Sarica (2006) unified heat transfer model is used for the pseudo gas/liquid heat transfer calculation.

In the second approach, oil and water are treated separately, the three phase hydrodynamic calculation is conducted using Zhang and Sarica (2005) unified model of gas/oil/water pipe flow. Based on different gas/oil/water flow patterns, the heat balance equations are derived. The temperature profile is then calculated along the pipe.

Activities Summary

After the preliminary model development, modifications have been made to the second model approach, including mixture temperature and heat balance equation changes. The modified model is added to the TUFFP Excel VBA software. A synthetic field case is used to test the performance of the model. The results are compared with OLGA and PIPESIM simulations.

Model Modification

Mixture Temperature

The mixture temperature is defined as the bulk temperature assuming the fluids are instantly mixed in the pipe segment. Previously, mixture temperature was the arithmetic average value of the temperatures of all phases. A new mixture temperature based on the mass fractions and heat capacities of all phases is proposed. Using the new mixture temperature, the derivations of overall heat transfer coefficient are updated.

Heat Transfer Between Phases

For gas/oil/water pipe flow, assuming there is no phase change, the energy changes caused by changes in pressure, volume, velocity and elevation are neglected. When fluids flow through a pipe and the surrounding temperature is colder than the fluids, heat is lost from the fluids. The heat loss of a specific phase in the pipe segment is equal to the heat transferred to the surroundings and other phases. The heat transfer between liquid and gas is considered since the property difference between the two phases is relatively large. The heat transfer between oil and water phase is ignored by assuming the same temperature for both phases. Under this assumption, the heat balance equations for gas/oil/water three layer stratified flow are updated. The temperature calculation along the pipe is then modified.

Program Implementation

After developing the heat transfer models for all flow patterns, TUFFP Excel VBA package is updated with the temperature calculation of gas/oil/water pipe flow. The user interface of the package is programmed by VBA, the hydrodynamic calculation and heat transfer calculation is programmed in FORTRAN.

The hydrodynamic calculation is conducted first, for specified flow condition, the flow pattern and other hydrodynamic parameters can be solved. The heat transfer calculation flow chart is shown in Fig. 1:

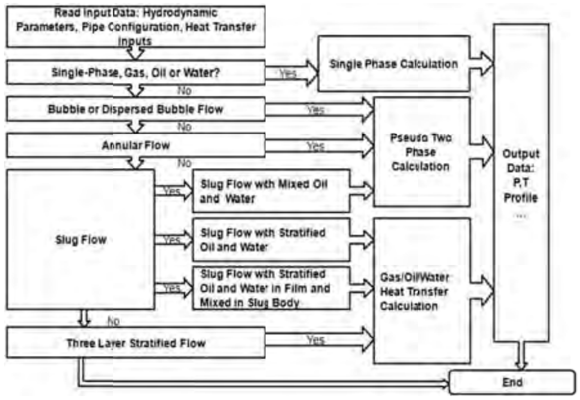

Figure 1. Heat Transfer Calculation Flow Chart

Program Debugging

After program implementation, the performance of the model is tested with a synthetic field case.

Synthetic Field Case

A synthetic field case is developed via a single subsea wellhead and pipeline to a platform. The well-head is on sea-bed in a water depth of 255 m, and it is located 4 km from the riser base. The platform stands in 270 m of water depth. The pipe is steel, its inner diameter is 6 in. and outer diameter is 7 in. Pipe wall absolute roughness is assumed to be 0.028 mm. The pipeline inlet pressure is 75 bara and the flowing wellhead temperature is assumed to be constant at 62 °C. The ambient temperature is 6 °C, and the sea current velocity is 0.05 m/s.

Result Comparison

After calculating the mixture fluid temperature for the subsea transportation pipeline, the TUFFP software results are compared with OLGA 7 and PIPESIM simulations. From the plots of the results, the mixture fluid temperature profiles along the pipeline show a similar trend. This demonstrates the TUFFP software is successfully debugged. To further judge the quality of the results, comparison with experimental data or field data is necessary.

Future Work

In the future work, gas/liquid heat transfer data from Manabe *et al.* (2001) will be used. The three-phase heat transfer model will be compared with two-phase flow, and sensitivity analysis will be carried out.

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Dittus, F.W. and Boelter, L.M.K. “Heat Transfer in Automobile Radiators of the Tubular Type,” Univ. Calif. Pub. Eng., **2**, 443 (1930).

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Manabe, R., Wang, Q., Zhang, H.-Q., Sarica, C., and Brill, J. “A Mechanistic Heat Transfer Model for Vertical Two-Phase Flow,” SPE Annual Technical Conference and Exhibition, Denver, Colorado, SPE 84226 (2003).

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Sieder, E.N. and Tate, G.E. “Heat Transfer and Pressure Drop of Liquids in Tubes,” Ind. Eng. Chem, **28**, 1429-1453 (1936).

Zhang, H.-Q., and Sarica, C. “Unified Modeling of Gas/Oil/Water Pipe Flow-Basic Approaches and Preliminary Validation,” SPE Annual Technical Conference and Exhibition, Dallas, Texas, SPE 95749 (2005).

Zhang, H.-Q., Wang, Q., Sarica, C. and Brill, J. “Unified Model of Heat Transfer in Gas/Liquid Pipe Flow,” SPE Production & Operations, **21** (1), pp.114-122 (2006).

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Simplified Transient Two-Phase Flow Modeling

Jinho Choi

Advisory Board Meeting, April 25, 2012

Outline

- Objectives
- Activities Summary
- Summary of Model Equations
- Code Upgrades
- Experimental Data Comparison
- Near Future Work

Objectives

- Develop a Simplified Model and Simulator for Two-Phase Flow in Pipelines
- Test Model Against Available Experimental Data

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Activities Summary

- Simulation Code Debugging
- Improvement of Drift-Flux Closure Relationship and Pressure Gradient Model
  - TUFFP Experimental Data Analysis
    - Vigneron *et al*.(1995), Fan(2005), Magrini(2009), Felizola(1992), Roumazeilles(1994), Gokcal(2005, 2008)
  - OLGA Steady-State Data Analysis (Multiphase Toolkit)
  - Tune-Up Methodology for Getting Parameters of Drift-Flux Closure Relationship

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Activities Summary

- Modification of Simulation Code from Last ABM
  - Matrix Solver (Implicit Scheme Implementation)
  - Implementation of Improved Drift-Flux Closure Relationship and Pressure Gradient
- Simulation Performance Tests

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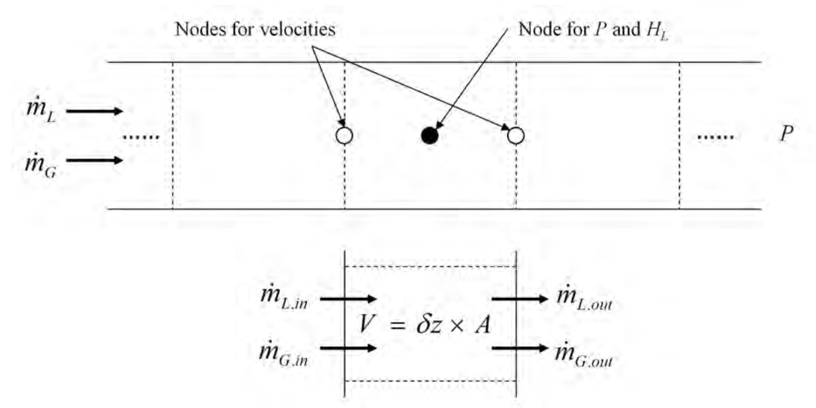
Summary of Model Equations

- Control Volume and Boundary Conditions



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Summary of Model Equations

- **Mass Continuities**

$$\begin{cases} \dfrac{dH_L}{dt} = \dfrac{u_{SL.in} - u_{SL.out}}{\delta z} \\ u_{SG.in} - u_{SG.out} + u_{SL.in} - u_{SL.out} = 0 \end{cases}$$

  - Assuming Constant Gas Density in a Control Volume

- **Drift Flux Closure Relationship**

$$u_G = \frac{1}{2}\frac{u_{SG}}{1-H_L} = \frac{1}{2}\frac{u_{SG.in} + u_{SG.out}}{1-H_L} = C_0(u_{SG} + u_{SL}) + u_D$$

Summary of Model Equations

- **Matrix Solver (Implicit Scheme Implementation)**
  - **Rearranging Equations**

$$2u_G{}^k H_L{}^k + u_{SG.out}{}^k = 2u_G{}^k - u_{SG.in}{}^k$$

$$H_L{}^k + \frac{dt}{dz}u_{SL.out}{}^k = H_L{}^{k-1} + \frac{dt}{dz}u_{SL.in}{}^k$$

$$u_{SG.out}{}^k + u_{SL.out}{}^k = u_{SG.in}{}^k + u_{SL.in}{}^k$$

✓ Known Variables: $u_{SG.in}{}^k, u_{SL.in}{}^k, H_L{}^{k-1}$

✓ Unknown Variables: $u_{SG.out}{}^k, u_{SL.out}{}^k, H_L{}^k, u_G{}^k$

o Initial Guess of u_G ➔ $u_G{}^k = u_{G.in}{}^k = C_0(u_{SG.in}{}^k + u_{SL.in}{}^k) + u_D$

Code Upgrades

- Matrix Solver (Implicit Scheme Implementation)
- Tune-Up Methodology for Getting Parameters of Drift-Flux Closure Relationship
- Pressure Gradient Models

Matrix Solver

- Implicit Scheme Implementation
  - Matrix Composition

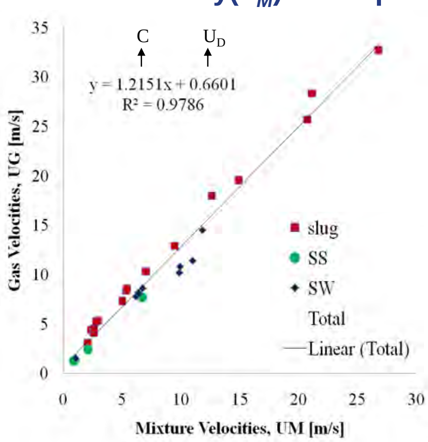
$$\begin{pmatrix} 2u_{G.in}{}^{k} & 1 & 0 \\ 1 & 0 & \dfrac{dt}{dz} \\ 0 & 1 & 1 \end{pmatrix} \begin{pmatrix} H_L{}^{k} \\ u_{SG.out}{}^{k} \\ u_{SL.out}{}^{k} \end{pmatrix} = \begin{pmatrix} 2u_{G.in}{}^{k} - u_{SG.in}{}^{k} \\ H_L{}^{k-1} + \dfrac{dt}{dz} u_{SL.in}{}^{k} \\ u_{SG.in}{}^{k} + u_{SL.in}{}^{k} \end{pmatrix}$$

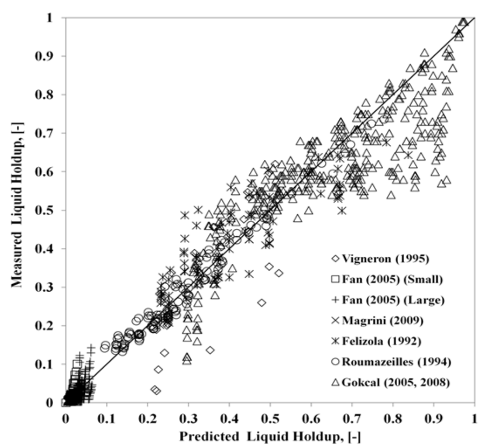
Tune-up Methodology

- **Tested Models**
  - **Linear Fitting of Gas Velocity(u_G) and Mixture Velocity(u_M) for Experimental Data**
  - **Zuber and Findlay, 1965**
  - **Ishii, 1977**
  - **Liao *et al.*, 1985**
  - **Jowitt, 1981**
  - **Sonnenburg, 1989**
  - **Toshiba, 1989**
  - **Bestion, 1985**
  - **Kataoka and Ishii, 1987**
  - **Shi *et al.*, 2005**

Tune-up Methodology

- **Linear Fitting of Gas Velocity(u_G) and Mixture Velocity(u_M) for Experimental Data**





Tune-up Methodology

Ishii, 1977

- **Turbulent Churn Flow**

$$C_0 = 1.2 - 0.2\sqrt{\frac{\rho_G}{\rho_L}}(1 - EXP(B\alpha_G))$$

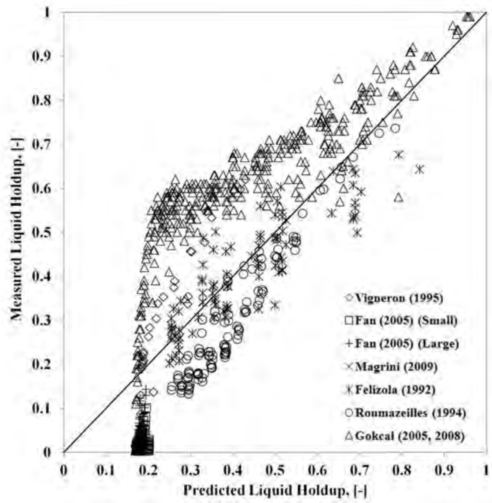
$$u_D = (C_0 - 1) + \sqrt{2}\left(\frac{g\sigma\Delta\rho}{\rho_L^2}\right)^{1/4}$$

α_G : Gas void fraction(=1-H_L)

- **Annular Flow**

$$C_0 = 1 + \frac{1-\alpha_G}{\alpha_G + \sqrt{\frac{1+75(1-\alpha_G)}{\sqrt{\alpha_G}}\frac{\rho_G}{\rho_L}}}$$

$$u_D = (C_0 - 1) + \sqrt{\frac{g d_h \Delta\rho(1-\alpha_G)}{0.015\rho_L}}$$



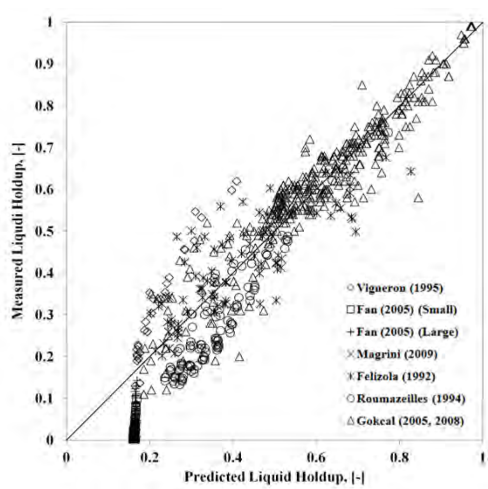
Tune-up Methodology

Proposed Model

$$C_O = \frac{2}{1+(Re/A)^2} + \frac{1.2 - 0.2\sqrt{\frac{\rho_G}{\rho_L}}(1 - EXP(B\alpha_G))}{1+(A/Re)^2}$$

$$Re = \frac{\rho_L U_M D}{\mu_L}$$

$$U_D = C\cos(\theta) + D\left(\frac{g\sigma\Delta\rho}{\rho_L^2}\right)^{1/4}\sin(\theta)$$



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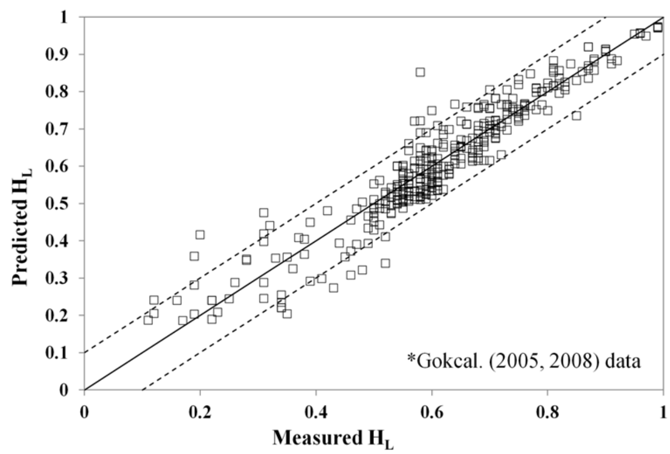
Tune-up Methodology

- Proposed Model Liquid Holdup Prediction Test



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Tune-up Methodology

- Error (Mean Absolute) Comparison of Applied Models

Correlation	Linear Fitting	Zuber and Findlay, 1965	Ishii, 1977	Liao et al., 1985	Jowitt, 1981	Sonnenburg, 1989	Toshiba, 1989	Bestion, 1985	Kataoka and Ishii, 1987	Shi et al., 2005	**Proposed Model**
Vigneron, 1995	0.12319	0.09071	0.08492	0.11962	0.08620	0.15635	0.11490	0.15688	0.08992	0.19551	**0.10684**
Fan (small), 2005	0.06109	0.16578	0.16846	0.09651	0.20468	0.26991	0.08947	0.16070	0.16002	0.01404	**0.14673**
Fan (large), 2005	0.03886	0.14449	0.14830	0.00288	0.13984	0.27515	0.06784	0.27793	0.14859	0.02644	**0.12803**
Magrini, 2009	0.00330	0.16257	0.15934	0.15477	0.14487	0.24188	0.07372	0.06203	0.15897	0.00701	**0.15619**
Felizola, 1992	0.18692	0.05842	0.08251	0.29511	0.14258	0.20085	0.07570	0.30781	0.06834	0.07616	**0.06612**
Roumazeilles, 1994	0.06161	0.09978	0.10632	0.18035	0.15421	0.19128	0.05820	0.14751	0.10145	0.02951	**0.08246**
Gokcal, 2005&2008	**0.12400**	0.17548	0.13716	0.20556	0.09646	0.08344	0.15057	0.15181	0.15957	0.24502	**0.04234**
Overall	**0.08272**	0.14708	0.13759	0.14988	0.13645	0.18856	0.10019	0.17560	0.14214	0.10324	**0.09584**

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Tune-up Methodology

Standard Deviation Comparison of Applied Models

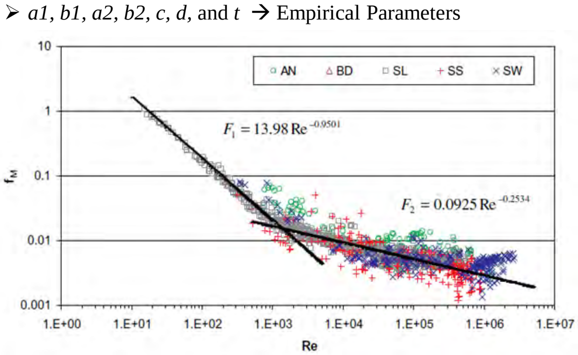
Correlation	Linear Fitting	Zuber and Findlay, 1965	Ishii, 1977	Liao et al., 1985	Jowitt, 1981	Sonnenburg, 1989	Toshiba, 1989	Bestion, 1985	Kataoka and Ishii, 1987	Shi et al., 2005	**Proposed Model**
Vigneron, 1995	0.07298	0.06240	0.05610	0.10789	0.06638	0.23257	0.05540	0.14045	0.06066	0.08131	**0.06402**
Fan (small), 2005	0.04256	0.01303	0.01564	0.07193	0.01893	0.02589	0.01798	0.07811	0.01327	0.01138	**0.01221**
Fan (large), 2005	0.02519	0.02425	0.02397	0.00522	0.02522	0.02690	0.02124	0.06747	0.02397	0.02163	**0.02506**
Magrini, 2009	0.00315	0.00353	0.00334	0.00385	0.00624	0.00332	0.00319	0.01472	0.00338	0.00381	**0.00369**
Felizola, 1992	0.08584	0.04735	0.05699	0.08743	0.06498	0.23483	0.05863	0.08495	0.05245	0.05076	**0.05319**
Roumazeilles, 1994	0.02402	0.04860	0.04519	0.05203	0.05117	0.10169	0.03251	0.01611	0.04586	0.02098	**0.04446**
Gokcal, 2005&2008	0.08556	0.09578	0.08224	0.09229	0.06434	0.06600	0.09042	0.09781	0.09203	0.13133	**0.03755**
Overall	0.07984	0.07076	0.05987	0.10884	0.06028	0.12271	0.06826	0.10610	0.06595	0.13101	**0.05684**

Pressure Gradient Models

Garcia *et al.* (2003)

$$f_M = F_2 + \frac{(F_1 - F_2)}{\left(1 + \left(\mathrm{Re}/t\right)^c\right)^d} \qquad F_1 = a_1 \,\mathrm{Re}^{b_1} \qquad F_2 = a_2 \,\mathrm{Re}^{b_2}$$

- *a1*, *b1*, *a2*, *b2*, *c*, *d*, and *t* → Empirical Parameters



Fluid Flow Projects
Advisory Board Meeting, April 25, 2012

Pressure Gradient Models

Al-Sarkhi & Sarica (2009)

- Stratified Flow

$$P^* = -\frac{\pi}{4}\left\{\frac{S_L^* f_L}{A_L^{*2}} + \frac{S_G^* f_G}{A_G^{*2}} X^{*-2}\right\}$$

- Annular Flow

$$P^* = \left(\frac{\pi}{4}\right)^2 \frac{1}{A_L^*}\left\{-\frac{S_L^* f_L}{A_L^{*2}} + \frac{S_i^* f_i}{A_G^{*2}} X^{*-2}\right\}$$

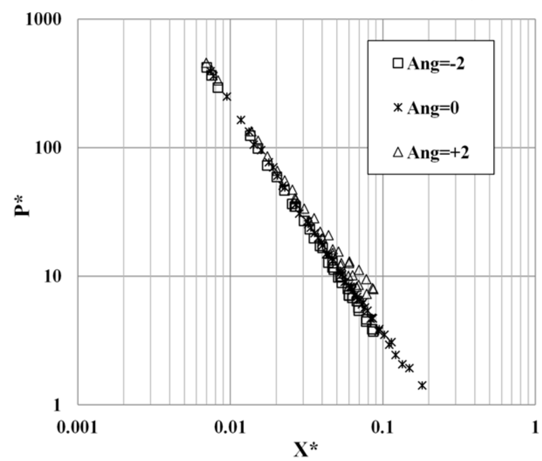
$$P^* = \frac{D\,(dP\ /\ dx\ )}{\frac{1}{2}\rho_l U_{SL}^2}$$

$$X^* = \frac{\dot{m}_L}{\dot{m}_G}\sqrt{\frac{\rho_G}{\rho_L}}$$

$$S_k^* = \frac{S_k}{D};\ A_k^* = \frac{A_k}{D^2}$$

$$P^* = A(X^*)^B$$

*Fan.(2005) data



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Pressure Gradient Models

Modified Al-Sarkhi & Sarica (Newly Proposed)

Al-Sarkhi and Sarica, 2009

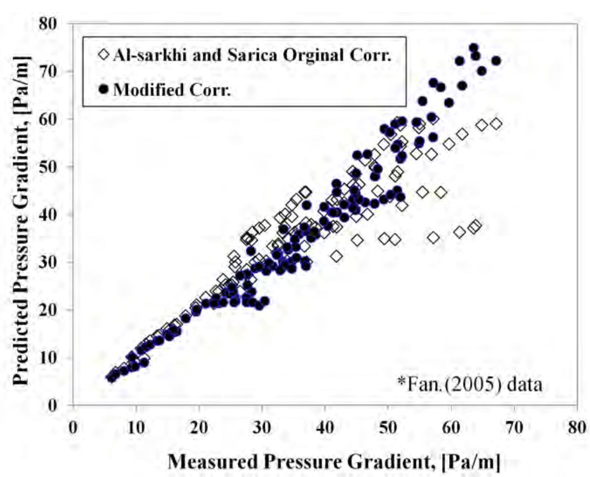
$$P^* = A(X^*)^B$$

Adding Gravitational Friction Term

$$Y^* = \frac{d(\rho_M g \sin\theta)}{\frac{1}{2}\rho_L u_{SL}^2}$$

New Model

$$P^* + Y^* = A X^{*B}$$



Fluid Flow Projects

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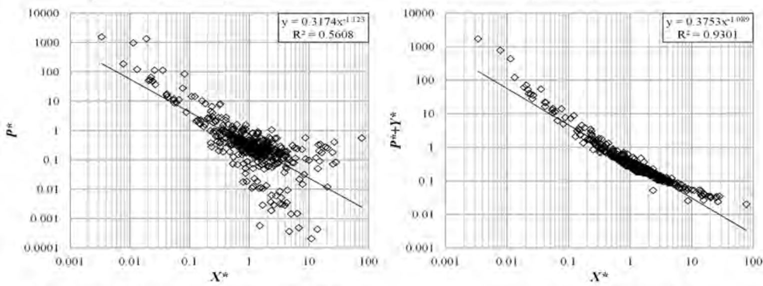
Pressure Gradient Models

- Steady-State Comparison with OLGA Multiphase Toolkit

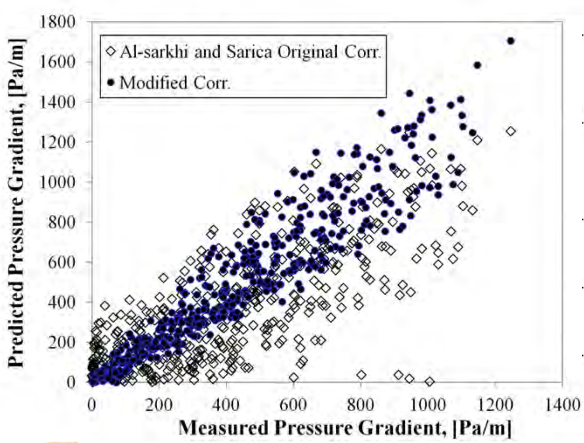
Variables	Inclination Angle	Gas Superficial Velocity	Liquid Superficial Velocity	Gas Density	Liquid Density	Gas Viscosity	Liquid Viscosity	Liquid/Gas Surface Tension
Unit	[Degree]	[m/s]	[m/s]	[kg/m³]	[kg/m³]	[N-s/m²]	[N-s/m²]	[N/m]
Top	10	15.0	1.000	3.000	820.00	0.000018	0.002	0.032
Bottom	-10	0.1	0.001	2.000	800.00		0.001	



(a) Al-sarkhi and Sarica (2009) original correlation (b) Modified correlation

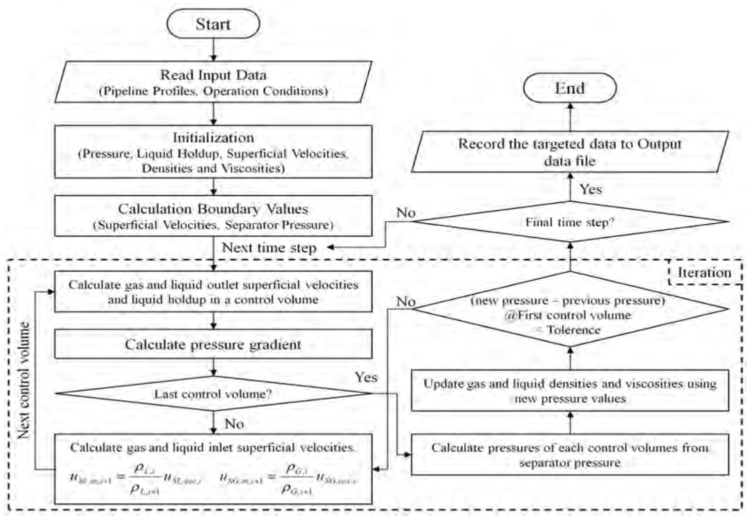
Pressure Gradient Models

- Steady-State Comparison with OLGA Multiphase Toolkit



Correlation	Mean Absolute Error	Standard Deviation
Al-sarkhi and Sarica Original Correlation	158.7	137.4
Modified Correlation	94.3	103.4
Garcia et al. Correlation	108.4	86.1

Simulation Flow Diagram



Experimental Data Comparison

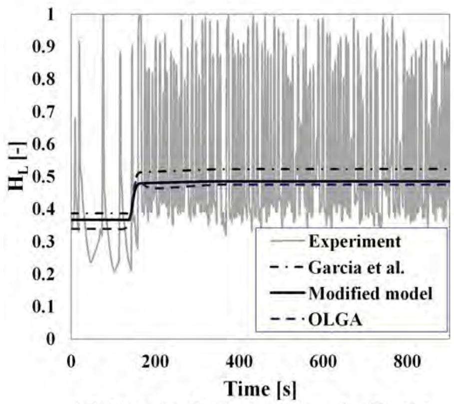
- Experiments by Vigneron *et al.* (1995)
  - Air and Kerosene Flow in Horizontal Pipe (L=420 m, d=77.9 mm) with Two Test Sections @ 61.4 m, 395.7 m
  - Transient by:
    - Liquid and Gas Flow Rate Changes
    - Liquid Blow Out
    - Start up

Test Matrix

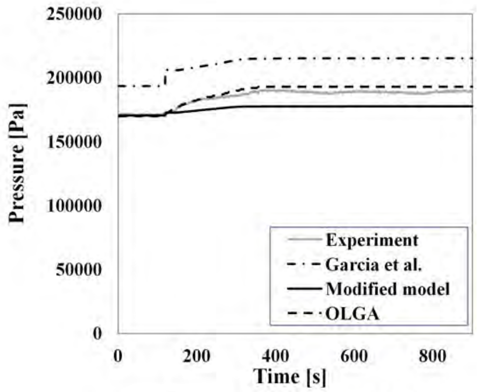
Test#	Initial(I) / Final(F)	Flow Rate Liquid $[m^3/d]$	Flow Rate Gas $[Sm^3/d]$	Flow Patten	$P_{separator}$ [Bar]
Liquid Flow Rate Changes					
1A	I	32.5	815	Slug	1.67
	F	168.4	815	Slug	
1B	I	8.4	400	SS	1.67
	F	31.8	400	SW	
Gas Flow Rate Changes					
2A	I	8	850	SS	1.67
	F	8	4520	SW	
2B	I	20.2	340	SS	1.67
	F	20.2	2530	SW	

Experimental Data Comparison

- Liquid Flow Rate Transient Cases
  - Test 1A



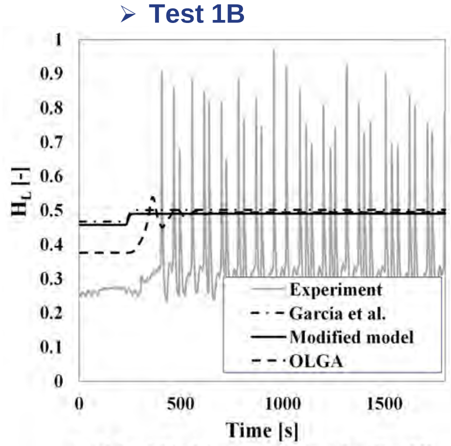
(a) Liquid holdup prediction for Test1A



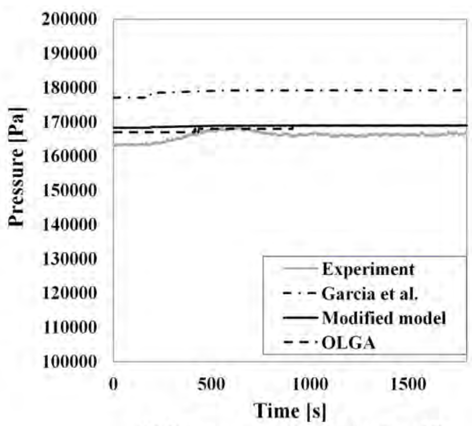
(b) Pressure prediction for Test1A

Experimental Data Comparison

- Liquid Flow Rate Transient Cases
  - Test 1B



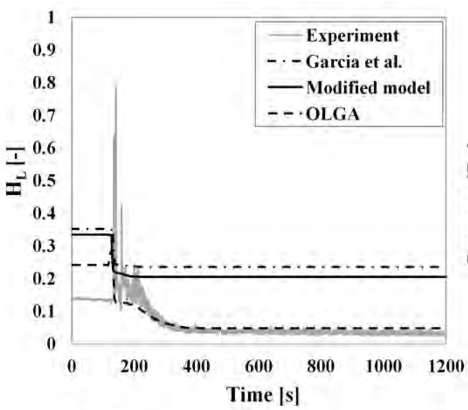
(a) Liquid holdup prediction for Test1B



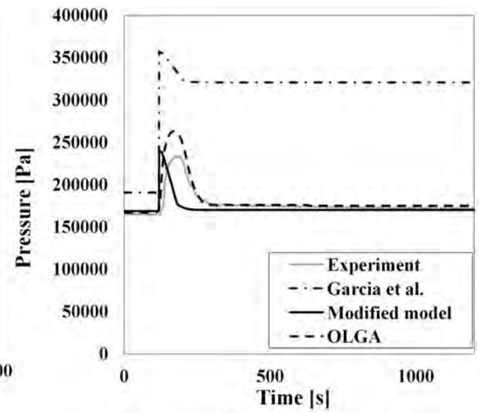
(b) Pressure prediction for Test1B

Experimental Data Comparison

- **Gas Flow Rate Transient Cases**
  - Test 2A



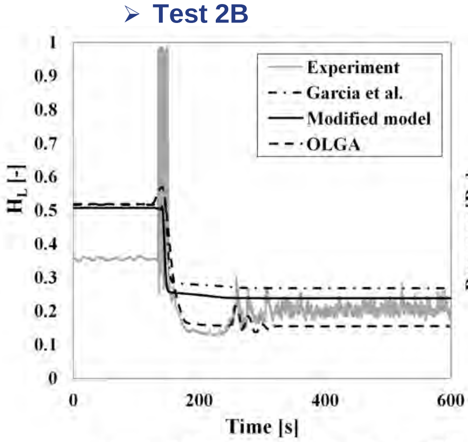
(a) Liquid holdup prediction for Test2A



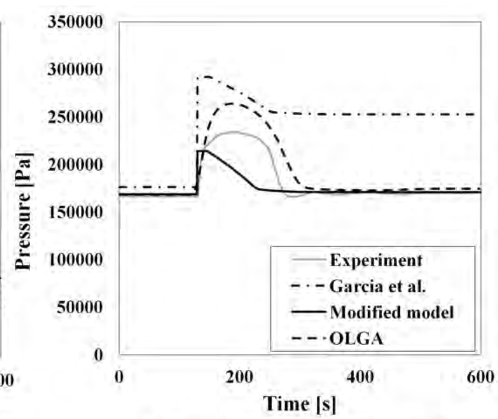
(b) Pressure prediction for Test2A

Experimental Data Comparison

- **Gas Flow Rate Transient Cases**
  - Test 2B



(a) Liquid holdup prediction for Test2B



(b) Pressure prediction for Test2B

Near Future Work

- Simulation Stability Analysis
- Implementation of Dynamic Drift-Flux Parameter Equations for Simulator
- Liquid-Liquid Two-Phase Applicability
- Preparation of Journal Papers and Dissertation

Thank you for listening!

Simplified Transient Gas-Liquid Two-Phase Flow Modeling

Jinho Choi

Project Completion Dates

Extension and Modification of Model and Code April.2012
Simulator Test April.2012
Final Report May.2012

Objectives

The main objective of this study is to develop a simple and fast transient two-phase flow simulator.

Introduction

The previously proposed TUFFP transient model was developed by combining two different models, namely, the Two-Fluid model and the Drift-Flux model. Each model is appropriate to different flow patterns. Two-Fluid model is suitable for stratified flow, while drift flux model is proper for slug and dispersed flow. The previous simulator required flow pattern prediction, which slowed down the calculation and increased the model complexity. The new proposed model is an extension of the Drift-Flux model to all flow patterns. Moreover, a simple model tune-up methodology is proposed to extend the applicability to different conditions.

Activities Summary

During this period, an implicit solution of the proposed model has been implemented. The new code has been tested against Vigneron *et al.* (1995) experimental data and OLGA simulation. A simple tune-up methodology has been proposed to estimate the Drift-Flux parameters; distribution parameter C_0 and drift velocity, u_d. A new pressure gradient model, which is based on Al-sarkhi and Sarica (2009), was developed and implemented.

Simple Tune-Up Methodology

The distribution parameter, C_0, and a drift velocity, u_d, are critical to calculate superficial velocities, liquid holdups, and pressures accurately. To find a proper model for these parameters, 11 models from literatures were tested against more than 1,000 data of TUFFP. A new model is proposed to extend the Drift-Flux model to transitional and laminar regimes. This new model has been tested against Gokcal (2005, 2008) data showing a fair agreement and the applicability of this formulation high viscous liquid two-phase flow.

Pressure Gradient

Pressure gradient can be calculated with any steady state model. The computational time of the proposed transient simulator strongly depend on the simplicity of the steady-state pressure drop model. In this study, two simple models are proposed. The accuracy of the models can be improved by calibrating the required parameters using either experimental data or results from a more rigorous mechanistic model. The suggested models are continuous and flow pattern independent. This characteristic facilitates the convergence of the final numerical scheme, resulting in a robust simulator. The two suggested methods are Al-sarkhi and Sarica (2009) or Garcia et al. (2003).

Modification of Al-sarkhi and Sarica (2009)

A modification of the power law correlation presented by Al-sarkhi and Sarica (2009) is suggested for pressure drop calculation. This correlation was tested against more than 1200 published experimental data points. The used data includes various flow patterns, different inclination angles, various liquid and gas viscosities, pipeline diameters, and operational pressure. The advantage of this model is its tuning capability. The proposed value for the coefficient A and B are given by 0.075 and -1.808, respectively. With a simple linear regression analysis these parameters can be modified for a particular set of data.

The tuning capability of the new power law model has been tested against 463 OLGA steady-state cases. The cases are generated from OLGA Multiphase Toolkit assuming gas-liquid two-phase flow in 0.0762mm (3.0in.) diameter pipeline. Inclination angle, gas and liquid superficial velocities, gas and liquid densities, and liquid viscosities are randomly generated.

The modified correlation shows much better relationship than original Al-sarkhi and Sarica (2009) correlation.

Garcia et al. (2003)

The power law correlation proposed before, presents a fair agreement as compared to experimental data corresponding to low viscosity liquids and low liquid loading. Garcia *et al.* (2003) presented a mixture friction approach, which is continuous, flow pattern independent and presents fair agreement for low and high liquid viscosity data. Pressure gradient is calculated with summation of friction and gravitation pressure gradient. The correlation has been developed by using 2435 experimental data points corresponding to different flow pattern, fluid properties and pipe geometries.

This method can be tuned by determining the values of the parameters presented before. For this case, a non-linear regression is required representing a disadvantage as compare to the simple linear regression required for the previous power law correlation.

Simulation Results

The upgraded simulator was validated with Vigneron *et al.* (1995) experimental data, which accounts for changes of inlet gas (air) and liquid (kerosene) flow rates. The flow loop is a 420m long horizontal pipeline with 77.9mm ID pipe. There were two measurement sections; one is placed at 61.4m, and the other is placed at 395.7m from inlet. This study analyzes the simulator performance for the front measurement section (61.4m from inlet). Simulation results followed the trends of experimental data, but a systematic bias is observed. These differences could be explained by inaccuracy on closure parameters (distribution parameter, drift velocity and friction factor) which can be corrected with proper calibration. Initially, constant C_0 and u_d values were applied in this study. Two pressure gradient models were tested for comparison, namely, Garcia *et al.* (2003) power law correlation and a new model based on Al-sarkhi and Sarica (2009). Simulation results are compared with OLGA simulation as well as experimental data corresponding to two cases, namely, liquid flow rate changes, and gas flow rate changes.

Tested Experimental Data Sets

Tests 1A and 1B are liquid flow rate change cases. Test1A is a case of transient flow from slug to slug flow pattern. Test1B is from stratified smooth to stratified wavy pattern. Tests 2A are 2B are gas flow rate change cases. The flow patterns of both cases change from stratified smooth to stratified wavy pattern. For all cases, outlet separator pressure is kept constant.

Liquid Flow Rate Changes

The simulations for the two liquid flow rate change cases are performed. The results are compared with the experimental data and OLGA simulations.

The proposed simulator matches well the liquid holdup of Test1A. However, pressure values are slightly different than the experimental data and the OLGA predictions. In the case of Test1B, a shift of the initial holdup is observed but at later times a fair agreement is reached.

Gas Flow Rate Changes

The simulations for the two gas flow rate change cases are performed. The results are compared with the experimental data and OLGA predictions.

The case of Test2A shows a systematic discrepancy with the data. This case corresponds to low liquid loading flow. The results suggest that the model and simulator need to be improved for low liquid loading conditions. Simulator holdup presents a good agreement with OLGA for the case of Test2B. For this case, initial holdup differs from the experimental data. Predicted pressures with Garcia *et al.* (2003) model are higher than the experiments and OLGA simulation in both cases. The newly developed pressure gradient model presents good agreement during all time intervals.

Discussion on Future Improvement of the Proposed Model

The developed simulator shows generally fair agreement in terms of liquid holdups and pressures although there are significant discrepancies in some cases. The major reasons of discrepancy and potential solutions are discussed below:

(1) For the Test1B, the initial holdup value is predicted higher than OLGA and experiment. This phenomenon is also shown in the cases of Test2A, and Test2B. Flow patterns in Test1B, Test2A, and Test2B cases are changed from stratified smooth to stratified wavy. Therefore, these gaps may come from the inability of drift-flux model to predict the steady state behaviour for these conditions. Any improvement of the drift flux model is expected to increase the accuracy of the proposed transient model predictions.

(2) For the Test2A, the final steady state holdup is higher than OLGA prediction and experiment result. This is due to the drift-flux closure relationship used in this simulator. Because of the constant C_0 and u_d values, the simulator over-predicts the holdup at low liquid loading cases. Holdups at low liquid loading cases should become near zero, but the constant drift-flux parameters force the holdups to be over a certain value. This problem can be solved by development of flow dependent C_0 and u_d correlations.

Summary and Conclusions

A simplified transient model for two-phase flow is presented. The simplified transient model and simulator developed in this study is composed of gas and liquid mass continuity equations, a pressure gradient model as a mixture momentum equation, and a drift-flux correlation as a closure relationship. For the drift-flux correlation, the equations for distribution parameter, C_0, and drift velocity, u_d, are proposed, showing fair agreement against 356 data points from Gokcal (2005, 2008). Two pressure gradient models, namely, Garcia *et al.* (2003) and the modified model based on Al-sarkhi and Sarica (2009), are proposed for the momentum equation. Although both models use a power law correlation with experimental data, Garcia *et al.* (2003) model obtains the parameter values from a non-linear regression, while the modified model can be tuned by a simple linear regression. The modified model is simpler and more accurate based on comparisons with the experimental data.

The developed simulator is tested against Vigneron *et al.* (1995) experimental data for two transient conditions, namely, liquid flow rate changes, and gas flow rate changes conditions. Two cases for each condition are tested. The developed simulator shows fair agreement in terms of liquid holdups and pressures although there are significant discrepancies in some cases.

The proposed model is simple and presents an easy tuning capability with either experimental data or synthetic data coming from steady-state simulators. This capability considerably improves the applicability and the accuracy of the model. The simplicity of the model, resulting in a set of ordinary differential equations, allows quick implementation yielding in a faster simulator as compared to available commercial software.

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Fluid Flow Projects

Modeling of Hydrodynamics of Gas-Liquid Pipe Flow using Energy Minimization Concept

Hoyoung Lee

Advisory Board Meeting, April 25, 2012

Outline

- Objectives
- Energy Minimization Concept
- Modeling Validation
- Conclusions
- Future Work

Objectives

- Development of a Novel Model for Gas-Liquid Flow Using Energy Minimization Concept

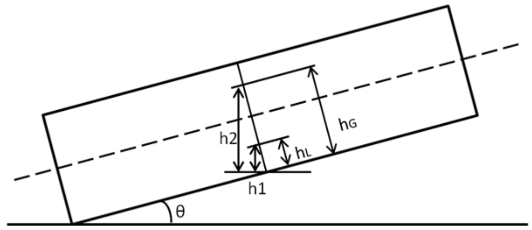
Energy Minimization Concept

- Any System Stabilizes to Its Minimum Total Energy
- Total Energy

TE = PE + KE
PE : Potential Energy
KE : Kinetic Energy

Energy Minimization Model

- TE = PE + KE



Side View

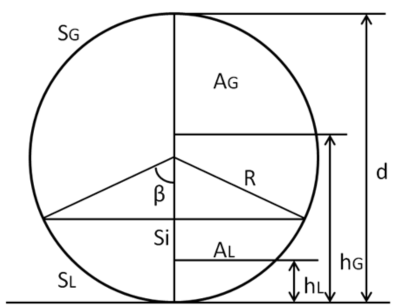
$$PE = A_L \rho_L g h_1 + A_G \rho_G g h_2$$

$$KE = \frac{1}{2} A_L \rho_L v_L^{\ 2} + \frac{1}{2} A_G \rho_G v_G^{\ 2}$$

Measured
Parameters : $\rho_L, \rho_G, v_{SL}, v_{SV}$
Unknown
Parameters : $A_L, A_G, h_1, h_2, v_L, v_G$

Energy Minimization Model …

- Calculate Unknown Parameters



Cross-Sectional View

Measured
Parameters : $\rho_L, \rho_G, \sigma_i, v_{SL}, v_{SV}$
Unknown
Parameters : $A_L, A_G, h_1, h_2, v_L, v_G, S_i$

h_L/d **(Dimensionless Liquid Level) is Used**

Energy Minimization Model …

Modeling Flow Chart (Stratified Flow)

Input Parameters Such as Fluid Properties, Pipe Dimensions, v_{SL} and v_{SG} etc. → Calculate Total Energy for Each Case Using h_L/d → Compare TE and Select Liquid Holdup (TE Minimum) → Report All Calculated Flow parameters Corresponding to TE Minimum

Energy Minimization Model …

Vsl [m/s]	Vsg [m/s]	Denl [kg/m3]	DenG [kg/m3]	VisL [Pa s]	VisG [Pa s]	D [m]	Ang [rad]	st [-]	Measured [-]
0.0003	5	1000	2.24	0.001	1.80E-05	0.0508	0	0.072	0.005

hLD [-]	TE [N=J/M]	PE [N=J/M]	KE [N=J/M]
0.001	0.059585055	0.001131	0.058454
0.002	0.05849235	0.001131	0.057361
0.003	0.05822612	0.001132	0.057094
0.004	0.05812057	0.001132	0.056988
0.005	0.058070609	0.001133	0.056937
0.006	0.058046003	0.001134	0.056912
0.007	0.058035131	0.001136	0.0569
0.008	0.058032663	0.001137	0.056895
0.009	0.058035843	0.001139	0.056896
0.01	0.058043114	0.001142	0.056901
0.011	0.058053538	0.001145	0.056909
0.012	0.058066515	0.001148	0.056919
0.013	0.05808165	0.001151	0.05693
0.014	0.05809867	0.001155	0.056943
0.015	0.058117382	0.00116	0.056957
0.016	0.058137648	0.001165	0.056973
0.017	0.058159364	0.001171	0.056989
0.018	0.058182453	0.001176	0.057006
0.019	0.058206857	0.001183	0.057024
0.02	0.05823253	0.00119	0.057043
0.021	0.058259438	0.001198	0.057062
0.022	0.058287553	0.001206	0.057082
0.023	0.058316854	0.001214	0.057102
0.024	0.058347326	0.001224	0.057124
0.025	0.058378954	0.001234	0.057145
0.026	0.05841173	0.001244	0.057168
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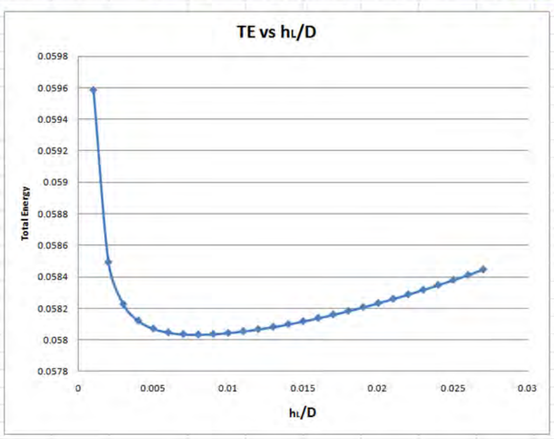
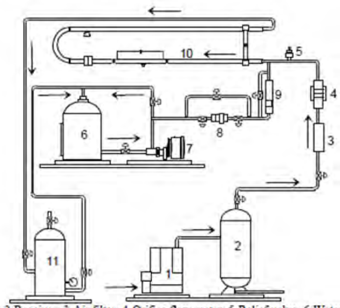


Model Validation

- **Experiments by Fan *et al.* (2005)**
  - **Air and Water**
  - **Test Section @ 19m, 50.8 mm**



1-Air compressor; 2-Receiver; 3-Air filter; 4-Orifice flow meter; 5-Relief valve; 6-Water tank; 7-Water pump; 8-Turbine flow meter; 9-Rotameter; 10-Test section; 11-Separator

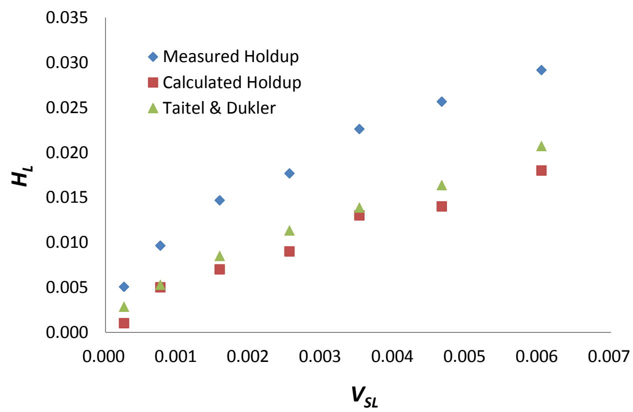
Model Validation …

- **Stratified Flow Experiments by Fan *et al.* (2005)**

Test No.	v_{SL} (m/s)	v_{SG} (m/s)	ρ_L (kg/m^3)	ρ_G (kg/m^3)	μ_L (pa.s)	μ_G (pa.s)	D (m)	β (°)	σ (N/m)	Measured HL (*l*)	Calculated HL(*l*)	T&D HL(*l*)
61	0.0003	5.0	1000	2.24	0.001	2E-05	0.051	0	0.072	0.005	0.001	0.002821
62	0.0008	5.1	1000	2.24	0.001	2E-05	0.051	0	0.072	0.010	0.005	0.005266
63	0.0016	5.0	1000	2.24	0.001	2E-05	0.051	0	0.072	0.015	0.007	0.008484
64	0.0025	5.0	1000	2.25	0.001	2E-05	0.051	0	0.072	0.018	0.009	0.011318
65	0.0035	4.9	1000	2.26	0.001	2E-05	0.051	0	0.072	0.023	0.013	0.013861
66	0.0047	5.0	1000	2.45	0.001	2E-05	0.051	0	0.072	0.026	0.014	0.016354
67	0.0060	5.0	1000	2.45	0.001	2E-05	0.051	0	0.072	0.029	0.018	0.020718

Model Validation …

- Test1
  - Gas Superficial Velocity = 5.0 m/s



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Conclusions

- Underestimate Liquid Holdup for Every Liquid Superficial Velocity
- Energy Equation Needs to Be Improves

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Near Future Works

- Define the Energy Equations and Constrains for Different Gas-Liquid Configurations
- Identify Independent Variables
- Formulate Minimization Problem
- Formulate New Pressure Gradient Equation using Energy Conservation Equation
- Verify the Resultant Model

Questions and Comments

?

Modeling of Hydrodynamics of Gas-Liquid Pipe Flow using Energy Minimization Concept

Hoyoung Lee

Project Completion Dates

Literature Review ....May 2012
Model Development .... August 2012
Model Verification ....October 2012

Objectives

The main objective of this study is to develop a novel model for gas-liquid flow using energy minimization concept.

Introduction

Sharma (2009) proposed a new hydrodynamics model for liquid-liquid pipe flow using energy minimization concept. Sharma (2009) model is capable of predict flow pattern, water fraction and pressure drop. In stratified flow, the additional relationship provided by the minimum energy allows the determination of average dispersed phase fraction in each layer.

The objective of this study is to formulate all different energy equations for all gas-liquid flow patterns, and apply energy minimization concept to predict the flow patterns and design variables such as liquid holdup and pressure gradient.

Model Development

The Energy Minimization Concept means a system stabilizes to its minimum total energy. Total energy (*TE*) in pipe flow system can be represented as summation of potential energy (*PE*) and kinetic energy (*KE*).

A preliminary model is developed to predict the liquid holup for the gas-liquid stratified (ST) flow by using energy minimization concept.

The model first takes all the inputs, including fluid properties, superficial velocities of the gas and liquid, etc. The dimensionless liquid level (h_L/d) varies from 0 to 1 and calculate *TE* for the energy equation. The solution is the value of h_L/d where the total energy is the minimum.

Results and Discussions

Model predictions have been compared with the experimental results reported by Fan (2005) and Taitel and Dukler (1976) model predictions. The liquid holdups predicted by the new proposed model are very similar to the Taitel and Dukler (1976) predictions. These model predictions underestimate the measured holdup but follow the increasing trend shown by the experiments as liquid velocity increases. The model is still under development. Further analysis is required, especially, to include viscous dissipation terms.

Near Future Tasks

The near future tasks are :

- Define the energy equations and constrains for different gas-liquid configurations
- Identify independent variables
- Formulate minimization problem
- Verify the model

References

Fan, Y.: "An Investigation of Low Liquid Loading Gas-Liquid Stratified Flow in Near-Horizontal Pipes," (2005)
Sharma, A.: "A Modeling of Hydrodynamics of Oil-Water Pipe Flow using Energy Minimization Concept," (2009)
Taitel, Y., Dukler, A.E.: "A Model for Predicting Flow Regime Transitions in Horizontal and Near Horizontal Gas-Liquid Flow", *AIChE J.*(1976), **22**, 47-55.

Fluid Flow Projects

Evaluation of Capacitance Sensor for Liquid Holdup Measurement in High Viscosity Oil and Gas Flow

Brito, R., Graham S., Pereyra, E. Sarica, C.

Advisory Board Meeting, April 25, 2011

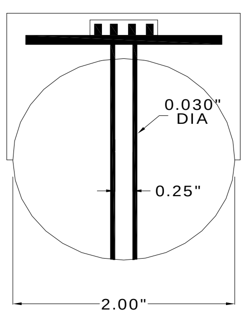
Outline

- Objective
- Capacitance Sensors
- Test Fluids
- Static Calibration
- Fluid Temperature Effect (Static Condition)
- Dynamic Calibration
- Conclusions

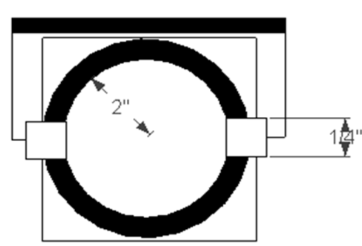
Objective

- Perform an Experimental Study to Determine Most Suitable Capacitance Sensor to be Used for Liquid Holdup Measurement in Highly Viscous Oil and Gas Flow

Capacitance Sensors



Two-Wire Capacitance Sensor



Ring Type Capacitance Sensor

Test Fluids

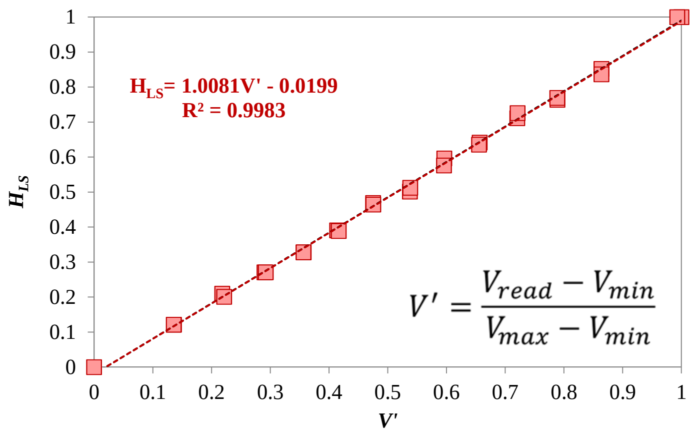
- Air and Citgo 220 Mineral Oil
- Temperatures: 70°F, 80°F, 90°F, and 100°F
- Oil Viscosities: 587 cP, 378 cP, 257 cP, and 181 cP
- Dynamic Calibration:
  - V_{SL}: 0.05 m/s - 1.0 m/s
  - V_{SG}: 0.5 m/s – 4.0 m/s

Capacitance Sensor Static Calibration

Static Calibration

Static Calibration

Static Calibration Curve for Two-Wire Capacitance Sensor



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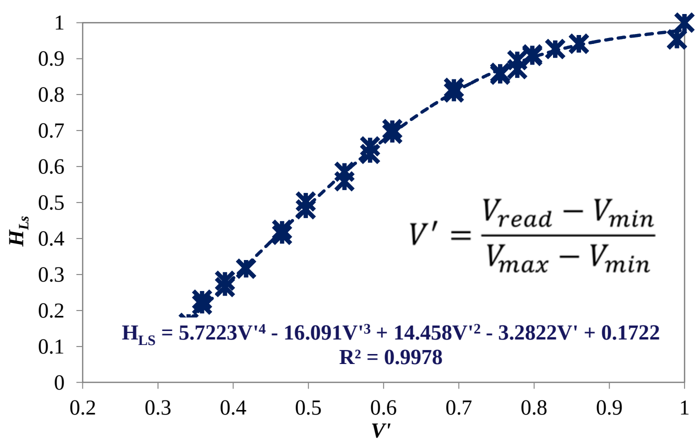
Static Calibration …

Static Calibration Curve for Ring Type Capacitance Sensor



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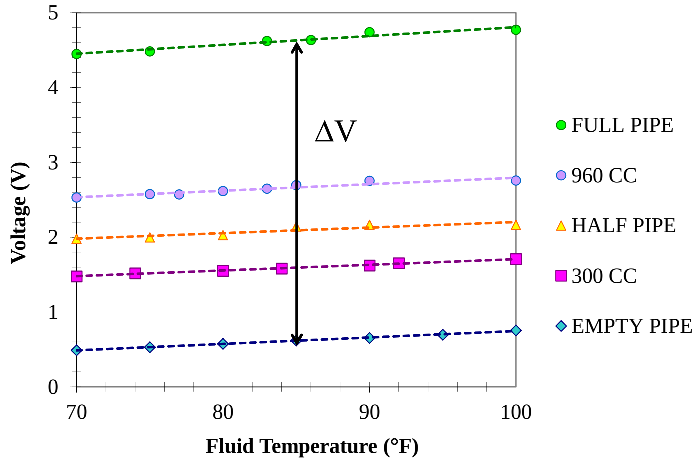
Fluid Temperature Effect (Static Condition)

Effect of Fluid Temperature on Ring Type Capacitance Sensor



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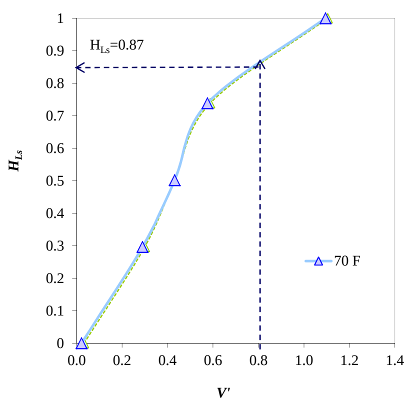
Fluid Temperature Effect (Static Condition) …

Ring Type Capacitance Sensor. H_{Ls} vs. V' Curve Without Temperature Compensation



$$V' = \frac{V_{read} - V_{\min @ 70°F}}{V_{max @ 70°F} - V_{\min @ 70°F}}$$

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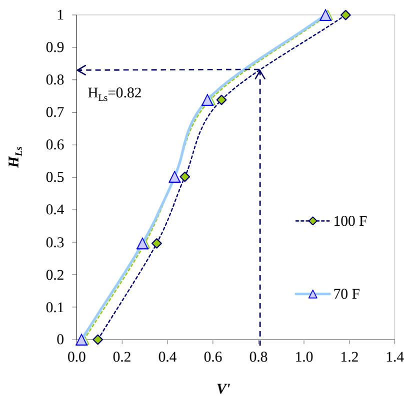
Fluid Temperature Effect (Static Condition) …

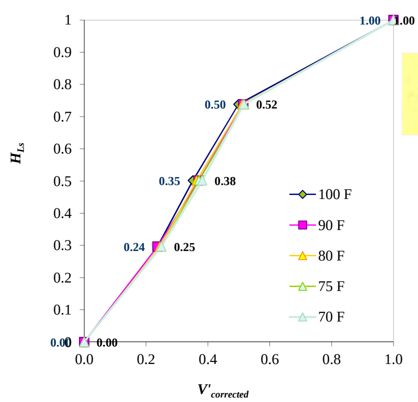
Ring Type Capacitance Sensor. H_{Ls} vs. V' Curve Without Temperature Compensation



$$V' = \frac{V_{read} - V_{\min @ 70^{\circ}F}}{V_{max@\,70^{\circ}F} - V_{\min @ 70^{\circ}F}}$$

Fluid Temperature Effect (Static Condition) …

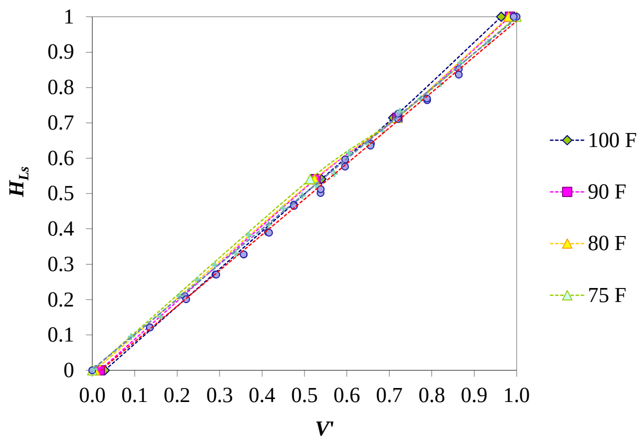
Ring Type Capacitance Sensor. H_{Ls} vs. V' Curve With Temperature Compensation



$$V_{corrected}' = \frac{V_{read} - V_{\min @\, Tfluid}}{V_{max@\, T_{fluid}} - V_{\min @\, Tfluid}}$$

Fluid Temperature Effect (Static Condition) …

Effect of Fluid Temperature on Two-Wire Capacitance Sensor



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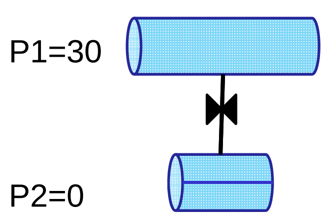
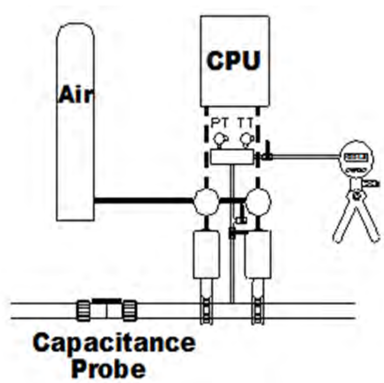
Liquid Holdup Calculation Using Quick Closing Valves

QCV System



P1 Pressure Drop
Pressure vs. Liquid Volume

QCV System Squematic



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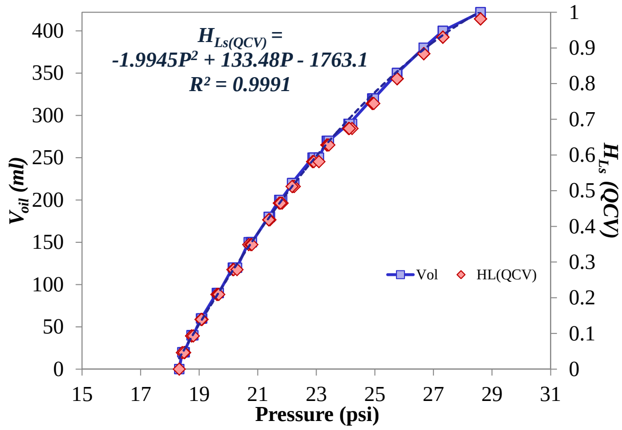
Liquid Holdup Calculation Using Quick Closing Valves …

Calibration Curve of Pressure Volume Holdup Measurements



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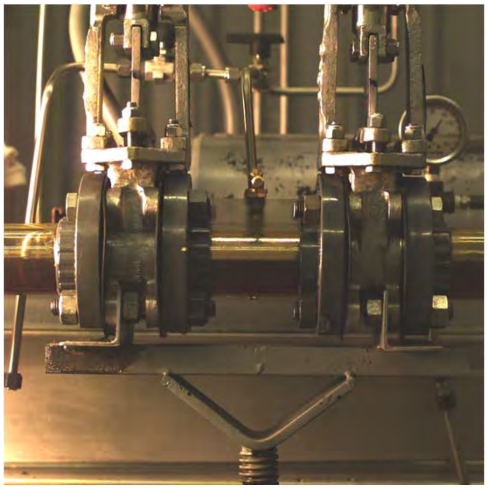
Dynamic Calibration



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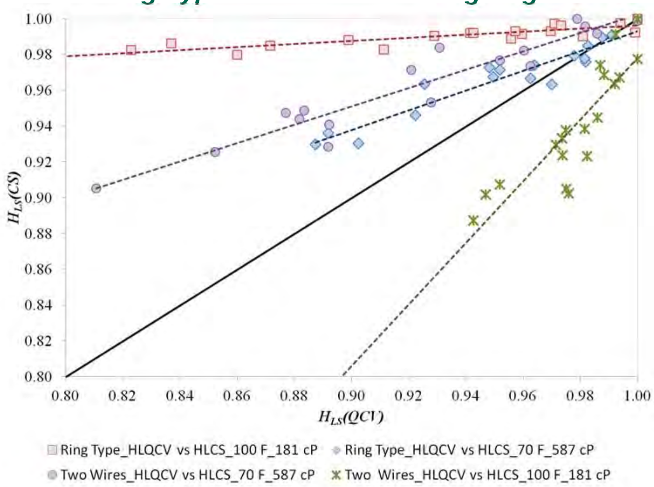
Dynamic Calibration

Ring Type and Two-Wire: Slug Region



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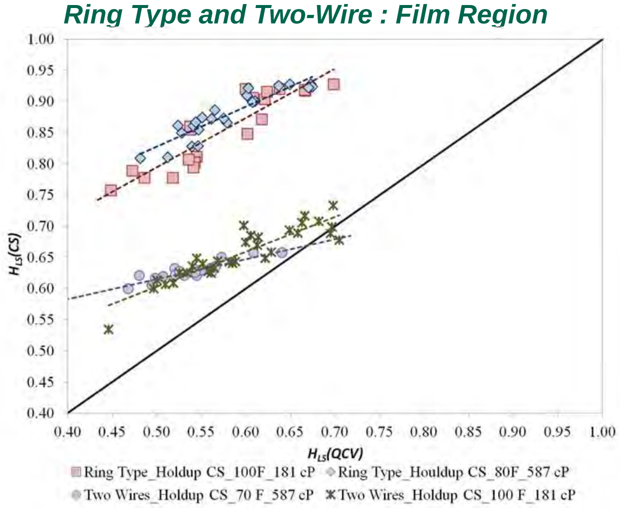
Dynamic Calibration…

Ring Type and Two-Wire : Film Region



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Uncertainty Analysis

Systematic Error Calculated using Dieck (2006) Methodology

$HL_{CS}=a*HL_{QCV}+b$

Sensor	Region	Temperature (°F)	Viscosity (cP)	a	b	bias
Ring	Slug	100	181	0.0861	0.8892	0.00093
Ring	Slug	70	587	0.5534	0.4319	0.00285
Ring	Film	100	181	0.7908	0.3988	0.00564
Ring	Film	70	587	0.6419	0.5063	0.00325
Two Wires	Slug	100	181	1.7192	-0.7412	0.00393
Two Wires	Slug	70	587	0.5119	0.4716	0.00219
Two Wires	Film	100	181	0.5599	0.3232	0.00320
Two Wires	Film	70	587	0.3204	0.4550	0.05958

Conclusions

- For Ring Type CS
  - H_L vs. V' Presents a Fourth Degree Polynomial Behavior
  - Tedious and Less Accurate Static Calibration
  - Static Calibration is Dependent on Fluid Temperature
- For the Two-Wire CS
  - H_L vs. V' Presents a Linear Behavior
  - Static Calibration is not Dependent on Fluid Temperature

Conclusions

- Dynamic Calibration Should be Performed for Each Desired Temperature to Compensate for Bubble Size and Temperature Effects in Slug Liquid Holdup Measurement
- Dynamic Calibration for Ring Type CS
  - Holdup is Higher than the QCVs Reading
  - Affected by Fluid Temperature in Film Region
- Dynamic Calibration for Two-wire CS
  - Presents Very Similar Correction Curves for Both Temperatures in Film Region

Conclusions

- Two-wire CS's Linear Response and Low Sensitivity to Temperature Change Made This Sensor Most Suitable to Measure Liquid Holdup for Slug Flow Conditions

Thanks …

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Questions

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Evaluation of Capacitance Sensor for Liquid Holdup Measurement in High Oil Viscosity Two-Phase Flow

Rosmer Brito

Objective

Perform an experimental study to determine the most suitable capacitance sensor to be used for the liquid holdup measurement in two phase high viscous oil and gas in horizontal pipes.

Introduction

In recent years research interest on gas-liquid flow with highly viscous liquid has increased dramatically. This has brought the need of sensors capable to measure two-phase parameter such as liquid fraction. Gokcal *et al.* (2005) observed that slug flow is the most likely flow pattern for high viscosity oils. This flow pattern is characterized by a liquid pocket (slug region), followed by a bubble region (film region). The liquid velocity in the film region is slower than the velocity in the slug region, and can be treated as stratified flow. On the other hand, the slug region is characterized as a homogeneous mixture of gas and liquid. The fraction of liquid in each region is an important variable to understand this complex flow pattern and requires a fast response in-line instrument. Capacitance sensors have been used in past for slug characterization in low and high viscosity liquids. These sensors are based on difference in dielectric values between two considered phases. This is utilized to detect the liquid fraction in a two-phase gas-liquid flow system. The change in the effective capacitance is detected by an electronic circuit and transmitted to a data acquisition system.

In this study, two types of capacitance sensors, namely, two-wire and ring, type have been evaluated for gas and highly viscous liquid flow. Preliminary calibration is required to relate the effective capacitance of the mixture with a liquid fraction. This study describes the different capacitance sensor calibrations that must be performed to assure the instrument accuracy and the correct interpretation of the acquired data. In addition, the effect of the fluid temperature is investigated under static and dynamic conditions.

Capacitance Sensors

The two-wire capacitance sensor consists of two parallel copper wires positioned perpendicular to the flow at a distance of 0.25. On the other hand, the ring type sensor comprises of two concave half rings which are fitted onto the inner circumference of the pipe (ID 2 in.). Both sensors required an electronic circuit to filter, amplify and convert the measured capacitance to a voltage. The MS3110 Universal Capacitive Readout IC has been utilized to convert the capacitance of the mixture to a 0 to 5 volts signal. This chip is equipped with a low pass filter providing an ultra-low noise and high resolution capacitive readout.

Test Fluids

Air and Citgo 220 mineral oil were used as test fluids. The experiments were performed at temperatures of 70 °F, 80 °F, 90 °F, and 100 °F. The correspondent oil viscosities are 587 cP, 378 cP, 257 cP, and 181 cP, respectively. For the dynamic calibration, the superficial velocities for the liquid and gas were from 0.05 m/s to 1.0 m/s and from 0.5 m/s to 4 m/s, respectively.

Static Calibration

Static calibration is the first step for proper holdup measurements. During static calibration known volumes of liquid were placed in an acrylic pipe tester with the capacitance sensor in the middle, resembling stratified flow conditions. The height of the fluid (h_L) in the pipe, temperature and the voltage output were measured. The voltage reading was converted to a dimensionless voltage (V') and liquid holdup is calculated using the measured liquid level. This procedure was applied to both the ring type and two-wire capacitance sensors.

The holdup (H_{Ls}) vs. dimensionless voltage (V') data was fitted for each capacitance sensor. Two-wire sensor was fitted by a straight line while the ring type sensor was fitted by fourth degree polynomial. Higher numbers of data points are required for the ring type capacitance sensor owing to its high degree polynomial characteristic curve. This results in longer time to perform the static calibration. Moreover, the ring type capacitance sensor presents more scatter for low and high liquid holdup region increasing the uncertainty in comparison with the two-wire sensor.

Effect of the Oil Temperature on the Output Signal

The effect of oil temperature on the capacitance sensor output signal under static conditions was evaluated. First hot air (empty pipe case) was flowed through the capacitance sensor recording voltage and air temperature. In addition, several oil volumes at different temperatures are placed in an acrylic pipe connected to the capacitance sensor. Output voltage was recorded as the oil temperature decreased. This procedure was repeated for both two-wire and ring type capacitance sensors.

The results indicate that, for the ring type sensor, the output voltage and fluid temperature is directly proportional. When the oil temperature decreases, the output voltage decreases with a linear trend. In addition, the span between the lowest voltage (empty pipe) and highest voltage (liquid full pipe) remains constant for the considered fluid temperatures (from 70 °F to 100 °F). This shows the need of temperature compensation to avoid an overestimation or underestimation of the liquid holdup when the fluid temperature changes. In order to perform the temperature compensation, it is necessary to read either the maximum or minimum holdup values for each desired fluid temperature. On the other hand, for the two-wire capacitance sensor, no significant effect of the fluid temperature in the output voltage is observed; thus no temperature compensation is required under static conditions.

Effect of the Ambient Temperature

The capacitance sensor circuit has been exposed to different ambient temperatures. It is shown that the ambient temperature does not affect the output signal obtained from the capacitance sensor.

Dynamic Calibration

Dynamic calibration of the capacitance sensor was conducted in a 50.8-mm ID, 18.9-m long flow loop. The quick-closing valve system is utilized to eliminate the uncertainty caused by the bubble size distribution under different gas and liquid velocities, and fluid temperatures. Kouba (1986) and Kora (2010) applied the dynamic calibration just to the slug region and used the static calibration for the film region. Owing to the large oil viscosities considered in this study, a considerable amount of gas bubbles are trapped in the liquid film as compared to low viscosity cases. Therefore, a dynamic calibration is also applied to the film region in order to compensate for the entrained bubbles. This dynamic calibration is performed for 70°F and 100 °F, corresponding to oil viscosities of 587 cP and 181 cP, respectively. The dynamic calibration curve is generated by plotting the liquid holdup data from the *QCVs* versus the calculated liquid holdup from the static calibration.

Slug Region

For the ring type capacitance sensor in the slug region, the liquid holdup from static calibration is larger than the *QCV* measurements. As the fluid temperature increases this difference also increases. On the other hand, for the two-wire capacitance sensor, the estimated liquid holdup from static calibration is less than the *QCV* measurements. In addition, for both sensors are sensitive to the fluid temperature within the slug region. This effect can be attributed to the different bubble size distribution generated at each viscosity. These results show the need to perform the dynamic calibration for each sensor at each desired oil temperature within the slug region.

Film Region

In the film region, the holdup from the static calibration of the ring type capacitance sensor is significantly larger than the *QCV* readings. Additionally, the correction curve obtained for each temperature is different, which once again indicates the effect of the fluid temperature on the output voltage. On the other hand, the two-wire capacitance sensor presents the same correction curve for both temperatures similar to the results obtained in the static calibration where the fluid temperature did not affect the output voltage. For this case, only one dynamic calibration is needed to compensate for any change on the phase configuration under dynamic conditions.

Conclusions

An experimental procedure is applied to determine the most accurate capacitance sensor to measure the liquid holdup for two-phase highly viscous oil and gas flow. For the ring type capacitance sensor the liquid holdup versus dimensionless voltage presents a fourth degree polynomial curve. This makes the static calibration more complex and time consuming when compared to the linear response of the two-wire capacitance sensor. Moreover, a higher scatter is observed for high and low liquid holdup regions.

The fluid temperature affects the ring type static calibration while the output voltage for the two-wire sensor is insensitive to the fluid temperature for static conditions.

Dynamic calibrations for both ring and two-wire capacitance sensors in the slug region are affected by the fluid temperature. This phenomenon can be attributed to different bubble sizes as a consequence of oil viscosity variation. For this reason, the dynamic calibration should be performed for each desired temperature in order to reduce the uncertainty in the slug liquid holdup measurement.

Dynamic calibration for the ring type sensor in the film region is affected by the fluid temperature, and the holdup obtained is highly over estimated. This result is similar to the static calibration results, where the fluid temperature affects the output voltage. On the other hand, the dynamic calibration for the two-wire capacitance sensor in the film region present the same correction curve for both temperatures, which is in agreement with the static calibration behavior of this sensor, where the fluid temperature does not affect the output voltage.

References

(1) Kora, C., "Effect of High Oil Viscosity on Slug Liquid Holdup in Horizontal Pipes", *M.S. Thesis, The University of Tulsa, OK,* 2010.

(2) Kouba, G., "Horizontal Slug Flow Modeling and Metering", PhD. Dissertation, *The University of Tulsa, OK, 1986*.

Fluid Flow Projects

Update on High Pressure Test Facility

Eduardo Pereyra, Scott Graham
and Cem Sarica

Advisory Board Meeting, April 25, 2012

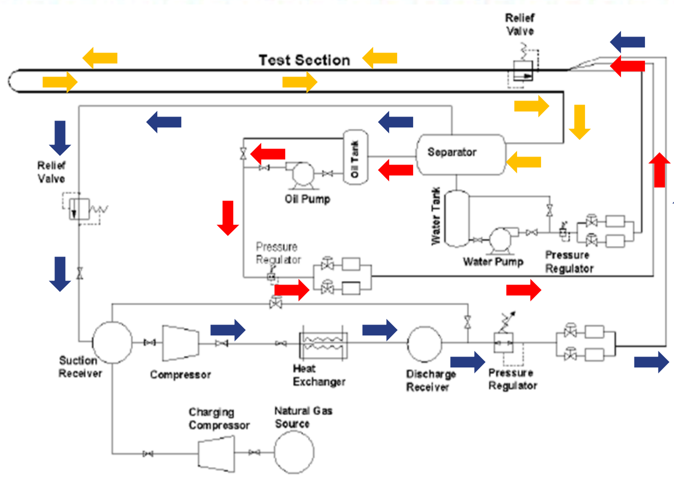
Outline

- Objectives
- Facility
- Instrumentation
- HAZOP Study
- Construction Schedule

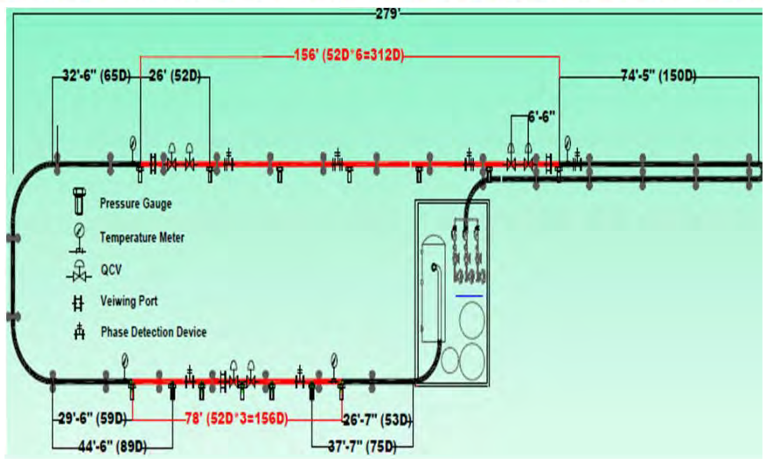
Objectives

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

Facility



Facility …



Test Fluids

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

Basic Instrumentation

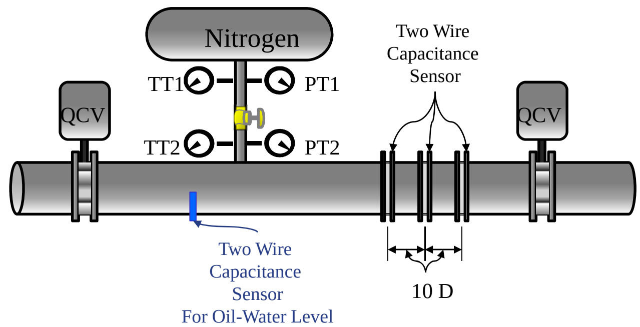
	Pressure (psig)	Capacity
Gas Flow Rate	600	18 MMSCFD
Water Flow Rate	600	200 GPM
Oil Flow Rate	600	200 GPM
Differential Pressure	500	0 – 50 in H_2O
Pressure	600	0 – 800 psi
Temperature	500	0-100 ° C
Quick Closing Valves	600	6 in. ID

Specialty Instrumentation

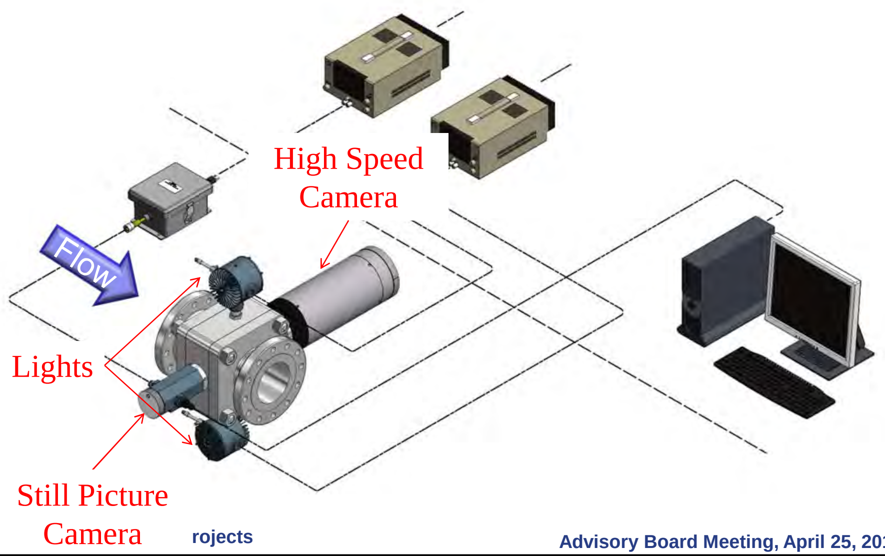
- Quick Closing Valves
- Visual Observation
- Capacitance Sensors
- Iso-kinetic Sampling
- Pitot Tube

Quick Closing Valves

- Calibration Methodology is Currently Under Development (Mujgan)



Visual Observation

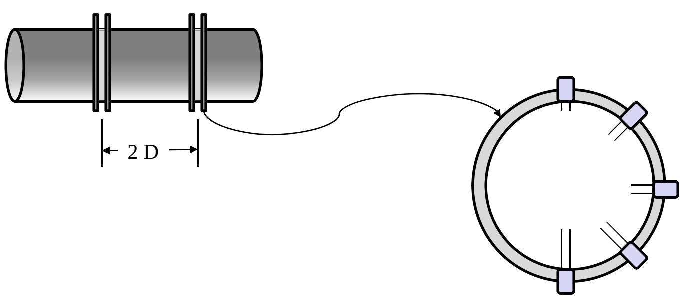


Visual Observation …

- System has been Ordered
- Drawing has been Delivered
- System is Expected by Fall

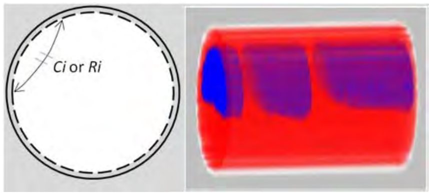
Capacitance Sensors

- Film Distribution and Waves Characteristics
  - Will be Tested in Low Pressure During Summer



Capacitance Sensors …

- Capacitance and Resistance Tomography
  - Meeting with Industrial Tomography Systems (ITS) in March 2012
    - Open Collaboration TUFFP-ITS is Expected
    - Plans to Evaluate the System in High Viscosity Loop



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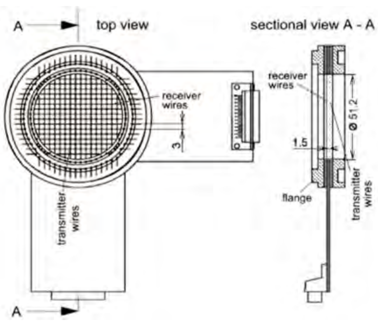
Capacitance Sensors …

- Wire Mesh Sensor
  - Maximum Pressure 150 psi
  - Working on increase it up to 500 psi
  - Plans to Evaluate the System in High Viscosity Loop



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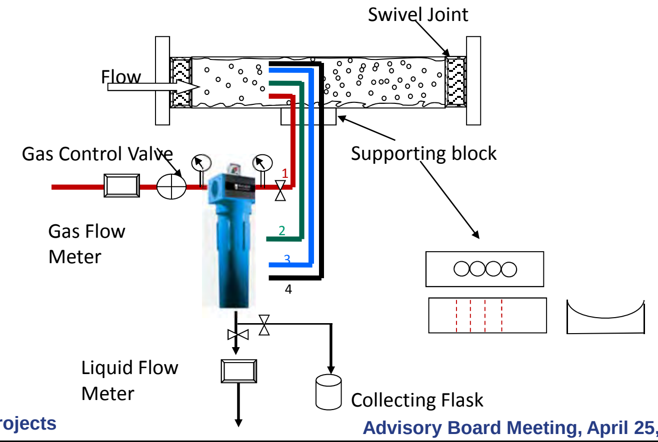
Iso-kinetic Sampling

- Multiple Probe Design
  - Will be Constructed and Tested on Spring 2013



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Pitot Tube

- Previously Used
  - Kawaji *et al.* (1987), Andreussi *et al.* (1986) and Williams (1990)
  - Evaluation at Low Pressure by Summer 2012

Omega High Accuracy Pitot Tube

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HAZOP Study

- Carried out Tuesday, March 27,2012, at University of Tulsa
- Facilitated by Cognascents Consulting Group, Inc.
- Participants:

First Name	Last Name	Company
John	Perez	Cognascents
Andrew	Madewell	Cognascents
Eduardo	Pereyra	University of Tulsa
Craig	Waldron	University of Tulsa
Scott	Graham	University of Tulsa
Abhijit	Zalte	University of Tulsa

HAZOP Study …

- Objectives
  - Identify Causes of Potential Deviations from the Design Intent
    - Safety, Environment, Commercial and Reputation Impacts
    - Process Operability
  - Estimate Hazard Scenario Consequences by Risk Matrix Categories

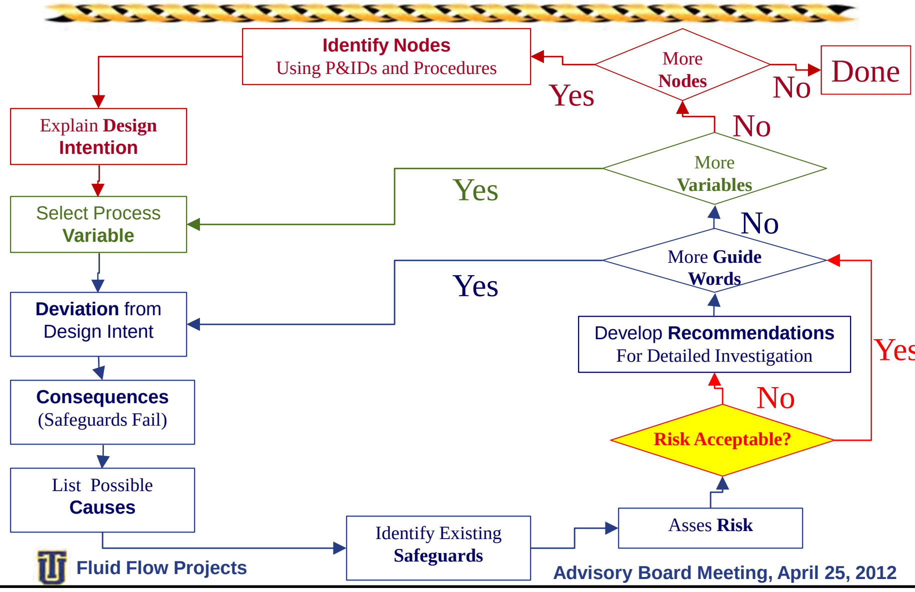
HAZOP Study…

- **Objectives…**
  - Identify Independent Protection Layers (IPLs) and Safeguards
  - Develop Risk Mitigation Measures and Assign Responsible for Actions
  - Identify Necessary Steps to Meet HAZOP Requirements
    - Safety Critical Alarms
    - Basic Process Controls System Loops

Fluid Flow Projects

Advisory Board Meeting, April 25, 2012

HAZOP Study …



Fluid Flow Projects

Advisory Board Meeting, April 25, 2012

HAZOP Study…

Deviation Matrix

Process Parameters	Guideword						
	More	Less	No	Reverse	Part of	As well as	Other than
Flow	More flow	Less flow	No flow	Reverse flow	Wrong ratio	Contamination	Wrong direction (reverse flow)
Pressure	High pressure	Low pressure	Vacuum				
Temperature	High temperature	Low temperature					
Level	High level	Low level	No level				
Reaction	High reaction	Low reaction	No reaction	Reverse reaction		Side reaction	Wrong reaction

HAZOP Study…

Risk Ranking

- Credible Causes and Consequences of Interest Could Exist
- Consequence Severity Evaluated from Safety, Environment and Commercial Point of View
- Consequence Likelihood also Assessed
- Risk Calculated Severity-Likelihood Pair by BP's Risk-Ranking Criteria

HAZOP Study…

- Recommendation Summary
  - Six Nodes Analyzed
  - Eighteen HAZOP Recommendations Documented
  - Facility Generally Found Safe
  - No Significant Construction Delay is Expected due to New Additions
  - HAZOP Report Available Upon Request

Construction Schedule

- Completion Dates

HAZOP	Mar. 2012
Instrumentation	Sep. 2012
Facility Commissioning	Oct. 2012
Preliminary Testing	Feb. 2013

Questions/Comments

Fluid Flow Projects Advisory Board Meeting, April 25, 2012

Fluid Flow Projects

Business Report

Cem Sarica

Advisory Board Meeting, April 25, 2012

Membership and Collaboration Status

- Current Membership Status
  - Membership Increases
    - Saudi Aramco Rejoins
    - 16 Industrial and MMS
- Efforts Continue to Increase TUFFP Membership
  - Pemex has Expressed Interest to Rejoin for 2012
- Collaboration with Seoul National University Continues
  - Visiting Research Scholars and Financial Contribution

Fluid Flow Projects

Advisory Board Meeting, April 25, 2012

Publications and Papers

- Sarica, C., Zhang, H. Q., and Wilkens, J. R.: "Sensitivity of Slug Flow Mechanistic Models on Slug Length," *Journal of Energy Resources Technology* Vol.133/4 Nov. 2011.
- Alsarkhi, A. and Sarica, C.: " Modeling of Droplet Entrainment in Co-current Annular Two-Phase Flow: A New Approach," *International Journal of Multiphase Flow,* pp.21-28, 39, March 2012.
- Zhang, H. Q., Sarica, C., and Pereyra, E.: "A Review of High-Viscosity Oil Multiphase Pipe Flow," Presented at the 1st International Conference on Upstream Engineering and Flow Assurance Houston, TX, April 1-5, 2012

Next Advisory Board Meetings

- Tentative Schedule
  - September 25, 2012
    - TUHOP Meeting
    - TUFFP Workshop
    - Facility Tour
    - TUHOP/TUHFP/TUFFP Reception
  - September 26, 2012
    - TUFFP Meeting
    - TUFFP/TUPDP Dinner
  - September 27, 2012
    - TUPDP Meeting
- Venue is Renaissance Hotel

Financial Report

- **Year 2011 Update**
  - **TUFFP Industrial Account**
  - **TUFFP BSEE Account**
- **Year 2012 Summary**
  - **TUFFP Industrial Account**
  - **TUFFP BSEE Account**

2011 Industrial Account Summary (April 14, 2012)

Anticipated Reserve Fund Balance on January 1, 2011					**($29,760)**
Income for 2011					
	2011 Anticipated Membership Fees (15 @ $55,000 - exludes MMS)				**825,000**
	Facility Utilization Fee (SNU)				**55,000**
	Facility Utilization Fee (Foam Project)				**60,000**
Total Budget					**$ 910,240**
Projected Budget/Expenditures for 2011					
		Projected 11/3/10	**Revised April 2011**	**Revised 10/10/11**	**2011 Expenditures**
90101 - 90103	Faculty Salaries	38,481.88	38,481.88	27,918.00	19,429.62
90600 - 90609	Professional Salaries	71,906.23	51,656.23	44,588.00	50,820.58
90700 - 90703	Staff Salaries	28,306.09	31,289.67	30,858.00	39,221.04
90800	Part-time/Temporary		24,000.00	20,339.35	12,011.07
91000	Student Salaries - Monthly	43,950.00	43,950.00	43,950.00	43,600.00
91100	Student Salaries - Hourly	15,000.00	15,000.00	10,000.00	10,880.54
91800	Fringe Benefits	48,542.97	42,500.00	36,177.00	38,314.92
92102	Fringe Benefits (Students)		3,516.00	3,516.00	3,488.00
81801	Tuition & Student Fees		-	19,223.00	11,626.00
81806	Fellowship			1,125.00	1,125.00
93100	General Supplies	3,000.00	3,000.00	3,500.00	4,387.94
93101	Research Supplies	100,000.00	100,000.00	120,000.00	131,624.19
93102	Copier/Printer Supplies	500.00	500.00	300.00	75.08
93104	Computer Software	4,000.00	4,000.00	3,000.00	3,400.92
93106	Office Supplies	2,000.00	2,000.00	1,200.00	1,379.48
93150	Computers ($1000 - $4999)			1,423.23	1,423.23
93200	Postage and Shipping	500.00	500.00	500.00	1,062.95
93300	Printing and Duplicating	2,000.00	2,000.00	3,000.00	3,758.33
93400	Telecommunications	3,000.00	3,000.00	2,500.00	766.91
93500	Membership	1,000.00	1,000.00	500.00	133.67
93601	Travel - Domestic	10,000.00	10,000.00	9,000.00	6,414.75
93602	Travel - Foreign	10,000.00	10,000.00	9,000.00	11,524.37
93700	Entertainment	10,000.00	16,000.00	16,000.00	20,916.62
94813	Outside Services	20,000.00	40,000.00	30,000.00	36,755.49
95103	Equipment Rental			15,000.00	17,359.55
95200	F&A (55.6%)	103,565.56	107,094.00	95,710.00	57,826.90
98901	Employee Recruiting	3,000.00	3,000.00	250.00	201.52
99001	Equipment	250,000.00	250,000.00	150,000.00	121,899.20
99002	Computers	8,000.00	8,000.00	6,155.51	6,155.51
99300	Bank Charges	40.00	40.00	40.00	32.00
Total Anticipated Expenditures		**776,792.73**	**810,527.78**	**704,773.09**	**657,615.38**
Anticipated Reserve as of 12/31/11					**252,624.36**

2011 BSEE Account Summary

(April 15, 2012)

Reserve Balance as of 12/31/10					**12,781.55**
2011 Budget					**48,000.00**
Total Budget					**60,781.55**
Projected Budget/Expenditures for 2011					
		Budget	**Revised Budget April 2011**	**2011 Expenditures**	
91000	Students - Monthly	29,000.00	36,425.00	35,700.00	
91202	Student Fringe Benefits	2,320.00	2,914.00	2,856.00	
95200	F&A	15,196.00	20,252.00	19,849.20	
Total Anticipated Expenditures as of 12/31/11		**46,516.00**	**59,591.00**	**58,405.20**	
Total Anticipated Reserve Fund Balance as of 12/31/11					**2,376.35**

2012 Industrial Account Budget (April 15, 2012)

(Prepared April 14, 2012)

Anticipated Reserve Fund Balance on January 1, 2012					**$252,624**
Income for 2012					
	2012 Anticipated Membership Fees (16 @ $55,000 - exludes MMS)				**880,000**
	Facility Utilization Fee (SNU)				**55,000**
Total Budget					**$ 1,187,624**
Projected Budget/Expenditures for 2012					
		Projected 10/01/11	**Revised April 2012**	**Expenditures April 2012**	
90101 - 90103	Faculty Salaries	30,712.47		3,885.93	
90600 - 90609	Professional Salaries	117,198.22	53,501.00	13,906.08	
90700 - 90703	Staff Salaries	34,597.60	12,914.00	15,107.08	
90800	Part-time/Temporary		24,000.00		
91000	Student Salaries - Monthly	54,050.00	35,350.00	9,600.00	
91100	Student Salaries - Hourly	15,000.00	15,000.00	2,110.00	
91800	Fringe Benefits	63,877.90	23,245.00	11,514.64	
92102	Fringe Benefits (Students)		2,828.00	768.00	
81801	Tuition & Student Fees	18,686.10	7,350.00		
81806	Fellowship				
93100	General Supplies	3,000.00	3,000.00	1,872.52	
93101	Research Supplies	120,000.00	150,000.00	64,857.34	
93102	Copier/Printer Supplies	750.00	750.00	59.97	
93104	Computer Software	4,000.00	4,000.00	266.07	
93106	Office Supplies	2,000.00	2,000.00	646.01	
93150	Computers ($1000 - $4999)			4,908.41	
93200	Postage and Shipping	500.00	500.00	179.69	
93300	Printing and Duplicating	3,000.00	3,000.00	70.22	
93400	Telecommunications	2,500.00	2,500.00	134.56	
93500	Membership	1,000.00	1,000.00	36.00	
93601	Travel - Domestic	10,000.00	10,000.00	2,170.00	
93602	Travel - Foreign	10,000.00	10,000.00	-	
93700	Entertainment	16,000.00	20,000.00	1,877.20	
94803	Consultant		10,000.00		
94813	Outside Services	20,000.00	20,000.00	3,796.92	
95103	Equipment Rental		20,000.00	-	
95200	F&A (55.6%)	144,392.55	73,761.00	23,435.47	
98901	Employee Recruiting	3,000.00	3,000.00	-	
99001	Equipment	300,000.00	300,000.00	6,769.73	
99002	Computers	8,000.00	8,000.00	-	
99300	Bank Charges	40.00	40.00	30.00	
Total Anticipated Expenditures		**982,304.84**	**815,739.00**	**168,001.84**	
Anticipated Reserve as of 12/31/12					**371,885.36**

2012 BSEE Account Budget

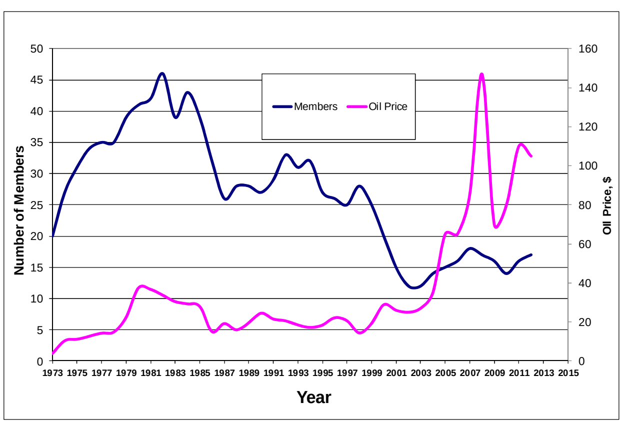
(April 15, 2012)

Reserve Balance as of 12/31/11			**2,376.35**
2012 Budget			**48,000.00**
Total Budget			**50,376.35**

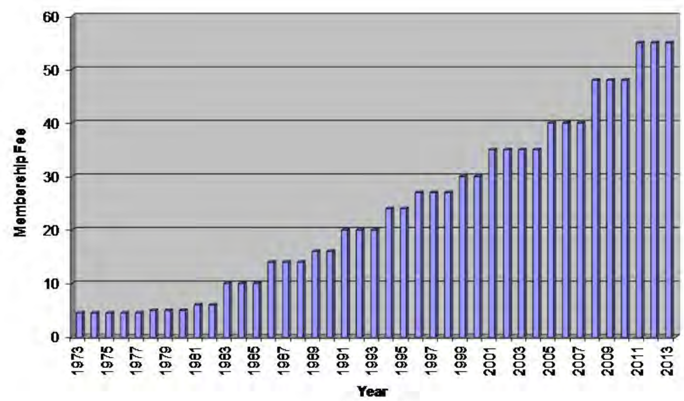
Projected Budget/Expenditures for 2012

	Budget	**2012 Expenditures**	
91000 Students - Monthly	28,125.00	28,125.00	
91202 Student Fringe Benefits	2,250.00	2,250.00	
95200 F&A	15,637.50	15,637.50	
Total Anticipated Expenditures as of 12/31/12	**46,012.50**	**46,012.50**	
Total Anticipated Reserve Fund Balance as of 12/31/12			**4,363.85**

History – Membership



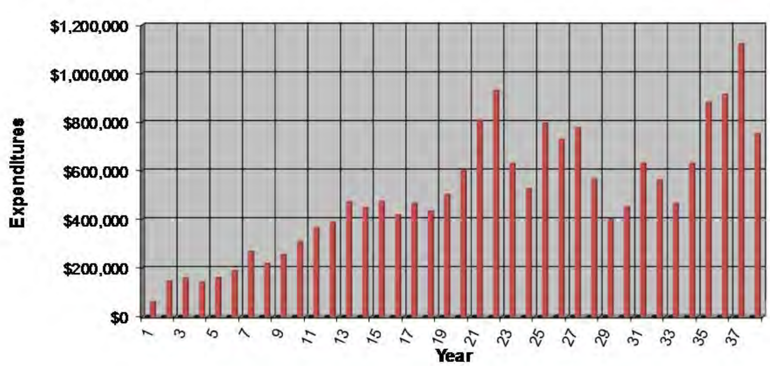
History – Membership Fees



Fluid Flow Projects

Advisory Board Meeting, April 25, 2012

History - Expenditures



Fluid Flow Projects

Advisory Board Meeting, April 25, 2012

Membership Fees

- 2012 Membership Dues
  - 13 Paid
  - 4 Unpaid
  - Prompt Payment is Appreciated

Introduction

This semi-annual report is submitted to Tulsa University Fluid Flow Projects (TUFFP) members to summarize activities since the October 26, 2011 Advisory Board meeting and to assist in planning for the next five months. It also serves as a basis for reporting progress and generating discussion at the 78th semi-annual Advisory Board meeting to be held in South Banquet room of Spirit Bank Event Center 10441 South Regal Blvd. Tulsa, OK 74133 on Wednesday, April 25, 2012.

The activities will start with Tulsa University High Viscosity Projects (TUHOP) Advisory Board meeting on April 24, 2012 between 8:00 a.m. and noon in South Banquet. Between 1:00 and 3:30 p.m. on April 24, 2012, there will be a facility tour. Several TUFFP/TUPDP/TUHOP facilities will be operating during the tour. TUFFP workshop will be held in South Banquet between 3:30 and 5:30 pm. There will be presentations made by TUFFP member companies. Following the workshop, there will be a TUHOP/TUFFP/TUHFP reception between 6:00 p.m. and 9:30 p.m. in same room.

TUFFP Advisory Board meeting will convene at 8:00 a.m. on April 25 and will adjourn at approximately 5:30 p.m. Following the meeting, there will be a joint TUFFP/TUPDP reception between 6:00 and 9:00 p.m. in South Banquet room of Spirit Bank Event Center.

The Tulsa University Paraffin Deposition Projects (TUPDP) Advisory Board meeting will be held on April 26 in in South Banquet room of Spirit Bank Event Center, between 8:30 a.m. and 1:15 p.m.

The following dates have tentatively been established for Fall 2012 Advisory Board meetings. The venue for Fall 2012 Advisory Board meetings is tentatively set to be Renaissance Hotel.

2012 Fall Meetings

September 25, 2012	Tulsa University High Viscosity Oil Projects (TUHOP) JIP Meeting
	Tulsa University Fluid Flow Projects (TUFFP) Workshop
	Facility Tour
	TUHOP/TUFFP Reception
September 26, 2012	Tulsa University Fluid Flow Projects (TUFFP) Advisory Board Meeting
	TUFFP/TUPDP Reception
September 27, 2012	Tulsa University Paraffin Deposition Projects (TUPDP) Advisory Board Meeting

Personnel

Dr. Cem Sarica, Professor of Petroleum Engineering, continues as Director of TUFFP and TUPDP, and as Co-Principal Investigator of TUHOP.

Dr. Holden Zhang, Associate Professor of Petroleum Engineering, serves as Principal Investigator of TUHOP and Associate Director of TUFFP.

Dr. Brill continues to be involved as the director emeritus on a voluntary basis.

Dr. Eduardo Pereyra continues as the lead Research Associate of TUFFP/TUHOP. Dr. Pereyra has a Ph.D. degree from the University of Tulsa. He was one of the research assistants in Tulsa University Separation Technologies Project (TUSTP).

Dr. Abdel Al-Sarkhi of King Fahd University of Petroleum and Minerals serves as Research Associate Professor.

Mr. Scott Graham continues to serve as Project Engineer. Scott oversees all of the facility operations and continues to be the senior electronics technician for TUFFP, TUPDP, and TUHOP.

Mr. Craig Waldron continues as Research Technician, addressing our needs in mechanical areas. He also serves as a flow loop operator for TUPDP and Health, Safety, and Environment (HSE) officer for TUFFP, TUPDP and TUHOP.

Mr. Norman Stegall continues as the electro-mechanical technician. He has been hired as the replacement of Brandon Kelsey.

Mr. Don Harris has recently joined TUFFP/TUPDP/TUHOP team as the electronic research technician. Don has been with TU for 23 years working for the College of Engineering and Natural Sciences as instrumentation technician. Prior to his TU tenure, Don worked for TELEX Computer Products in their Design and Development laboratory for 10 years. He has an Associate Degree in Electro-Mechanical Technology from OSU Stillwater.

Ms. Linda Jones continues as Project Coordinator of TUFFP, TUPDP and TUHOP projects. She keeps the project accounts in addition to other responsibilities such as external communications, providing computer support for graduate students, publishing and distributing all research reports and deliverables, managing the computer network and web sites, and supervision of part-time office help.

Ms. Lori Watts of Petroleum Engineering is the web master for TUFFP/TUPDP/TUHOP websites.

Table 1 updates the current status of all graduate students conducting research on TUFFP projects for the last six months.

Mr. Kiran Gawas, from India, is pursuing his Ph.D. degree in Petroleum Engineering. Kiran has a BS degree in Chemical Engineering from University of Mumbai, Institute of Chemical Technology and a Master of Technology degree from Indian Institute of Technology (IITB). He is studying Low Liquid Loading Three-phase Flow.

Mr. Ge (Max) Yuan, from Peoples Republic of China (PRC), completed his MS degree studies in Petroleum Engineering in December 2011. Max studied Liquid Loading in Gas Wells. He is currently working for SPT in Houston, TX.

Ms. Mujgan Guner has dual BS degrees in Petroleum and Mechanical Engineering from Middle East Technical University, Turkey. Mujgan is pursuing MS degree in Petroleum Engineering. She is continuing the Liquid Loading in Gas Wells studies.

Ms. Rosmer Brito has petroleum engineering BS degree from La Universidad del Zulia. She has worked as production technologist for Petroregional del Lago (Joint Venture PDVSA and Shell Venezuela) for over three years before joining TU. Rosmer has the prestigious Fulbright Scholarship to study abroad. Rosmer is pursuing an MS degree in petroleum engineering. She is studying medium viscosity oil two-phase flow.

Ms. Wei Zheng has a BS degree in petroleum engineering from China Petroleum University in Beijing. Wei is currently one of the teaching assistants in Petroleum Engineering Department at TU. She is pursuing her MS degree in Petroleum Engineering. She is working on the improvements of multiphase heat transfer of the unified mechanistic model.

Mr. Feras Al-Ruhaimani, from Kuwait, is pursuing a Ph.D. Degree in Petroleum Engineering. He is fully funded by Kuwait University. Mr. Al-Ruhaimani has BS and MS degrees in Petroleum Engineering from Kuwait University. He has also worked as petroleum engineer for Kuwait Oil Company for six years. He is studying High Viscosity Oil Multiphase Flow.

Mr. Hamid Karami, from Iran, is pursuing his Ph.D. degree in Petroleum Engineering. Hamid has an MS degree in Petroleum Engineering from The University of Tulsa. He is investigating the Effects of MEG on Multiphase Flow as part of his Ph.D. study.

Mr. Yasser Al-Saadi, from Saudi Arabia, joined TUFFP team in August 2011 as a research assistant to pursue an MS degree in Petroleum Engineering. He has worked for Saudi Aramco as a petroleum engineer prior to starting his MS degree program at the University of Tulsa. His graduate study is fully funded by Saudi Aramco. He is assigned to the project titled "Liquid Loading in Gas Wells".

Mr. Jinho Choi and Mr. Hoyoung Lee participate in two of the TUFFP projects as part of the research collaboration between Seoul National University (SNU) and TUFFP. Mr. Choi and Mr. Lee are Ph.D. candidates in the department of Energy Resources Engineering at SNU. Mr. Choi is assigned to TUFFP project titled "Simplified Transient Gas-Liquid Two-phase Flow Modeling". Mr. Lee is assigned to a project titled "Two-phase Gas-Liquid Flow Modeling Using Energy Minimization Concept".

Mr. Selcuk Fidan, from Turkey, has recently started his Ph.D. studies. Selcuk has an MS degree from Stanford University and a BS degree from Istanbul Technical University both in Petroleum Engineering. Selcuk is currently focusing on course work. He will be assigned a project later this year.

A list of all telephone numbers and e-mail addresses for TUFFP personnel are given in Appendix D.

Table 1

2011 Fall Research Assistant Status

Name	Origin	Stipend	Tuition	Degree Pursued	TUFFP Project	Completion Date
Al-Ruhaimani, Feras	Kuwait	Kuwait University	Kuwait University	Ph.D. PE	High Viscosity Oil Multiphase Flow	Spring 2014
Al-Saadi, Yasser	Saudi Arabia	Saudi Aramco	Saudi Aramco	MS – PE	TBD	Fall 2013
Brito, Rosmer	Venezuela	No – Fulbright	No – Fulbright	MS – PE	Medium Viscosity Oil Two-phase Flow	Spring 2012
Choi, Jinho	South Korea	SNU	N/A	Ph.D. (SNU)	Simplified Transient Gas-Liquid Two-Phase Flow Modeling	Spring 2013
Fidan, Selcuk	Turkey	Self	Self	Ph.D. – PE	TBD	Spring 2016
Gawas, Kiran	India	Yes – TUFFP	Waived (TU)	Ph.D. – PE	Three-phase Gas-Oil-Water Low Liquid Loading	Spring 2012
Guner, Mujgan	Turkey	Yes – TUFFP	Waived – (BSEE)	Ph.D. – PE	Liquid Loading of Gas Wells	Fall 2012
Karami, Hamid	Iran	Yes TUFFP	Yes TUFFP	Ph.D. PE	Effects of MEG on Multiphase Flow	Fall 2014
Lee, Hoyoung	South Korea	SNU	N/A	Ph.D. (SNU)	Two-phase Gas-Liquid Flow Modeling Using Energy Minimization Concept	Spring 2013
Zheng, Wei	PRC	Partial – TU	Waived – (TU)	MS – PE	Unified Heat Transfer Modeling of Gas/Oil/Water Pipe Flow	Spring 2012

Membership

With Saudi Aramco's rejoining, the current membership of TUFFP stands 17 for 2012: 16 industrial members and Bureau of Safety and Environmental Enforcement (BSEE) formerly, MMS of Department of Interior (MMS).

Our efforts to increase the TUFFP membership level continues. PEMEX have informed us that their intention to rejoin TUFFP in 2012. PTT PLC, Ltd. (National Oil Company in Thailand) considers becoming a TUFFP member.

Table 2 lists all the current 2012 TUFFP members. A list of all Advisory Board representatives for these members with pertinent contact information appears in Appendix B. A detailed history of TUFFP membership is given in Appendix C.

The collaboration with Seoul National University is underway. We are in year two of a three-year period with possible two-year extension. Through the collaboration TUFFP receive about $110,000/year and visiting research scholars.

Table 2

2012 Fluid Flow Projects Membership

Aspen Tech	KOC
Baker Atlas	Marathon Oil Company
BP Exploration	Petrobras
BSEE	Saudi Aramco
Chevron	Schlumberger
ConocoPhillips	Shell Global Solutions
Exxon Mobil	SPT
General Electric	Total
JOGMEG	

Equipment and Facilities Status

Test Facilities

The 6 in. ID High Pressure Facility construction is near completion. Recently, the generator has been commissioned and HAZOP review has been completed.

Three-phase 2 in. ID facility has already been modified for better temperature control. The modifications involve installment of oil and water heaters and insulation of the facility. This facility will be utilized in High Viscosity Oil Multiphase Flow studies.

The mixing tee of the 2 in. ID High Viscosity Two-phase flow facility has been replaced with a newly designed mixing tee to investigate the entrance effects.

Detailed descriptions of these modification efforts appear in progress presentations given in this brochure. A site plan showing the location of the various TUFFP and TUPDP test facilities on the North Campus is given in Fig. 1.

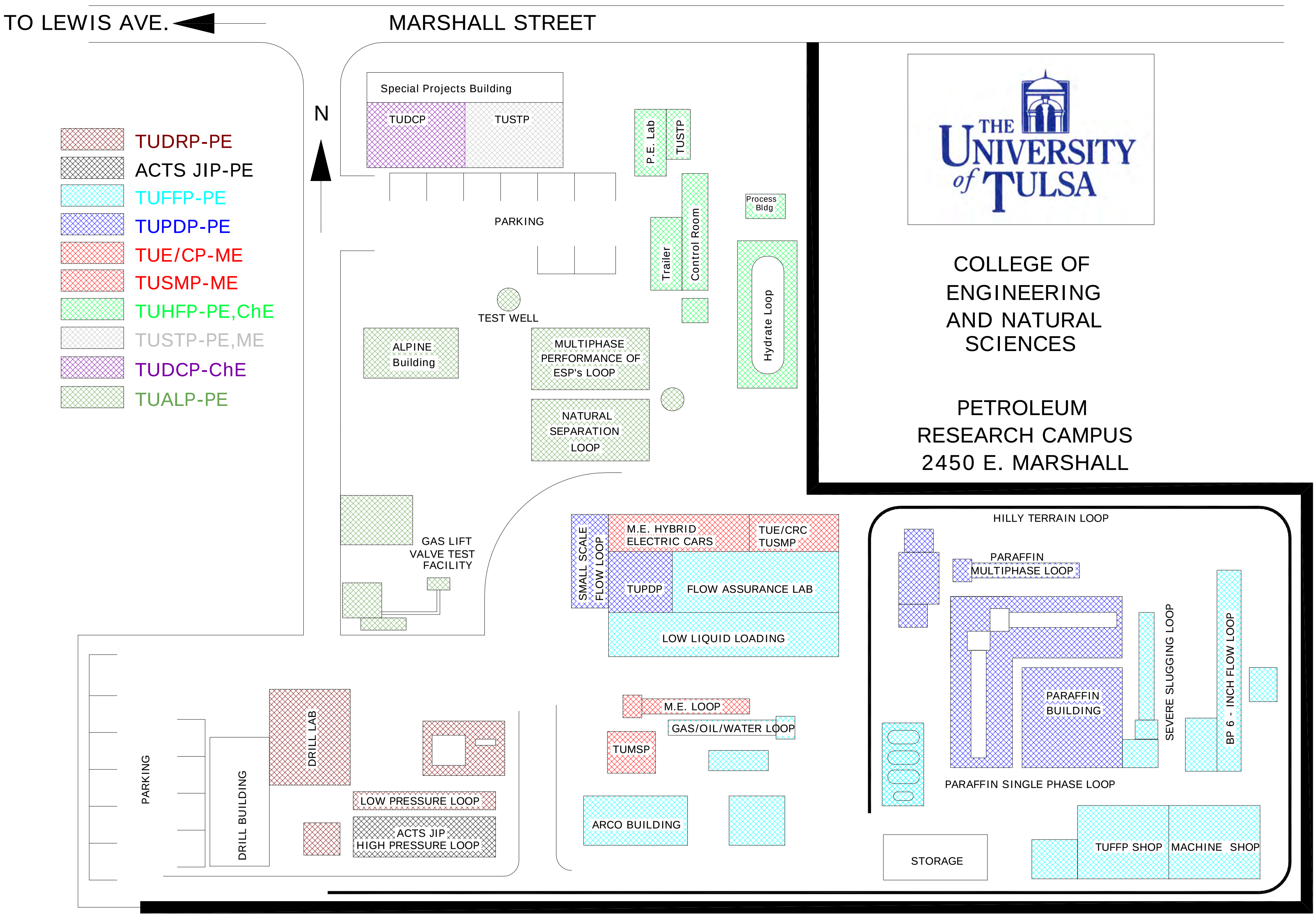


Figure 1 - Site Plan for the North Campus Research Facilties

Financial Status

TUFFP maintains separate accounts for industrial and U.S. government members. Thus, separate accounts are maintained for BSEE funds.

Table 3 presents a financial analysis of income and expenditures for the 2011 Industrial Member Account as of April 2012. Also shown are previous 2011 budgets that have been reported to the members. The total industry expenditures for 2011 are anticipated to be $657,615.38. This results in an estimated carryover of $252,624.36 to 2012 fiscal year.

Table 4 presents a financial analysis of expenditures and income for the BSEE Account for 2011. This account is used primarily for graduate student stipends. A balance of $2,376.35 is anticipated to carry over to 2012.

The University of Tulsa waives up to 19 hours of tuition for each graduate student that is paid a stipend from the United States government, BSEE funds. Moreover, The University of Tulsa has granted tuition waiver for one Ph.D. student. A total of 54 hours of tuition (equivalent of $50,000) were waived for 2011.

Tables 5-6 present the proposed budgets and income for the Industrial, and BSEE accounts for 2012. The 2012 TUFFP industrial budged is based on 16 members. This provides $880,000.00 of industrial membership income for 2012. In addition TUFFP receives facility utilization fee from SNU in the amount of $55,000.00. The total of the 2012 income and the reserve account is projected to be $1,187,624. The expenses for the industrial member account are revised to be $863,720.44 leaving a carryover balance of $323,903.92 to 2013. The BSEE account is expected to have a carryover of $4,363.85 to 2013.

13 of the 17 members have paid their membership dues. We anticipate that the remaining 4 will pay theirs soon.

Table 3: 2011 Industrial Budget Summary

(Prepared April 14, 2012)

Anticipated Reserve Fund Balance on January 1, 2011			**($29,760)**
Income for 2011			
	2011 Anticipated Membership Fees (15 @ $55,000 - exludes MMS)		**825,000**
	Facility Utilization Fee (SNU)		**55,000**
	Facility Utilization Fee (Foam Project)		**60,000**
Total Budget		**$**	**910,240**

Projected Budget/Expenditures for 2011

		Projected Budget 11/3/10	Revised Budget April 2011	Revised Budget 10/10/11	2011 Expenditures
90101 - 90103	Faculty Salaries	38,481.88	38,481.88	27,918.00	19,429.62
90600 - 90609	Professional Salaries	71,906.23	51,656.23	44,588.00	50,820.58
90700 - 90703	Staff Salaries	28,306.09	31,289.67	30,858.00	39,221.04
90800	Part-time/Temporary		24,000.00	20,339.35	12,011.07
91000	Student Salaries - Monthly	43,950.00	43,950.00	43,950.00	43,600.00
91100	Student Salaries - Hourly	15,000.00	15,000.00	10,000.00	10,880.54
91800	Fringe Benefits	48,542.97	42,500.00	36,177.00	38,314.92
92102	Fringe Benefits (Students)		3,516.00	3,516.00	3,488.00
81801	Tuition & Student Fees		-	19,223.00	11,626.00
81806	Fellowship			1,125.00	1,125.00
93100	General Supplies	3,000.00	3,000.00	3,500.00	4,387.94
93101	Research Supplies	100,000.00	100,000.00	120,000.00	131,624.19
93102	Copier/Printer Supplies	500.00	500.00	300.00	75.08
93104	Computer Software	4,000.00	4,000.00	3,000.00	3,400.92
93106	Office Supplies	2,000.00	2,000.00	1,200.00	1,379.48
93150	Computers ($1000 - $4999)			1,423.23	1,423.23
93200	Postage and Shipping	500.00	500.00	500.00	1,062.95
93300	Printing and Duplicating	2,000.00	2,000.00	3,000.00	3,758.33
93400	Telecommunications	3,000.00	3,000.00	2,500.00	766.91
93500	Membership	1,000.00	1,000.00	500.00	133.67
93601	Travel - Domestic	10,000.00	10,000.00	9,000.00	6,414.75
93602	Travel - Foreign	10,000.00	10,000.00	9,000.00	11,524.37
93700	Entertainment	10,000.00	16,000.00	16,000.00	20,916.62
94813	Outside Services	20,000.00	40,000.00	30,000.00	36,755.49
95103	Equipment Rental			15,000.00	17,359.55
95200	F&A (55.6%)	103,565.56	107,094.00	95,710.00	57,826.90
98901	Employee Recruiting	3,000.00	3,000.00	250.00	201.52
99001	Equipment	250,000.00	250,000.00	150,000.00	121,899.20
99002	Computers	8,000.00	8,000.00	6,155.51	6,155.51
99300	Bank Charges	40.00	40.00	40.00	32.00
Total Anticipated Expenditures		**776,792.73**	**810,527.78**	**704,773.09**	**657,615.38**

Anticipated Reserve as of 12/31/11	**252,624.36**

Table 4: 2011 BSEE Budget Summary

(Prepared April 15, 2012)

Reserve Balance as of 12/31/10					**12,781.55**
2011 Budget					**48,000.00**
Total Budget					**60,781.55**
Projected Budget/Expenditures for 2011					
		Budget	**Revised Budget April 2011**	**2011 Expenditures**	
91000	Students - Monthly	29,000.00	36,425.00	35,700.00	
91202	Student Fringe Benefits	2,320.00	2,914.00	2,856.00	
95200	F&A	15,196.00	20,252.00	19,849.20	
Total Anticipated Expenditures as of 12/31/11		**46,516.00**	**59,591.00**	**58,405.20**	
Total Anticipated Reserve Fund Balance as of 12/31/11					**2,376.35**

Table 5: 2012 Industrial Budget

(Prepared April 14, 2012)

Anticipated Reserve Fund Balance on January 1, 2012					**$252,624**
Income for 2012					
	2012 Anticipated Membership Fees (16 @ $55,000 - exludes MMS)				**880,000**
	Facility Utilization Fee (SNU)				**55,000**
Total Budget					**$ 1,187,624**
Projected Budget/Expenditures for 2012					
		Projected 10/01/11	**Revised April 2012**	**Expenditures April 2012**	
90101 - 90103	Faculty Salaries	30,712.47		3,885.93	
90600 - 90609	Professional Salaries	117,198.22	53,501.00	13,906.08	
90700 - 90703	Staff Salaries	34,597.60	12,914.00	15,107.08	
90800	Part-time/Temporary		24,000.00		
91000	Student Salaries - Monthly	54,050.00	35,350.00	9,600.00	
91100	Student Salaries - Hourly	15,000.00	15,000.00	2,110.00	
91800	Fringe Benefits	63,877.90	23,245.00	11,514.64	
92102	Fringe Benefits (Students)		2,828.00	768.00	
81801	Tuition & Student Fees	18,686.10	7,350.00		
81806	Fellowship				
93100	General Supplies	3,000.00	3,000.00	1,872.52	
93101	Research Supplies	120,000.00	150,000.00	64,857.34	
93102	Copier/Printer Supplies	750.00	750.00	59.97	
93104	Computer Software	4,000.00	4,000.00	266.07	
93106	Office Supplies	2,000.00	2,000.00	646.01	
93150	Computers ($1000 - $4999)			4,908.41	
93200	Postage and Shipping	500.00	500.00	179.69	
93300	Printing and Duplicating	3,000.00	3,000.00	70.22	
93400	Telecommunications	2,500.00	2,500.00	134.56	
93500	Membership	1,000.00	1,000.00	36.00	
93601	Travel - Domestic	10,000.00	10,000.00	2,170.00	
93602	Travel - Foreign	10,000.00	10,000.00	-	
93700	Entertainment	16,000.00	20,000.00	1,877.20	
94803	Consultant		10,000.00		
94813	Outside Services	20,000.00	20,000.00	3,796.92	
95103	Equipment Rental		20,000.00	-	
95200	F&A (55.6%)	144,392.55	73,761.00	23,435.47	
98901	Employee Recruiting	3,000.00	3,000.00	-	
99001	Equipment	300,000.00	300,000.00	6,769.73	
99002	Computers	8,000.00	8,000.00	-	
99300	Bank Charges	40.00	40.00	30.00	
Total Anticipated Expenditures		**982,304.84**	**815,739.00**	**168,001.84**	
Anticipated Reserve as of 12/31/12					**371,885.36**

Table 6: 2012 BSEE Budget

(Prepared April 15, 2012)

Reserve Balance as of 12/31/11			**2,376.35**
2012 Budget			**48,000.00**
Total Budget			**50,376.35**

Projected Budget/Expenditures for 2012

	Budget	**2012 Expenditures**	
91000 Students - Monthly	28,125.00	28,125.00	
91202 Student Fringe Benefits	2,250.00	2,250.00	
95200 F&A	15,637.50	15,637.50	
Total Anticipated Expenditures as of 12/31/12	**46,012.50**	**46,012.50**	
Total Anticipated Reserve Fund Balance as of 12/31/12			**4,363.85**

Miscellaneous Information

Fluid Flow Projects Short Course

The 36th TUFFP "Two-Phase Flow in Pipes" short course offering is scheduled for May 7-11, 2012. For this short course to be self sustaining, at least 10 enrollees are needed. We urge our members to let us know soon if they plan to enroll people in the short course.

Dr. Abdel Al-Sarkhi Returns to TUFFP

Dr. Abdel Al-Sarkhi has spent very productive 1 ½ months with TUFFP during summer of 2011. He has helped TUFFP graduate students and worked on the droplet homo-phase project concentrating on entrainment fraction closure relationship development. He has agreed to be back for the summer of 2012 to work with TUFFP researchers.

BHR Group Conference on Multiphase Technology

Since 1991, TUFFP has participated as a co-supporter of BHR Group Conferences on Multiphase Production. TUFFP personnel participate in reviewing papers, serving as session chairs, and advertising the conference to our members. This conference is one of the premier international event providing delegates with opportunities to discuss new research and developments, to consider innovative solutions in multiphase production area.

BHRg in collaboration with SPT Group Canada and Tulsa University Fluid Flow Projects (TUFFP) organizes 8th North American Conference on Multiphase Technology. The conference is scheduled to be held June 20-22, 2012 in Banff, Canada. The conference will benefit anyone engaged in the application, development and research of multiphase technology for the oil and gas industry. Applications in the oil and gas industry will also be of interest to engineers from other industries for which multiphase technology offers a novel solution to their problems. The conference will also be of particular value to designers, facility and operations engineers, consultants and researchers from operating, contracting, consultancy and technology companies. The conference brings together experts from across the American Continents and Worldwide. Cem Sarica will serve as the Technical Program Chair and Editor of the Conference.

The scope of the conference includes variety of subjects pertinent to Multiphase Production in both technology development and applications of the existing technologies. The detailed information about the conference can be found in BHRg's (www.brhgroup.com).

Publications & Presentations

Since the last Advisory Board meeting, the following publications and presentations are made.

1) Sarica, C., Zhang, H. Q., and Wilkens, J. R.: "Sensitivity of Slug Flow Mechanistic Models on Slug Length," *Journal of Energy Resources Technology* Vol.133/4 Nov. 2011.
2) Alsarkhi, A. and Sarica, C.: " Modeling of Droplet Entrainment in Co-current Annular Two-Phase Flow: A New Approach," *International Journal of Multiphase Flow*, pp.21-28, 39, March 2012.
3) Zhang, H. Q., Sarica, C., and Pereyra, E.: "A Review of High-Viscosity Oil Multiphase Pipe Flow," Presented at the 1st International Conference on Upstream Engineering and Flow Assurance Houston, TX, April 1-5, 2012

Tulsa University Paraffin Deposition Projects (TUPDP) Activities

The fourth three year phase of TUPDP is underway. The studies concentrate on the paraffin deposition characterization of single-phase turbulent flow with new oils, gas-oil-water paraffin deposition, and field verification.

Tulsa University Heavy Oil Projects (TUHOP) Activities

TUHOP is an outgrowth of one of the projects initiated through Tulsa University Center of Research Excellence (TUCoRE) initiated by Chevron. Current members of the JIP are BP, Chevron, ConocoPhillips, ExxonMobil, Petrobras, and Petrochina. The primary objective of the JIP is to investigate the effects of high oil viscosity on multiphase flow behavior.

Tulsa University Foam Flow Conditions (TUFFCP) Joint Industry Project (JIP)

This JIP investigates unloading of vertical gas wells using surfactants for a period of three years. The JIP is funded by Research Partnership to Secure Energy for America (RPSEA), which is an organization managing DOE funds, and various oil and gas operating and service companies. This JIP is utilizing some of the TUFFP capabilities. If a member of the JIP is not a member of TUFFP, a facility utilization fee of $30,000 is paid to TUFFP. Current industrial members of the JIP are Chevron, ConocoPhillips, Marathon, Shell, Nalco and Multichem.

TU Forming a New Research Consortium Focused on Natural Gas and Oil Production from Shales

The efforts are underway to form a consortium called "Tulsa University Horizontal Well Artificial Lift Projects" TUHWALP. The consortium primarily will address the artificial lift needs of horizontal wells drilled into gas and oil shales. TUHWALP will start its activities in 2012. The membership fee is $50,000. Currently, BP, Chesapeake, ConocoPhillips, and Shell have joint the consortium. More are expected to join soon.

TUHWALP mission is to:

- Advance the knowledge and effectiveness of people who design and operate horizontal wells,
- Develop recommended practices for artificial lift of horizontal wells,
- Make recommendations to improve the design and operability of artificial lift for horizontal wells,
- Make recommendations to improve the selection, deployment, operation, monitoring, control, and maintenance of artificial lift equipment, and
- Recommend artificial lift practices to optimize recovery of natural gas and associated liquids from horizontal wells.

Two-Phase Flow Calendar

Several technical meetings, seminars, and short courses involving two-phase flow in pipes are scheduled for 2012. Table 9 lists meetings that would be of interest to TUFFP members.

Table 9

2012 Meeting and Conference Calendar

Apr. 25	TUHOP Spring Advisory Board Meeting, Tulsa, Oklahoma
	TUFFP Spring Workshop, Tulsa, Oklahoma
Apr. 26	TUFFP Spring Advisory Board Meeting, Tulsa, Oklahoma
Apr. 27	TUPDP Spring Advisory Board Meeting, Tulsa, Oklahoma
Apr. 30 – May 3	Offshore Technology Conference (OTC), Houston, TX, USA
June 10 – 12	OMAE 2012 Rio de Janeiro, Brazil
June 20 – 22	BHRg's 8th North American Conference on Multiphase Technology, Banff, Canada
Sept. 10 – 13	World Heavy Oil Congress, Aberdeen, Scotland
Sept. 23 - 26	SPE Heavy Oil Workshop Dalian, China
Sept. 25	TUHOP Fall Advisory Board Meeting, Tulsa, Oklahoma
	TUFFP Fall Workshop, Tulsa, Oklahoma
Sept. 26	TUFFP Fall Advisory Board Meeting, Tulsa, Oklahoma
Sept. 27	TUPDP Fall Advisory Board Meeting, Tulsa, Oklahoma
Oct. 7 – 10	SPE Annual Technical Conference and Exhibition, San Antonio, TX, USA
Oct. 14 - 17	SPE Flow Assurance Workshop Phuket, Thailand
Nov. 20 - 21	SPE Flow Assurance and Production Chemistry: Finding Integrated Solutions Across the Value Chain Workshop Dubai, UAE

Appendix A

Fluid Flow Projects Deliverables[1]

1. "An Experimental Study of Oil-Water Flowing Mixtures in Horizontal Pipes," by M. S. Malinowsky (1975).

2. "Evaluation of Inclined Pipe Two-Phase Liquid Holdup Correlations Using Experimental Data," by C. M. Palmer (1975).

3. "Experimental Evaluation of Two-Phase Pressure Loss Correlations for Inclined Pipe," by G. A. Payne (1975).

4. "Experimental Study of Gas-Liquid Flow in a Pipeline-Riser Pipe System," by Z. Schmidt (1976).

5. "Two-Phase Flow in an Inclined Pipeline-Riser Pipe System," by S. Juprasert (1976).

6. "Orifice Coefficients for Two-Phase Flow Through Velocity Controlled Subsurface Safety Valves," by J. P. Brill, H. D. Beggs, and N. D. Sylvester (Final Report to American Petroleum Institute Offshore Safety and Anti-Pollution Research Committee, OASPR Project No. 1; September, 1976).

7. "Correlations for Fluid Physical Property Prediction," by M. E. Vasquez A. (1976).

8. "An Empirical Method of Predicting Temperatures in Flowing Wells," by K. J. Shiu (1976).

9. "An Experimental Study on the Effects of Flow Rate, Water Fraction and Gas-Liquid Ratio on Air-Oil-Water Flow in Horizontal Pipes," by G. C. Laflin and K. D. Oglesby (1976).

10. "Study of Pressure Drop and Closure Forces in Velocity- Type Subsurface Safety Valves," by H. D. Beggs and J. P. Brill (Final Report to American Petroleum Institute Offshore Safety and Anti-Pollution Research Committee, OSAPR Project No. 5; July, 1977).

11. "An Experimental Study of Two-Phase Oil-Water Flow in Inclined Pipes," by H. Mukhopadhyay (September 1, 1977).

12. "A Numerical Simulation Model for Transient Two-Phase Flow in a Pipeline," by M. W. Scoggins, Jr. (October 3, 1977).

13. "Experimental Study of Two-Phase Slug Flow in a Pipeline-Riser Pipe System," by Z. Schmidt (1977).

14. "Drag Reduction in Two-Phase Gas-Liquid Flow," (Final Report to American Gas Association Pipeline Research Committee; 1977).

15. "Comparison and Evaluation of Instrumentation for Measuring Multiphase Flow Variables in Pipelines," Final Report to Atlantic Richfield Co. by J. P. Brill and Z. Schmidt (January, 1978).

16. "An Experimental Study of Inclined Two-Phase Flow," by H. Mukherjee (December 30, 1979).

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[1] Completed TUFFP Projects – each project consists of three deliverables – report, data and software. Please see the TUFFP website

17. "An Experimental Study on the Effects of Oil Viscosity, Mixture Velocity and Water Fraction on Horizontal Oil-Water Flow," by K. D. Oglesby (1979).

18. "Experimental Study of Gas-Liquid Flow in a Pipe Tee," by S. E. Johansen (1979).

19. "Two Phase Flow in Piping Components," by P. Sookprasong (1980).

20. "Evaluation of Orifice Meter Recorder Measurement Errors in Lower and Upper Capacity Ranges," by J. Fujita (1980).

21. "Two-Phase Metering," by I. B. Akpan (1980).

22. "Development of Methods to Predict Pressure Drop and Closure Conditions for Velocity-Type Subsurface Safety Valves," by H. D. Beggs and J. P. Brill (Final Report to American Petroleum Institute Offshore Safety and Anti-Pollution Research Committee, OSAPR Project No. 10; February, 1980).

23. "Experimental Study of Subcritical Two-Phase Flow Through Wellhead Chokes," by A. A. Pilehvari (April 20, 1981).

24. "Investigation of the Performance of Pressure Loss Correlations for High Capacity Wells," by L. Rossland (1981).

25. "Design Manual: Mukherjee and Brill Inclined Two-Phase Flow Correlations," (April, 1981).

26. "Experimental Study of Critical Two-Phase Flow through Wellhead Chokes," by A. A. Pilehvari (June, 1981).

27. "Experimental Study of Pressure Wave Propagation in Two-Phase Mixtures," by S. Vongvuthipornchai (March 16, 1982).

28. "Determination of Optimum Combination of Pressure Loss and PVT Property Correlations for Predicting Pressure Gradients in Upward Two-Phase Flow," by L. G. Thompson (April 16, 1982).

29. "Hydrodynamic Model for Intermittent Gas Lifting of Viscous Oils," by O. E. Fernandez (April 16, 1982).

30. "A Study of Compositional Two-Phase Flow in Pipelines," by H. Furukawa (May 26, 1982).

31. "Supplementary Data, Calculated Results, and Calculation Programs for TUFFP Well Data Bank," by L. G. Thompson (May 25, 1982).

32. "Measurement of Local Void Fraction and Velocity Profiles for Horizontal Slug Flow," by P. B. Lukong (May 26, 1982).

33. "An Experimental Verification and Modification of the McDonald-Baker Pigging Model for Horizontal Flow," by S. Barua (June 2, 1982).

34. "An Investigation of Transient Phenomena in Two-Phase Flow," by K. Dutta-Roy (October 29, 1982).

35. "A Study of the Heading Phenomenon in Flowing Oil Wells," by A. J. Torre (March 18, 1983).

36. "Liquid Holdup in Wet-Gas Pipelines," by K. Minami (March 15, 1983).

37. "An Experimental Study of Two-Phase Oil-Water Flow in Horizontal Pipes," by S. Arirachakaran (March 31, 1983).

38. "Simulation of Gas-Oil Separator Behavior Under Slug Flow Conditions," by W. F. Giozza (March 31, 1983).

39. "Modeling Transient Two-Phase Flow in Stratified Flow Pattern," by Y. Sharma (July, 1983).

40. "Performance and Calibration of a Constant Temperature Anemometer," by F. Sadeghzadeh (August 25, 1983).

41. "A Study of Plunger Lift Dynamics," by L. Rosina (October 7, 1983).

42. "Evaluation of Two-Phase Flow Pressure Gradient Correlations Using the A.G.A. Gas-Liquid Pipeline Data Bank," by E. Caetano F. (February 1, 1984).

43. "Two-Phase Flow Splitting in a Horizontal Pipe Tee," by O. Shoham (May 2, 1984).

44. "Transient Phenomena in Two-Phase Horizontal Flowlines for the Homogeneous, Stratified and Annular Flow Patterns," by K. Dutta-Roy (May 31, 1984).

45. "Two-Phase Flow in a Vertical Annulus," by E. Caetano F. (July 31, 1984).

46. "Two-Phase Flow in Chokes," by R. Sachdeva (March 15, 1985).

47. "Analysis of Computational Procedures for Multi-Component Flow in Pipelines," by J. Goyon (June 18, 1985).

48. "An Investigation of Two-Phase Flow Through Willis MOV Wellhead Chokes," by D. W. Surbey (August 6, 1985).

49. "Dynamic Simulation of Slug Catcher Behavior," by H. Genceli (November 6, 1985).

50. "Modeling Transient Two-Phase Slug Flow," by Y. Sharma (December 10, 1985).

51. "The Flow of Oil-Water Mixtures in Horizontal Pipes," by A. E. Martinez (April 11, 1986).

52. "Upward Vertical Two-Phase Flow Through An Annulus," by E. Caetano F. (April 28, 1986).

53. "Two-Phase Flow Splitting in a Horizontal Reduced Pipe Tee," by O. Shoham (July 17, 1986).

54. "Horizontal Slug Flow Modeling and Metering," by G. E. Kouba (September 11, 1986).

55. "Modeling Slug Growth in Pipelines," by S. L. Scott (October 30, 1987).

56. "RECENT PUBLICATIONS" - A collection of articles based on previous TUFFP research reports that have been published or are under review for various technical journals (October 31, 1986).

57. "TUFFP CORE Software Users Manual, Version 2.0," by Lorri Jefferson, Florence Kung and Arthur L. Corcoran III (March 1989)

58. "Simplified Modeling and Simulation of Transient Two Phase Flow in Pipelines," by Y. Taitel (April 29, 1988).

59. "RECENT PUBLICATIONS" - A collection of articles based on previous TUFFP research reports that have been published or are under review for various technical journals (April 19, 1988).

60. "Severe Slugging in a Pipeline-Riser System, Experiments and Modeling," by S. J. Vierkandt (November 1988).

61. "A Comprehensive Mechanistic Model for Upward Two-Phase Flow," by A. Ansari (December 1988).

62. "Modeling Slug Growth in Pipelines" Software Users Manual, by S. L. Scott (June 1989).

63. "Prudhoe Bay Large Diameter Slug Flow Experiments and Data Base System" Users Manual, by S. L. Scott (July 1989).

64. "Two-Phase Slug Flow in Upward Inclined Pipes", by G. Zheng (Dec. 1989).

65. "Elimination of Severe Slugging in a Pipeline-Riser System," by F. E. Jansen (May 1990).

66. "A Mechanistic Model for Predicting Annulus Bottomhole Pressures for Zero Net Liquid Flow in Pumping Wells," by D. Papadimitriou (May 1990).

67. "Evaluation of Slug Flow Models in Horizontal Pipes," by C. A. Daza (May 1990).

68. "A Comprehensive Mechanistic Model for Two-Phase Flow in Pipelines," by J. J. Xiao (Aug. 1990).

69. "Two-Phase Flow in Low Velocity Hilly Terrain Pipelines," by C. Sarica (Aug. 1990).

70. “Two-Phase Slug Flow Splitting Phenomenon at a Regular Horizontal Side-Arm Tee,” by S. Arirachakaran (Dec. 1990)

71. "RECENT PUBLICATIONS" - A collection of articles based on previous TUFFP research reports that have been published or are under review for various technical journals (May 1991).

72. "Two-Phase Flow in Horizontal Wells," by M. Ihara (October 1991).

73. "Two-Phase Slug Flow in Hilly Terrain Pipelines," by G. Zheng (October 1991).

74. "Slug Flow Phenomena in Inclined Pipes," by I. Alves (October 1991).

75. "Transient Flow and Pigging Dynamics in Two-Phase Pipelines," by K. Minami (October 1991).

76. "Transient Drift Flux Model for Wellbores," by O. Metin Gokdemir (November 1992).

77. "Slug Flow in Extended Reach Directional Wells," by Héctor Felizola (November 1992).

78. "Two-Phase Flow Splitting at a Tee Junction with an Upward Inclined Side Arm," by Peter Ashton (November 1992).

79. "Two-Phase Flow Splitting at a Tee Junction with a Downward Inclined Branch Arm," by Viswanatha Raju Penmatcha (November 1992).

80. "Annular Flow in Extended Reach Directional Wells," by Rafael Jose Paz Gonzalez (May 1994).

81. "An Experimental Study of Downward Slug Flow in Inclined Pipes," by Philippe Roumazeilles (November 1994).

82. "An Analysis of Imposed Two-Phase Flow Transients in Horizontal Pipelines Part-1 Experimental Results," by Fabrice Vigneron (March 1995).

83. "Investigation of Single Phase Liquid Flow Behavior in a Single Perforation Horizontal Well," by Hong Yuan (March 1995).

84. "1995 Data Documentation User's Manual", (October 1995).

85. "Recent Publications" A collection of articles based on previous TUFFP research reports that have been published or are under review for various technical journals (February 1996).

86. "1995 Final Report - Transportation of Liquids in Multiphase Pipelines Under Low Liquid Loading Conditions", Final report submitted to Penn State University for subcontract on GRI Project.

87. "A Unified Model for Stratified-Wavy Two-Phase Flow Splitting at a Reduced Tee Junction with an Inclined Branch Arm", by Srinagesh K. Marti (February 1996).

88. "Oil-Water Flow Patterns in Horizontal Pipes", by José Luis Trallero (February 1996).

89. "A Study of Intermittent Flow in Downward Inclined Pipes" by Jiede Yang (June 1996).

90. "Slug Characteristics for Two-Phase Horizontal Flow", by Robert Marcano (November 1996).

91. "Oil-Water Flow in Vertical and Deviated Wells", by José Gonzalo Flores (October 1997).

92. "1997 Data Documentation and Software User's Manual", by Avni S. Kaya, Gerad Gibson and Cem Sarica (November 1997).

93. "Investigation of Single Phase Liquid Flow Behavior in Horizontal Wells", by Hong Yuan (March 1998).

94. "Comprehensive Mechanistic Modeling of Two-Phase Flow in Deviated Wells" by Avni Serdar Kaya (December 1998).

95. "Low Liquid Loading Gas-Liquid Two-Phase Flow in Near-Horizontal Pipes" by Weihong Meng (August 1999).

96. "An Experimental Study of Two-Phase Flow in a Hilly-Terrain Pipeline" by Eissa Mohammed Al-Safran (August 1999).

97. "Oil-Water Flow Patterns and Pressure Gradients in Slightly Inclined Pipes" by Banu Alkaya (May 2000).

98. "Slug Dissipation in Downward Flow – Final Report" by Hong-Quan Zhang, Jasmine Yuan and James P. Brill (October 2000).

99. "Unified Model for Gas-Liquid Pipe Flow – Model Development and Validation" by Hong-Quan Zhang (January 2002).

100. "A Comprehensive Mechanistic Heat Transfer Model for Two-Phase Flow with High-Pressure Flow Pattern Validation" Ph.D. Dissertation by Ryo Manabe (December 2001).

101. "Revised Heat Transfer Model for Two-Phase Flow" Final Report by Qian Wang (March 2003).

102. "An Experimental and Theoretical Investigation of Slug Flow Characteristics in the Valley of a Hilly-Terrain Pipeline" Ph.D. Dissertation by Eissa Mohammed Al-safran (May 2003).

103. "An Investigation of Low Liquid Loading Gas-Liquid Stratified Flow in Near-Horizontal Pipes" Ph.D. Dissertation by Yongqian Fan.

104. “Severe Slugging Prediction for Gas-Oil-Water Flow in Pipeline-Riser Systems,” M.S. Thesis by Carlos Andrés Beltrán Romero (2005)

105. “Droplet-Homophase Interaction Study (Development of an Entrainment Fraction Model) – Final Report,” Xianghui Chen (2005)

106. “Effects of High Oil Viscosity on Two-Phase Oil-Gas Flow Behavior in Horizontal Pipes” M.S. Thesis by Bahadir Gokcal (2005)

107. “Characterization of Oil-Water Flows in Horizontal Pipes” M.S. Thesis by Maria Andreina Vielma Paredes (2006)

108. “Characterization of Oil-Water Flows in Inclined Pipes” M.S. Thesis by Serdar Atmaca (2007).

109. “An Experimental Study of Low Liquid Loading Gas-Oil-Water Flow in Horizontal Pipes” M.S. Thesis by Hongkun Dong (2007).

110. “An Experimental and Theoretical Investigation of Slug Flow for High Oil Viscosity in Horizontal Pipes” Ph.D. Dissertation by Bahadir Gokcal (2008).

111. “Modeling of Gas-Liquid Flow in Upward Vertical Annuli” M.S. Thesis by Tingting Yu (2009).

112. “Modeling of Hydrodynamics of Oil-Water Pipe Flow using Energy Minimization Concept” M.S. Thesis by Anoop Kumar Sharma (2009).

113. “Liquid Entrainment in Annular Gas-Liquid Flow in Inclined Pipes” M.S. Thesis by Kyle L. Magrini (2009).

114. "Effects of High Oil Viscosity on Slug Liquid Holdup in Horizontal Pipes" M.S. Thesis by Ceyda Kora (2010).

115. "Effect of Pipe Inclination on Flow Characteristics of High Viscosity Oil-Gas Two-Phase Flow" M.S. Thesis by Benin Chelinsky Jeyachandra (2011).

116. “Liquid Loading of Gas Wells” M.S. Thesis by Ge Yuan.

Appendix B

2012 Fluid Flow Projects Advisory Board Representatives

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Appendix C

History of Fluid Flow Projects Membership

		1973	
1.	TRW Reda Pump	12 Jun. '72	T: 21 Oct. '77
2.	Pemex	15 Jun. '72	T: 30 Sept. '96 R: Dec '97 T: 2010
3.	Getty Oil Co.	19 Jun. '72	T: 11 Oct. '84 with sale to Texaco
4.	Union Oil Co. of California	7 Jul. '72	T: for 2001
5.	Intevep	3 Aug. '72	TR: from CVP in '77; T: 21 Jan '05 for 2006
6.	Marathon Oil Co.	3 Aug. '72	T: 17 May '85 R: 25 June '90 T: 14 Sept. '94 R: 3 June '97 **Current**
7.	Arco Oil and Gas Co.	7 Aug. '72	T: 08 Dec. '97
8.	AGIP	6 Sep. '72	T: 18 Dec. '74
9.	Otis Engineering Corp.	4 Oct. '72	T: 15 Oct. '82
10.	ConocoPhillips, Inc.	5 Oct. '72	T: Aug. '85 R: 5 Dec. '86 **Current**
11.	Mobil Research and Development Corp.	13 Oct. '72	T: 27 Sep. 2000
12.	Camco, Inc.	23 Oct. '72	T: 15 Jan. '76 R: 14 Mar. '79 T: 5 Jan. '84
13.	Crest Engineering, Inc.	27 Oct. '72	T: 14 Nov. '78 R: 19 Nov. '79 T: 1 Jun. '84
14.	Chevron	3 Nov. '72	**Current**
15.	Aminoil	9 Nov. '72	T: 1 Feb. '77

16.	Compagnie Francaise des Petroles (TOTAL)	6 Dec. '72	T: 22 Mar. '85 R: 23 Oct. '90 T: 18 Sep. '01 for 2002 R: 18 Nov. '02 **Current**
17.	Oil Service Co. of Iran	19 Dec. '72	T: 20 Dec. '79
18.	Sun Exploration and Production Co.	4 Jan. '73	T: 25 Oct. '79 R: 13 Apr. '82 T: 6 Sep. '85
19.	Amoco Production Co. (now as BP Amoco)	18 May '73	
20.	Williams Brothers Engrg. Co.	25 May '73	T: 24 Jan. '83
		1974	
21.	Gulf Research and Development Co.	20 Nov. '73	T: Nov. '84 with sale to Chevron
22.	El Paso Natural Gas Co.	17 Dec. '73	T: 28 Oct. '77
23.	Arabian Gulf Exploration Co.	27 Mar. '74	T: 24 Oct. '82
24.	ExxonMobil Upstream Research	27 Mar. '74	T: 16 Sep. '86 R: 1 Jan. '88 T: 27 Sep. 2000 R: 2007 **Current**
25.	Bechtel, Inc.	29 May '74	T: 14 Dec. '76 R: 7 Dec. '78 T: 17 Dec. '84
26.	Saudi Arabian Oil Co.	11 Jun. '74	T: for 1999 R: for 2003 T: for 2007 R: for 2012 **Current**
27.	Petrobras	6 Aug. '74	T: for 2000 R: for 2005 **Current**
		1975	
28.	ELF Exploration Production (now as TotalFina Elf)	24 Jul. '74	T: 24 Feb. '76 Tr. from Aquitaine Co. of Canada 19 Mar. '81 T: 29 Jan. '87 R: 17 Dec. '91
29.	Cities Service Oil and Gas Corp.	21 Oct. '74	T: 25 Oct. '82 R: 27 Jun. '84

			T: 22 Sep. '86
30.	Texas Eastern Transmission Corp.	19 Nov. '74	T: 23 Aug. '82
31.	Aquitaine Co. of Canada, Ltd.	12 Dec. '74	T: 6 Nov. '80
32.	Texas Gas Transmission Corp.	4 Mar. '75	T: 7 Dec. '89
		1976	
33.	Panhandle Eastern Pipe Line Co.	15 Oct. '75	T: 7 Aug. '85
34.	Phillips Petroleum Co.	10 May '76	T: Aug. 94 R: Mar 98 T: 2002
		1977	
35.	N. V. Nederlandse Gasunie	11 Aug. '76	T: 26 Aug. '85
36.	Columbia Gas System Service Corp.	6 Oct. '76	T: 15 Oct. '85
37.	Consumers Power Co.	11 Apr. '77	T: 14 Dec. '83
38.	ANR Pipeline Co.	13 Apr. '77	TR: from Michigan- Wisconsin Pipeline Co. in 1984 T: 26 Sep. '84
39.	Scientific Software-Intercomp	28 Apr. '77	TR: to Kaneb from Intercomp 16 Nov. '77 TR: to SSI in June '83 T: 23 Sep. '86
40.	Flopetrol/Johnston-Schlumberger	5 May '77	T: 8 Aug. '86
		1978	
41.	Norsk Hydro a.s	13 Dec. '77	T: 5 Nov. '82 R: 1 Aug. '84 T: 8 May ‘96
42.	Dresser Industries Inc.	7 Jun. '78	T: 5 Nov. '82
		1979	
43.	Sohio Petroleum Co.	17 Nov. '78	T: 1 Oct. '86
44.	Esso Standard Libya	27 Nov. '78	T: 2 Jun. '82
45.	Shell Internationale Petroleum MIJ B.V. (SIPM)	30 Jan. '79	T: Sept. 98 for 1999
		1980	
46.	Fluor Ocean Services, Inc.	23 Oct. '79	T: 16 Sep. '82
47.	Texaco	30 Apr. '80	T: 20 Sep. ’01 for 2002

48.	BG Technology (Advantica)	15 Sep. '80	T: 2003
	1981		
49.	Det Norske Veritas	15 Aug. '80	T: 16 Nov. '82
	1982		
50.	Arabian Oil Co. Ltd.	11 May '82	T: Oct.'01 for 2002
51.	Petro Canada	25 May '82	T:28 Oct. '86
52.	Chiyoda	3 Jun. '82	T: 4 Apr '94
53.	BP	7 Oct. '81	**Current**
	1983		
54.	Pertamina	10 Jan. '83	T: for 2000 R: March 2006
	1984		
55.	Nippon Kokan K. K.	28 Jun. '83	T: 5 Sept. '94
56.	Britoil	20 Sep. '83	T: 1 Oct. '88
57.	TransCanada Pipelines	17 Nov. '83	T:30 Sep. '85
58.	Natural Gas Pipeline Co. of America (Midcon Corp.)	13 Feb. '84	T:16 Sep. '87
59.	JGC Corp.	12 Mar. '84	T: 22 Aug. '94
	1985		
60.	STATOIL	23 Oct. '85	T:16 Mar. '89
	1986		
61.	JOGMEC (formerly Japan National Oil Corp.)	3 Oct. '86	T: 2003 R: 2007 **Current**
	1988		
62.	China National Oil and Gas Exploration and Development Corporation	29 Aug. '87	T:17 Jul. '89
63.	Kerr McGee Corp.	8 Jul. '88	T:17 Sept. '92
	1989		
64.	Simulation Sciences, Inc.	19 Dec. '88	T: for 2001
	1991		
65.	Advanced Multiphase Technology	7 Nov. '90	T:28 Dec. '92

66.	Petronas	1 Apr. '91	T: 02 Mar. 98 R: 1 Jan 2001 T: Nov. 2008 for 2009
	1992		
67.	Instituto Colombiano Del Petroleo	19 July '91	T: 3 Sep. '01 for 2002
68.	Institut Francais Du Petrole	16 July. '91	T: 8 June 2000
69.	Oil & Natural Gas Commission of India	27 Feb. '92	T: Sept. 97 for 1998
	1994		
70.	Baker Jardine & Associates	Dec. '93	T: 22 Sept. '95 for 1996
	1998		
71.	Baker Atlas	Dec. 97	**Current**
72.	Bureau of Ocean Energy Management, Regulation, and Enforcement (BOEMRE)	May. 98	**Current**
	2002		
73.	Schlumberger Overseas S.A.	Aug. 02	**Current**
74.	Saudi Aramco	Mar. 03	T: for 2007
	2004		
75.	YUKOS	Dec. '03	T: 2005
76.	Landmark Graphics	Oct. '04	T: 2008
	2005		
77.	Rosneft	July '05	T: 2010
	2006		
78.	Tenaris		T: Sept 2008 – for 2009
79.	Shell Global		**Current**
80.	Kuwait Oil Company		**Current**
	2009		
81.	SPT		**Current**
	2011		
82.	General Electric		**Current**
83.	Aspen Technology, Inc.		**Current**

Note: T = Terminated; R = Rejoined; and TR = Transferred

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