THE UNIVERSITY of TULSA

McDougall School of Petroleum Engineering

Fluid Flow Projects

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

October 26, 2011

Tulsa University Fluid Flow Projects
Seventy Seventh Semi-Annual Advisory Board Meeting Agenda
Wednesday, October 26, 2011

Tuesday, October 25, 2011

Tulsa University High-Viscosity Oil Projects
Advisory Board Meeting
University of Tulsa – Allen Chapman Activity Center - Gallery
440 South Gary
Tulsa, Oklahoma
8:00 a.m. – Noon

Tulsa University High-Viscosity Oil Projects, Tulsa University Hydrate Flow Performance JIP, and Tulsa University Fluid Flow Projects Workshop Luncheon
University of Tulsa – Allen Chapman Activity Center - Great Hall B
440 South Gary
Tulsa, Oklahoma
12:00 – 1:00 p.m.

Tulsa University Fluid Flow Projects Workshop
University of Tulsa – Allen Chapman Activity Center - Gallery
440 South Gary
Tulsa, Oklahoma
1:00 – 3:00 p.m.

Tulsa University High-Viscosity Oil Projects, Tulsa University Hydrate Flow Performance JIP, and Tulsa University Fluid Flow Projects
Tour of Test Facilities
University of Tulsa North Campus
2450 East Marshall
Tulsa, Oklahoma
3:30 – 5:30 p.m.

Tulsa University High-Viscosity Oil Projects, Tulsa University Hydrate Flow Performance JIP, and Tulsa University Fluid Flow Projects
Reception
University of Tulsa – Allen Chapman Activity Center - Great Hall B
440 South Gary
Tulsa, Oklahoma
6:00 – 9:00 p.m.

Wednesday, October 26, 2011

Tulsa University Fluid Flow Projects
Advisory Board Meeting
University of Tulsa – Allen Chapman Activity Center - Gallery
440 South Gary
Tulsa, Oklahoma
8:00 a.m. – 5:00 p.m.

Tulsa University Fluid Flow Projects and Tulsa University Paraffin Deposition Projects
Reception
University of Tulsa – Allen Chapman Activity Center - Atrium
440 South Gary
Tulsa, Oklahoma
5:30 – 9:00 p.m.

Thursday, October 27, 2011

Tulsa University Paraffin Deposition Projects
Advisory Board Meeting
University of Tulsa – Allen Chapman Activity Center - Gallery
440 South Gary
Tulsa, Oklahoma
8:00 a.m. – 1:00 p.m.

Tulsa University Fluid Flow Projects
Seventy Seventh Semi-Annual Advisory Board Meeting Agenda
Wednesday, October 26, 2011

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

5:30 **TUFFP/TUPDP Reception - Allen Chapman Activity Center - Atrium**

Table of Contents

Executive Summary **1**

Introductory Presentation **5**

TUFFP Progress Reports

Executive Summary of Research Activities
Presentation 13

Effect of Pipe Inclination on Flow Characteristics of High Viscosity Oil-Gas Two-Phase Flow – Benin Chelinsky Jeyachandra
Presentation 31
Project Summary 57

Downward Two-Phase Stratified Flow for Highly Viscous Oils - Rosmer Brito, Eduardo Pereyra and Cem Sarica
Presentation 61
Project Summary 79

Effect of Medium Oil Viscosity on Two-Phase Oil-Gas Flow Behavior in Horizontal Pipes - Rosmer Brito
Presentation 83
Project Summary 105

Characterization of High Viscosity Slug Flow in Horizontal Pipes - Eissa Al-safran
Presentation 109
Project Summary 121

Low Liquid Loading Gas-Oil-Water in Pipe Flow - Kiran Gawas
Presentation 123
Project Summary 139

Effects of MEG on Multiphase Flow Behavior - Hamidreza Karami
Presentation 141
Project Summary 151

Modeling of Droplet Entrainment in Co-current Annular Two-Phase Flow: A New Approach - Abdel Al-Sarkhi
Presentation 153
Project Summary 169

High Pressure Test Facility Construction Update - Eduardo Pereyra and Abdel Al-Sarkhi
Presentation 175
Project Summary 189

Liquid Loading of Gas Wells (Part 1) - Ge (Max) Yuan
Presentation 193
Project Summary 211

Liquid Loading of Gas Wells (Part 2) - Mujgan Guner
Presentation 213
Project Summary 223

Simplified Transient Two-Phase Flow Modeling - Jinho Choi
Presentation 225
Project Summary 241

Unified Heat Transfer Modeling of Gas/Oil/Water Pipe Flow - Wei Zheng
Presentation 243
Project Summary 263

TUFFP Business Report
Presentation 265
Introduction 273
Personnel 275
Membership 279
Equipment and Facilities 281
Financial Status 283
Miscellaneous Information 289

Appendices
Appendix A – Fluid Flow Projects Deliverables 293
Appendix B – Fluid Flow Projects Advisory Board Representatives 299
Appendix C – History of Fluid Flow Projects Membership 305
Appendix D – Contact Information 311

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 this 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 is 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 will be done during the summer of 2012.

  2. *Transition from Stratified Smooth Flow:* During this period, an additional testing program has been carried out to specifically investigate the transition from stratified smooth flow and transition boundary prediction models have been evaluated.

  3. *Slug Length Study:* 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 will be completed soon. It is expected that experimental testing will be started right after the Fall 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 proper instruments to characterize the flow have been identified. Currently, Standard Operating Procedures are being prepared prior to a detailed HAZOP review of the facility

- *"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 a new isokinetic probe setup consisting of four fixed probes a foot apart from each other was designed and implemented in the flow loop. This will significantly speed the data acquisition.

- *"Effect of MEG on Multiphase Flow Behavior."* This project is rated very high in TUFFP questionnaire. It has been started effectively this summer. Mr. Hamid Karami, a new Ph.D. student is assigned to the project. 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.

- *"Droplet Homo-phase Interaction Study."* There are many cases in multiphase flow where droplets are entrained from or coalesced into a continuous homo-phase. Droplet homo-phase covers a broad range of possibilities. For example, in annular mist flow, the liquid droplets are in dynamic equilibrium with the film on the walls, experiencing both entrainment and coalescence. Very few mechanistic models exist for entrainment fraction. Understanding the basic physics is essential to model situations of practical interest to the industry.

  The results of the experimental study conducted by Magrini (2009) for various inclination angles showed the dependency of entrainment fraction to the inclination angle of the pipe. Currently, our efforts are focused on developing a better entrainment fraction closure relationship valid for all inclination angles. Dr. Abdel Al-Sarkhi, Research Associate Professor of Petroleum Engineering, has developed a new entrainment fraction closure relationship during his visit this summer.

  Moreover, entrainment fraction part of the low liquid loading study can be considered under droplet homo-phase.

- *"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. Therefore, earlier this year a new model based on the drift flux approach for all flow patterns have been developed. Model verification and improvement efforts currently underway.

- *"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 available models will be improved or a new model developed based on the experimental measurements and observations.

  The facility modifications and data acquisition are completed. The data analysis is currently underway. Due to the immigration restrictions, the current research assistant will not be able complete all of the TUFFP's objectives of this project. Therefore, this study will be continued with another MS student in 2012.

- "*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, we have embarked on a new research project. The main objective of this project is to develop a unified heat transfer model for gas/oil/water flow in pipes of all inclinations -90° to +90°. The resultant model will be included in the TUFFP Excel VBA software package for wellbore and pipeline thermal calculations.

TUFFP membership is steady at 16 (15 industrial companies and BOEMRE) members. Efforts continue to further increase the TUFFP membership level. We expect 2 new members for 2012. A detailed financial report is provided in this report. The sum of the 2011 income and

the reserve account is projected to be $910,240. The expenses for the industrial member account are estimated to be $704,773 leaving a positive balance of $205,467.

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 2012. The membership fee is estimated to be $50,000.

Fluid Flow Projects

77th Fluid Flow Projects Advisory Board Meeting

Welcome

Safety Moment

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

Introductory Remarks

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

Team

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

Team …

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

Team …

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

Team …

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

Guests

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

Agenda

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

Agenda …

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

Agenda …

- 3:15 Progress Reports
  - Liquid Loading of Gas Wells (Part 1)
  - Liquid Loading of Gas Wells (Part 2)
  - Simplified Transient Two-Phase Modeling
  - Unified Heat Transfer Modeling of Gas-Oil-Water Pipe Flow

Agenda …

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

Other Activities

- October 25, 2011
  - TUHOP Meeting
  - TUFFP Workshop
    - Excellent Presentations
    - Beneficial for Everybody
  - Facility Tour
- October 27, 2011
  - TUPDP Meeting

Fluid Flow Projects

Executive Summary of Research Activities

Cem Sarica

Advisory Board Meeting, October 26, 2011

Current Projects

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

Current Projects …

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

High Viscosity Multiphase Flow

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

High Viscosity Multiphase Flow

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

High Viscosity Multiphase Flow …

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

High Viscosity Multiphase Flow …

- Current Studies …
  - Holistic Analysis of Slug Flow Characteristics in Horizontal Pipes (Al-Safran)
  - Transition from Stratified Smooth to Other Flow Patterns (Brito and Pereyra)
    - Progress
      - Experimental and Model Comparison is Completed
    - Future Study
      - Lower Oil Viscosities

High Viscosity Multiphase Flow …

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

Low Liquid Loading Flow

- Significance
  - Wet Gas Transportation
    - Holdup and Pressure Drop Prediction
    - Corrosion Inhibitor Delivery (Top of the Line Corrosion)
- Objectives
  - Develop Better Predictive Tools

Low Liquid Loading Flow …

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

Low Liquid Loading Flow …

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

Low Liquid Loading Flow …

- Current Study (Gawas)
  - Three-phase, Large Diameter, Low Pressure Inclined Flow
    - Air-Mineral Oil-Water
    - 6 in. ID and ±2° Inclination Angles from Horizontal
    - Objectives
      - Acquire Similar Data as in Horizontal Flow Study
      - Develop Improved Closure Relationships

Low Liquid Loading Flow …

- Progress
  - Design and Construction of a New Isokinetic Device with Multiple Probes
  - Droplet Field Image Capture
- Near Future Activity
  - Data Acquisition and Analysis

Up-Scaling Studies

- Significance
  - Better Design and Operation
- Objective
  - Testing and Improvement of Existing Models for Large Diameter and Relatively High Pressures
- Past Studies
  - Low Pressure and 6 in. ID Low Liquid Loading (Fan and Dong)
  - High Pressure 2 in. ID (Manabe)

Up-Scaling Studies …

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

Up-Scaling Studies …

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

Effects of MEG on Multiphase Flow

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

Effects of MEG on Multiphase Flow

- Progress
  - Mr. Hamid Karami, Ph.D. Student Assigned to the Project
  - Literature Review Underway
- Near Future Activity
  - Test Matrix
  - Flow Loop Modification

Droplet Homo-phase Studies

- Significance
  - Better Predictive Tools Lead to Better Design and Practices
- General Objective
  - Development of Closure Relationships
- Past Study
  - Earlier TUFFP Study Showed
    - Entrainment Fraction (FE) is Most Sensitive Closure Parameter in Annular Flow
    - Developed New FE Correlation
      - Utilizing In-situ Flow Parameters
      - Limited Data, Especially for Inclined Flow Conditions

Droplet Homo-phase Studies …

- Current Study
  - Liquid Entrainment in Annular Two-Phase Flow in Inclined Pipes
  - Objectives
    - Develop Better Closure Relationships

Droplet Homo-phase Studies …

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

Liquid Loading of Gas Wells

- Objectives
  - Explore Mechanism Controlling Onset of Liquid Loading
  - Investigate Effects of Well Deviation on Liquid Loading
- Ge (Max) Yuan is Research Assistant

Liquid Unloading from Gas Wells …

- Past Studies
  - Primarily on Droplet Transfer {Turner (1969), Coleman (1991), etc.}
  - Film Reversal {Barnea (1987), Veeken (2009)}
  - No Comprehensive Study on Inclination Angle Effect

Liquid Unloading from Gas Wells …

- Progress
  - Data Acquisition Complete
- Near Future Activity
  - Data Analysis
  - Model Evaluation
- Study will Continue with Ms. Guner in 2012

Transient Modeling

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

Transient Modeling …

- Objective
  - Development and Testing of a Simple and Fast Transient Flow Simulator
- Several TUFFP Studies
  - Scoggins, Sharma, Dutta-Roy, Taitel, Vierkandt, Sarica, Vigneron, Minami, Gokdemir, Zhang, Tengesdal, and Beltran

Transient Modeling …

- Current Study (Choi)
  - Approach is Changed
    - Drift Flux is Chosen
    - Development of a Simplified Isothermal Drift Flux Transient Model
      - Simulator Structure Design
      - Code Development (Explicit Solver)

Transient Modeling …

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

Unified Model

- Objective
  - Develop and Maintain an Accurate and Reliable Steady State Multiphase Simulator
- Past Studies
  - Zhang *et al.* Developed "Unified Model" in 2002 for Two-phase Flow
    - Became TUFFP's Flagship Steady State Simulator
    - Applicable for All Inclination Angles
  - "Unified Model was Extended to Three-phase in 2006

Unified Model …

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

Multiphase Flow Modeling Using Energy Minimization Concept

- Past
  - Sharma (2009) Successfully Applied the Concept to Oil/Water Flow
- Objective of Current Project
  - Apply Energy Minimization Approach for Gas/Liquid Flow
    - Objective Function Determination
      - Energy Equation in Meso-Scale and Macro Scale
    - Definition of Constrain Functions Based on Gas/Liquid Physics

Multiphase Flow Modeling Using Energy Minimization Concept …

- Status
  - Hoyoung Lee, Visiting Scholar from SNU is Assigned to the Project
  - Project was on Hold Due to Mr. Lee's Military Service Obligations in His Home Country

Multiphase Flow Modeling Using Energy Minimization Concept …

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

Fluid Flow Projects

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

Benin Chelinsky Jeyachandra

Advisory Board Meeting, October 26, 2011

Outline

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

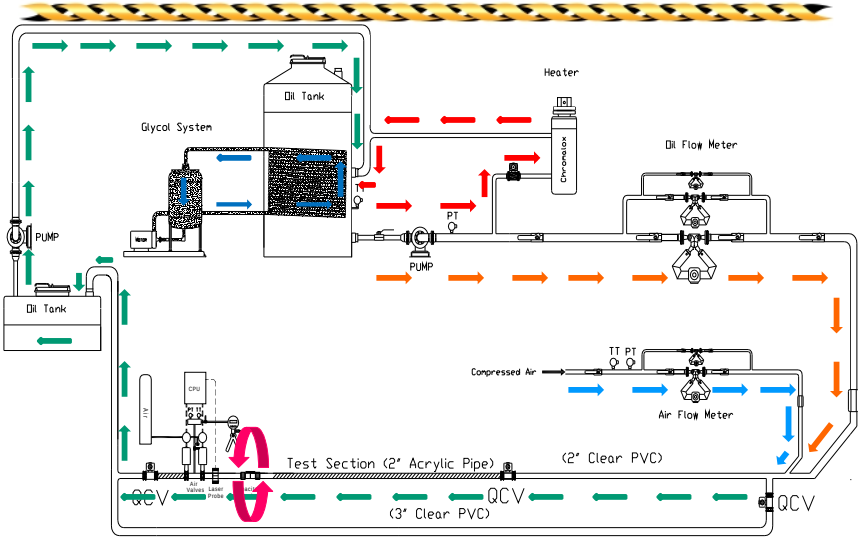
Objectives

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

Introduction

- Increase in High Viscosity Oil Offshore Discoveries
- Current Multiphase Flow Models Developed for Low Viscosity Oils
- Horizontal Flow Experiments- Gokcal (2005,2008) and Kora (2010)
- Multiphase Flows May Exhibit Significantly Different Behavior for Higher Viscosity Oils

Experimental Facility…



Experimental Matrix

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

Two Phase Flow Characteristics

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

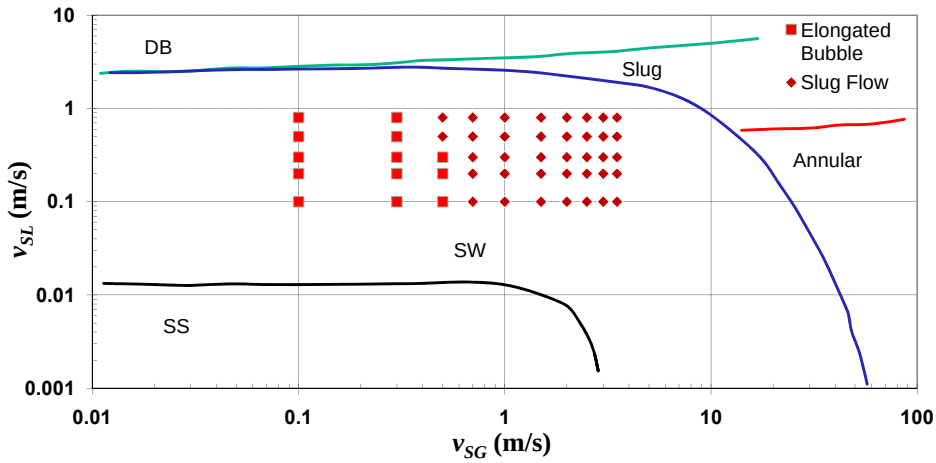
Fluid Flow Projects

1. Flow Patterns

A. Downward Inclined Flow

Advisory Board Meeting, October 26, 2011

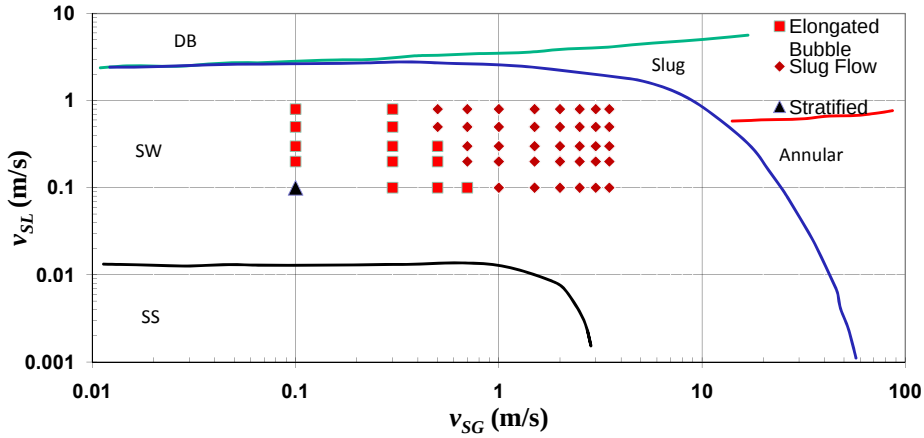
Viscosity Effects- 585 cP Viscosity Oil-Air vs. Water-Air Downward Inclined Two-Phase Flow



Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

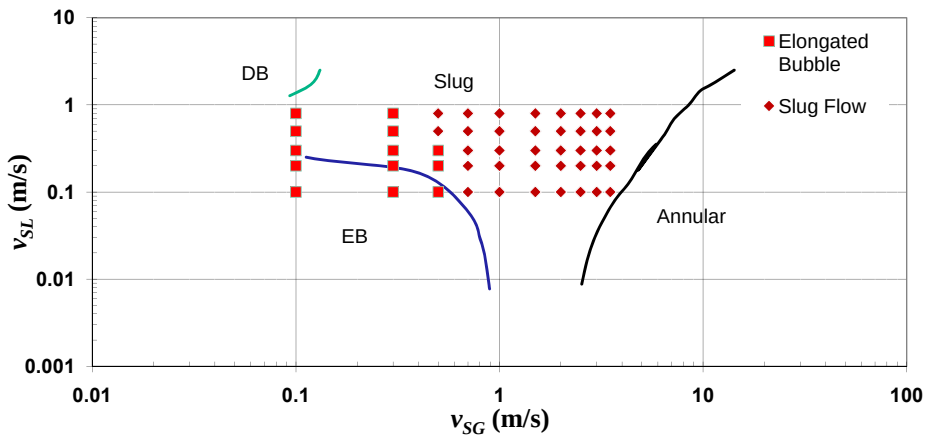
Viscosity Effects- 181 cP Viscosity Oil-Air vs. Water-Air Downward Inclined Two-Phase Flow



Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

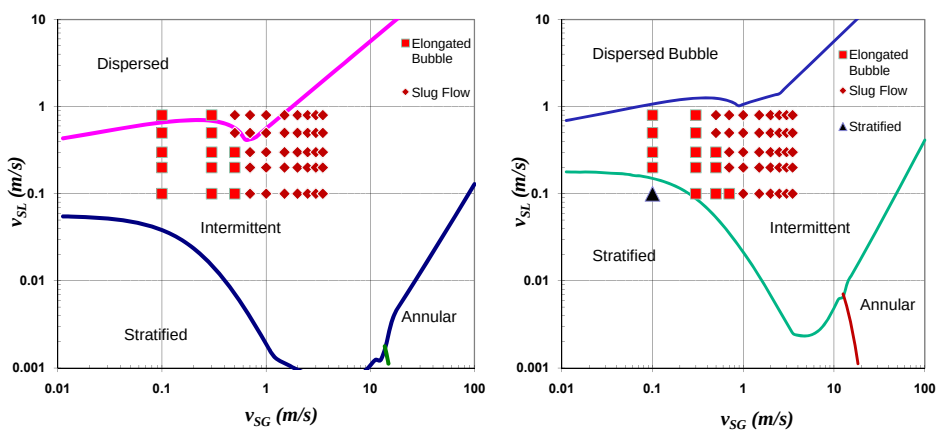
Inclination Effects- Horizontal vs. Downward Inclined 585 cP Viscosity Oil-Air Flow



Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

Downward Inclined Flow vs. TUFFP Model Prediction



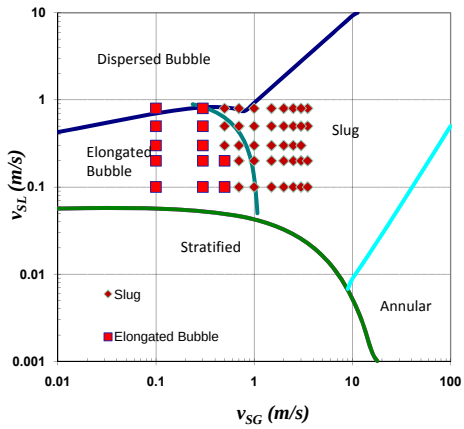
585 cP

181 cP

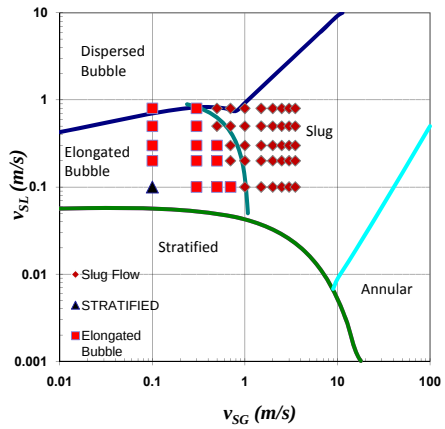
Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

Downward Inclined Flow vs. Barnea Model Prediction



585 cP



181 cP

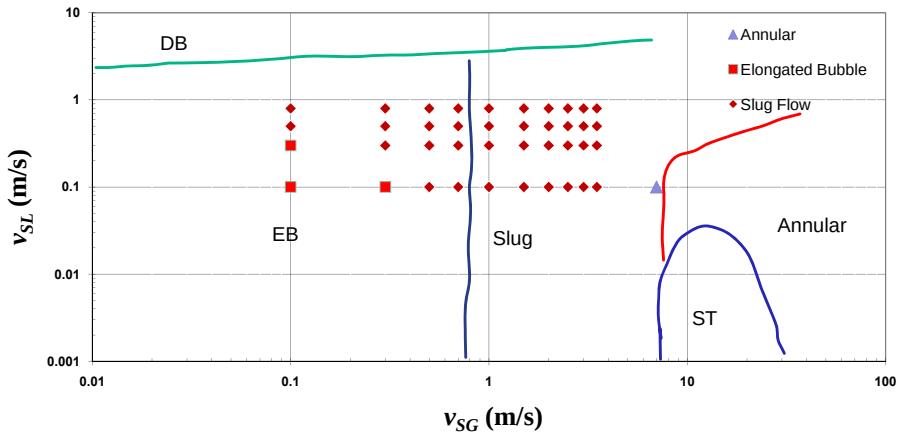
Fluid Flow Projects

1. Flow Patterns

B. Upward Inclined Flow

Advisory Board Meeting, October 26, 2011

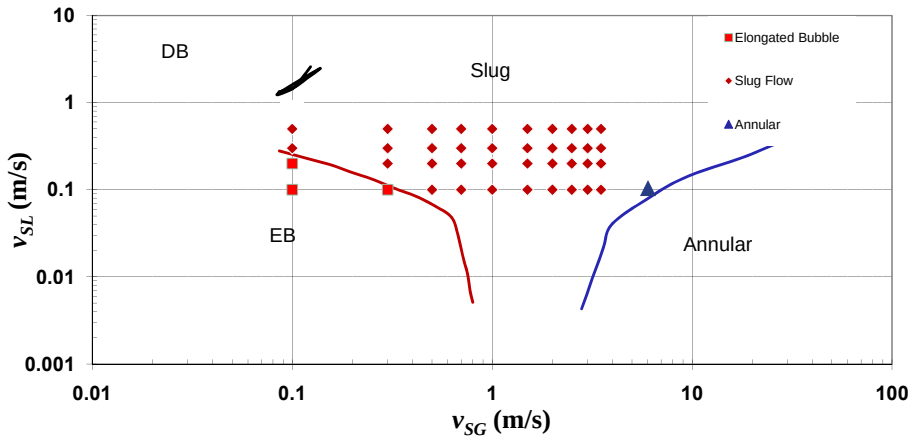
Viscosity Effects- 585 cP Viscosity Oil-Air vs. Water-Air Two-Phase Flow



Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

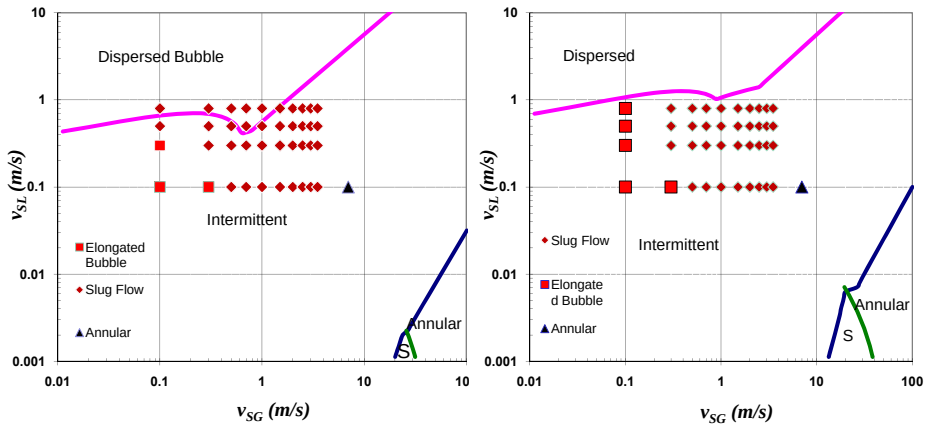
Inclination Effects- Horizontal vs. Upward Inclined 585 cP Viscosity Oil-Air Flow



Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

Downward Inclined Flow vs. TUFFP Model Prediction



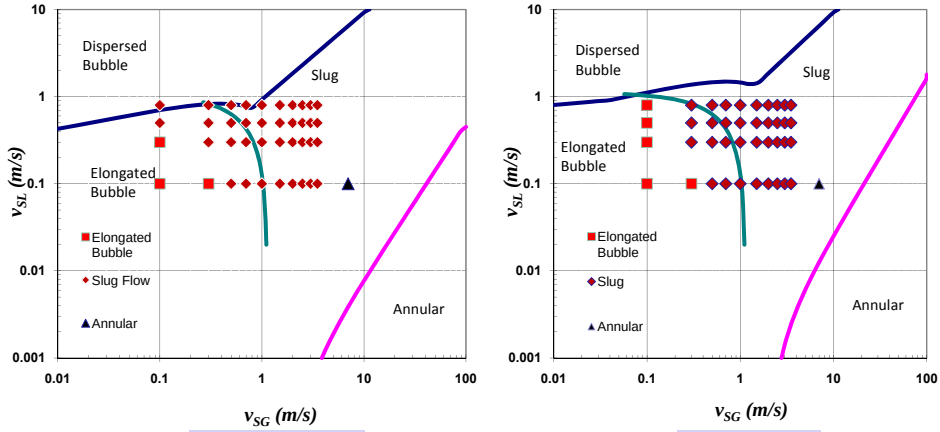
585 cP

181 cP

Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

Upward Inclined Flow vs. Barnea Model Prediction



585 cP

181 cP

Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

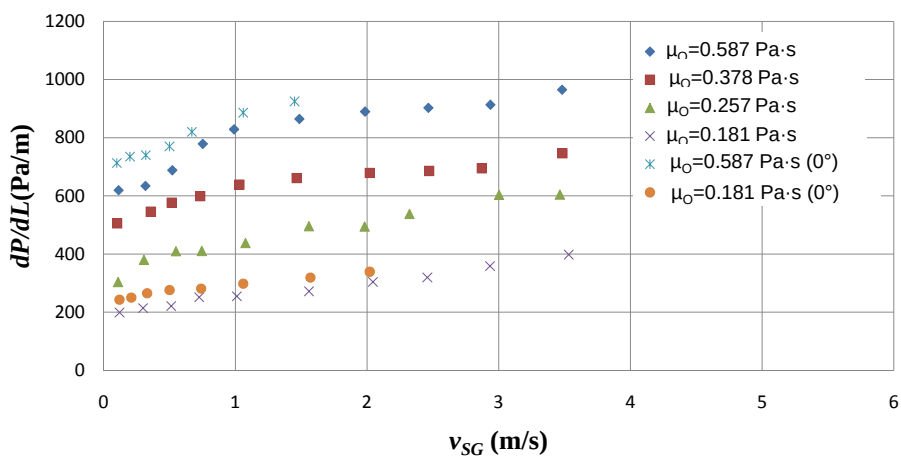
Fluid Flow Projects

2. Pressure Gradient

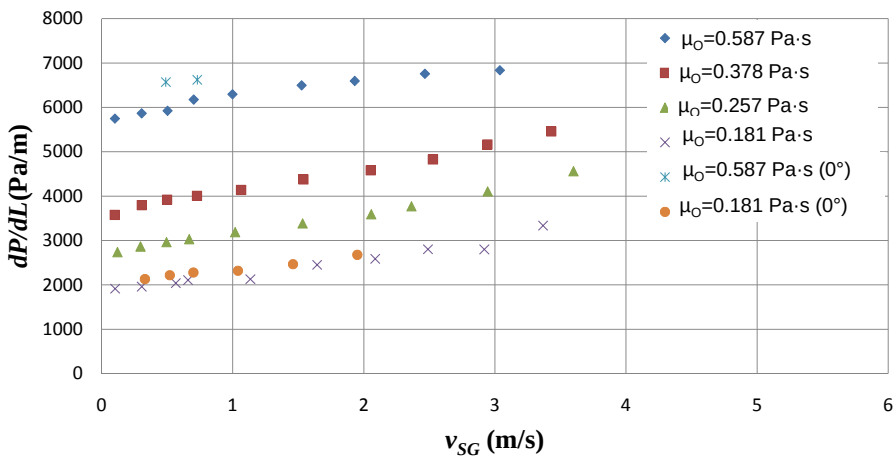
A. Downward Inclined Flow

Advisory Board Meeting, October 26, 2011

Inclination Effects- Pressure Gradients for v_{SL}=0.1 m/s



Inclination Effects- Pressure Gradients for v_{SL}=0.8 m/s



Error Analysis

Correlation/Model	Statistical Parameters					
	ε1 (%)	ε2 (%)	ε3 (%)	ε4 (Pa/m)	ε5 (Pa/m)	ε6 (Pa/m)
TUFFP Unified Model	-16.51	20.46	20.12	-129.91	285.89	368.10
OLGA-S	-42.49	42.60	21.14	-607.49	611.64	345.15
Xiao (1990)	-37.29	38.33	21.865	-511.37	556.23	413.03

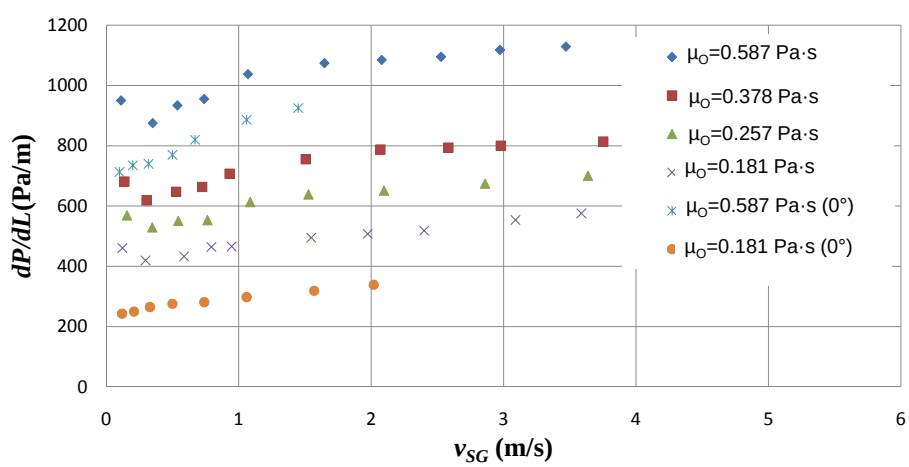
Fluid Flow Projects

2. Pressure Gradient

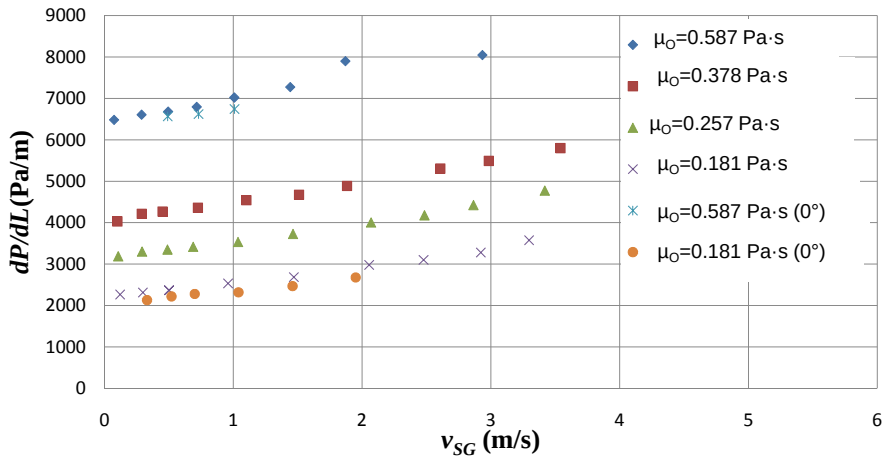
B. Upward Inclined Flow

Advisory Board Meeting, October 26, 2010

Inclination Effects- Pressure Gradients for v_{SL}=0.1 m/s



Inclination Effects- Pressure Gradients for v_{SL}=0.8 m/s



Error Analysis

Correlation/Model	Statistical Parameters					
	ε1 (%)	ε2 (%)	ε3 (%)	ε4 (Pa/m)	ε5 (Pa/m)	ε6 (Pa/m)
TUFFP Unified Model	-2.45	5.67	6.31	-34.46	131.04	192.37
OLGA-S	-10.64	12.15	9.52	-309.32	320.95	321.75
Xiao (1990)	-14.32	16.26	12.95	-400.16	426.56	469.45

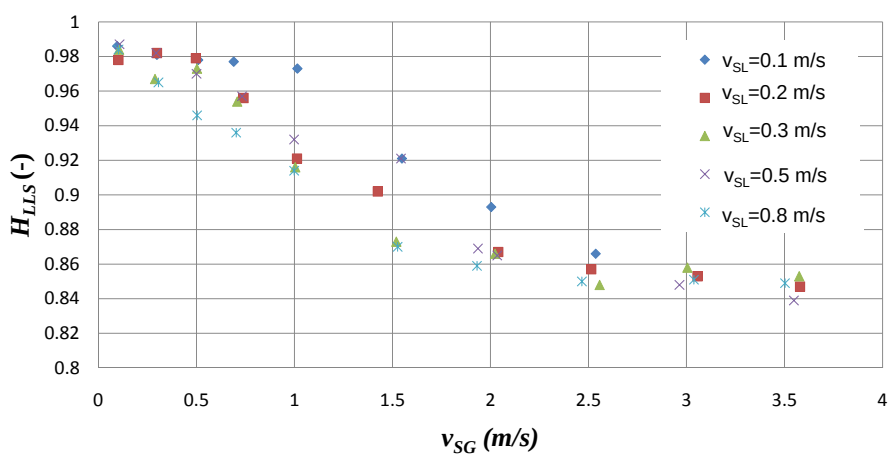
Fluid Flow Projects

3. Slug Liquid Holdup

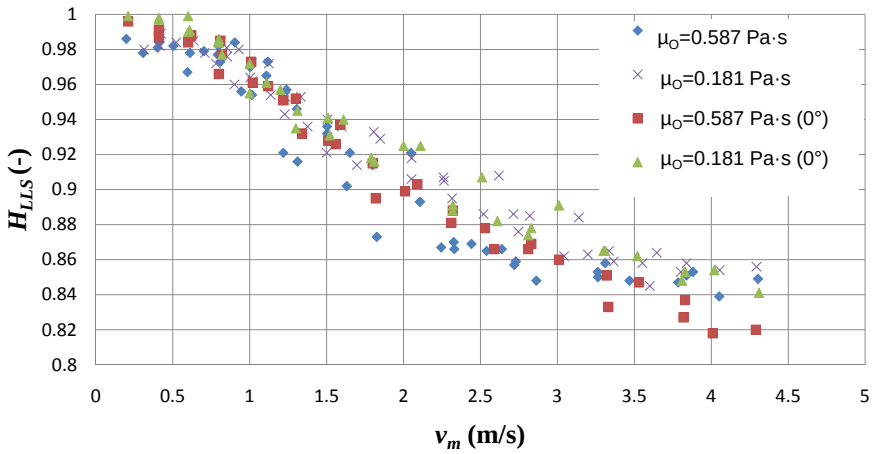
A. Downward Inclined Flow

Advisory Board Meeting, October 26, 2011

Velocity Effects- Slug Liquid Holdup for 585 cP Viscosity Oil-Air Flow



Inclination Effects- Downward and Horizontal Slug Liquid Holdup for v_{SL} = 0.3 m/s



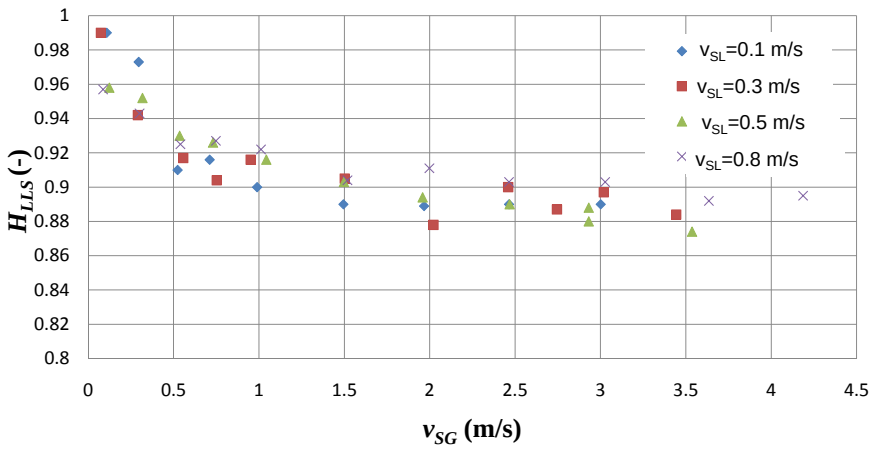
Fluid Flow Projects

3. Slug Liquid Holdup

B. Upward Inclined Flow

Advisory Board Meeting, October 26, 2011

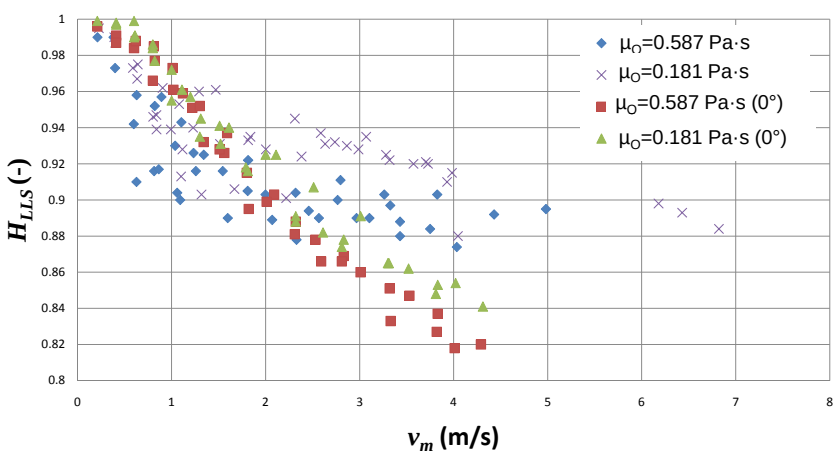
Velocity Effects- Slug Liquid Holdup for 585 cP Viscosity Oil-Air Flow



Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

Inclination Effects- Upward and Horizontal Slug Liquid Holdup for v_{SL} = 0.3 m/s



Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

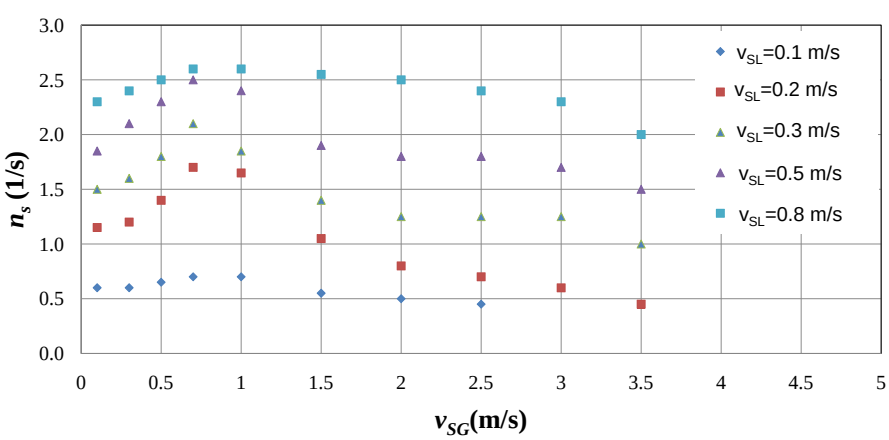
Fluid Flow Projects

4. Slug Frequency

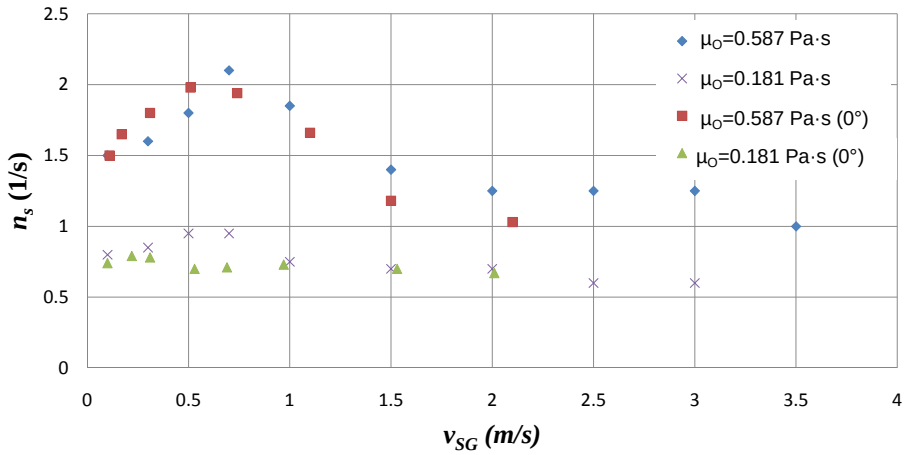
A. Downward Inclined Flow

Advisory Board Meeting, October 26, 2011

Velocity Effects- Slug Frequency for 585 cP Viscosity Oil-Air Flow



Downward Slug frequency Comparison with Horizontal for v_{SL} = 0.3 m/s



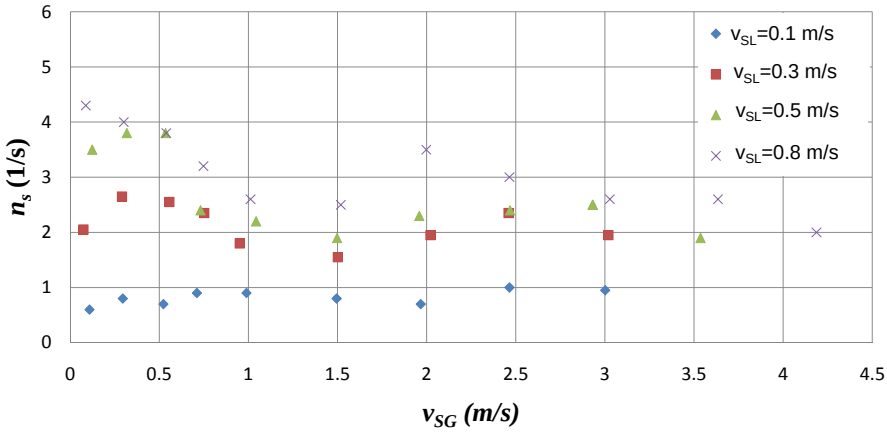
Fluid Flow Projects

4. Slug Frequency

B. Upward Inclined Flow

Advisory Board Meeting, October 26, 2011

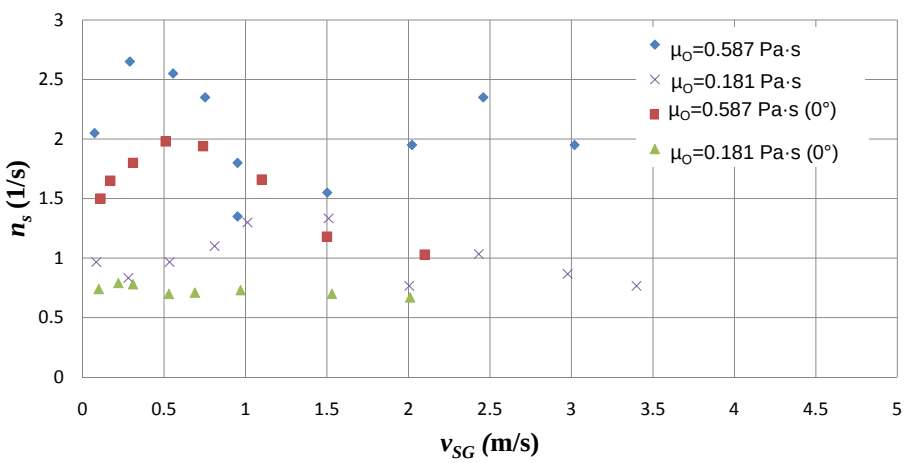
Velocity Effects- Slug Frequency for 585 cP Viscosity Oil-Air Flow



Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

Upward Slug frequency Comparison with Horizontal for v_{SL} = 0.3 m/s



Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

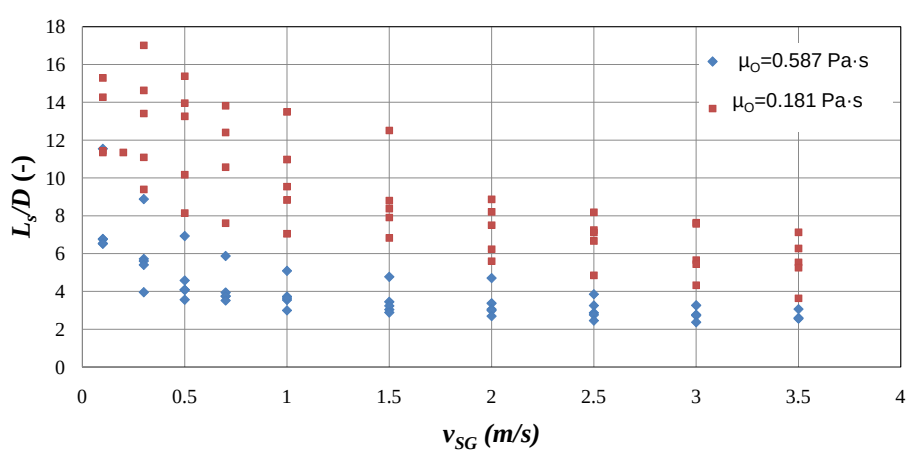
Fluid Flow Projects

5. Slug Length

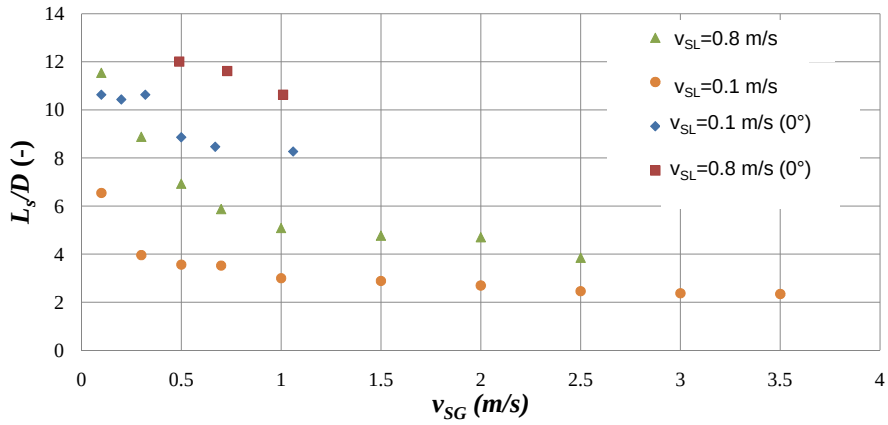
A. Downward Inclined Flow

Advisory Board Meeting, October 26, 2011

Viscosity Effects in Slug Length



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



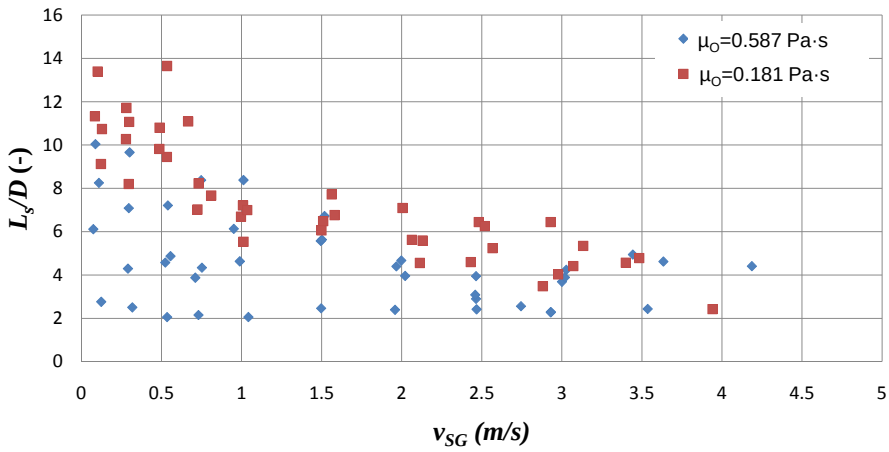
Fluid Flow Projects

5. Slug Length

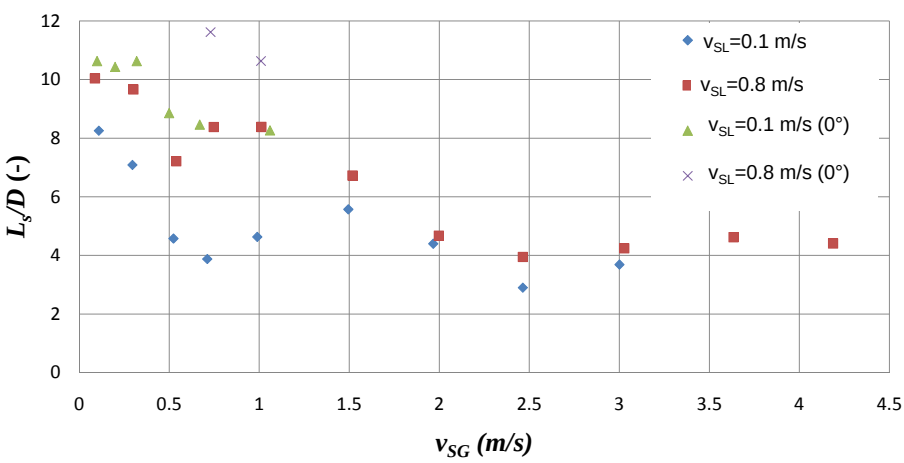
B. Upward Inclined Flow

Advisory Board Meeting, October 26, 2011

Viscosity Effects in Slug Length



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



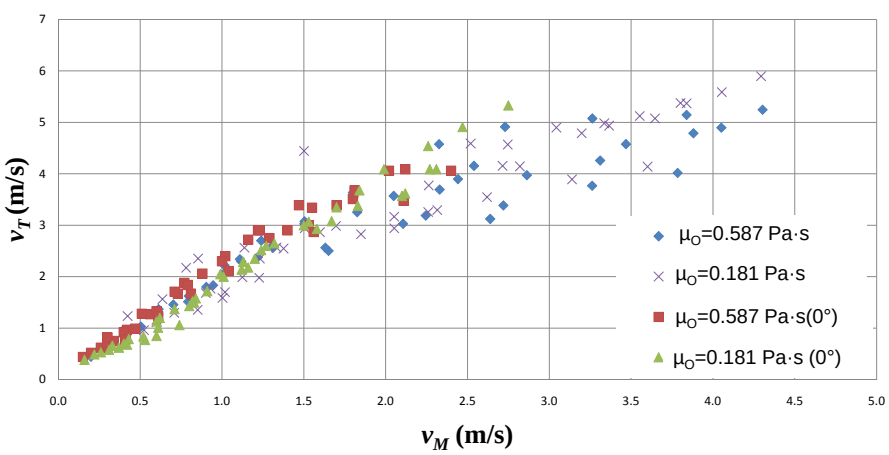
Fluid Flow Projects

6. Translational Velocity

A. Downward Inclined Flow

Advisory Board Meeting, October 26, 2011

Inclination Effects in Translational Velocity



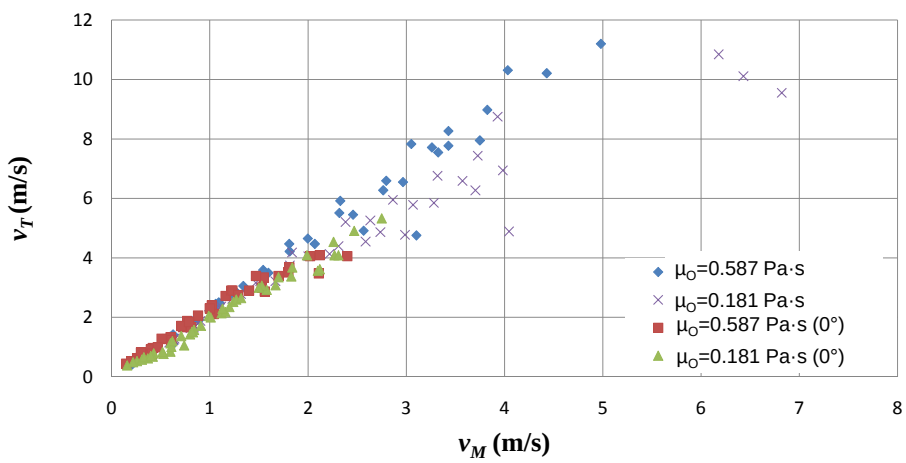
Fluid Flow Projects

6. Translational Velocity

B. Upward Inclined Flow

Advisory Board Meeting, October 26, 2011

Inclination Effects in Translational Velocity



Conclusion

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

Questions/Comments

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

Benin Chelinsky Jeyachandra

Project Completion Dates

Literature Review	Completed
Experimental Program for -2° Inclination	Completed
Facility Modification for +2° Inclination	Completed
Experimental Program for +2° Inclination	Completed
Data Evaluation	Completed
Final Report	Completed

Objectives

The main objectives of the study are

- Experimental study for pipe inclination angle effect on oil-gas two-phase with high oil viscosity
- Compare with models/correlations and suggest improvements if necessary

Introduction

An experimental study was conducted on the two-phase 50.8 mm ID high viscosity facility. The facility consists of heating and cooling systems, metering and an inclinable test section between -2° and 2°. The test section is made of acrylic pipe and instrumented with differential pressure, capacitance and laser sensors to obtain the flow characteristics. A high speed video camera was used for flow pattern identification and enhanced observations about the flow characteristics. A visual databank was created including recordings of each test conducted in this study.

A new ring type capacitance sensor was designed and built by TUFFP for this study. The capacitance sensor was calibrated in static and dynamic conditions using static section and quick closing valves, respectively. This calibration allows the measurement of average liquid holdup, slug liquid holdup and film thickness.

A total of 400 tests were carried out for different oil viscosities, upward and downward inclinations, and several superficial oil and gas velocities. The tests were performed at temperatures of 21.1, 26.7, 32.2 and 37.8 °C. The corresponding oil viscosities were 0.587, 0.378, 0.257 and 0.181 Pa·s, respectively. Superficial liquid and gas velocities varied from 0.1 to 0.8 m/s and 0.1 to 3.5 m/s (7 m/s in some cases), respectively.

A thorough data analysis was performed to understand the effects of high viscosity oil on flow pattern, pressure drop, average liquid holdup and slug characteristics, namely, slug length, slug frequency, translational velocity, slug liquid holdup, film holdup. Differences in flow behavior between high and low viscosity oils were identified. Experimental data were also used to evaluate the performances of different models and correlations

Activities Summary

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

Flow Pattern

For the downward inclined flow, stratified smooth, elongated bubble, slug flow patterns were observed. The increase in oil viscosity enhances the intermittency of the flow, and the downward inclination promotes the stratification of the phases. Stratified smooth flow was only seen at the lowest viscosity (0.181 Pa·s) and superficial gas and liquid velocity of 0.1 m/s. Elongated bubble and slug flows were observed for the other viscosities and velocities. Stratified wavy flow was not observed. A direct transition from stratified smooth to elongated bubble was noticed.

For the upward inclined flow, elongated bubble, slug flow and annular flow were observed. Annular flow was identified for all viscosities at v_{SL} = 0.1 m/s and v_{SG} = 7 m/s. Based on the analyses of the high speed videos, the film flow reversal did not take place at high superficial liquid velocities. Large and small entrained bubbles were detected in the liquid slug region. Large bubbles were observed at mixture velocities from 0.6 to 3.5 m/s. For both inclination angles, pseudo slugs were observed for v_m > 2m/s.

For both inclination angles, TUFFP unified model predicted the flow patterns better when compared with Taitel and Dukler (1976), Barnea (1987) models. For upward flow, observed annular flow was not predicted by any of the models.

Average Liquid Holdup

Liquid holdup decreased with an increase in superficial gas velocity for both inclination angles. No significant effect of high viscosity on liquid holdup was observed. Average liquid holdup for upward inclined pipe was higher compared to the

downward inclined pipe owing to gas slippage effects.

Experimental data for liquid holdup was compared against the TUFFP unified (Zhang, 2003), OLGA-S and Xiao (1990) models. Comparatively, the TUFFP unified model gave better results for liquid holdup in downward inclination and Xiao (1990) model gave better results for upward inclination.

Pressure Gradient

For downward inclined flow, pressure gradient monotonically increased with an increase in liquid viscosity. This became more pronounced with increasing superficial oil and gas velocities. The pressure gradient for downward flow was less compared with horizontal flow owing to the negating effect of gravitational pressure gradient.

For upward inclined flow and v_{SL} = 0.1 m/s, a decrease in pressure gradient is observed at low gas velocities and an increasing trend was observed for larger velocities. This phenomenon is due to the competing effects of gravitational and frictional pressure gradient. For higher superficial liquid velocities, pressure gradient increased with an increase in liquid viscosity. The total pressure gradient was higher compared to horizontal flow owing to the additional effect of gravitational pressure gradient.

Experimental data for pressure drop was compared against the TUFFP unified (Zhang, 2003), OLGA-S and Xiao mechanistic (1990) models. The TUFFP unified model gave much better results for pressure gradient compared to OLGA-S and Xiao (1990).

Translational Velocity

Translational velocity increases with increasing mixture velocity. The flow coefficient *Co* is almost 2.0, indicating the laminar flow expected in high viscosity-oil gas two-phase flow. But due to pseudo slug generation, a dispersion in translation velocity was observed after v_m > 2m/s. This dispersion was centered around *Co* = 2.0 for upward inclined flow but for downward inclined flow, dispersion is centered around *Co* = 1.2 indicating the existence of not fully developed slugs.

Experimental data for translational velocity was compared with Petalas and Aziz (2000), and Fabre (1994) correlations. There was a lot of discrepancy between the model and experimental data. For downward inclination, Petalas and Aziz (2000) correlation worked better while for upward inclinations, Fabre (1994) presented better agreement.

Slug Frequency

Slug frequency increases with increasing superficial liquid velocity and liquid viscosity. Moreover, slug frequency appears to be a strong function of liquid viscosity. When compared with horizontal, the inclined cases have higher slug frequencies, owing to inclination effects. As superficial gas velocity increases, the slug frequency increases, attains a peak and then decreases. Secondary peaking phenomena were observed with increase of superficial gas velocity for upward inclined pipes owing to higher generation of pseudo slugs.

The collected slug frequency data has been compared with TUFFP unified model, Gregory and Scott (1969), Hill and Wood (1990), Schulkes (2011) and Gokcal (2008) correlations. For both the inclination angles, Gokcal (2008) correlation performed better compared to other models/correlations.

Slug Length

Slug length decreases with the 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*D*-18*D* for downward inclined flow and 2*D*-14*D* for upward inclined flow. As v_M increases, the slug length decreased for both inclinations.

Slug Liquid Holdup

For both inclination angles and all oil viscosities, slug liquid holdup decreased with increasing superficial gas velocity. A slight decrease in slug liquid holdup was observed as superficial liquid velocity increases.

No significant change in slug liquid holdup was observed with changing oil viscosity from 0.587 to 0.181 Pa·s. Nevertheless, slightly high liquid holdups were observed at high mixture velocities for 0.181 Pa·s oil viscosity case. This may be due to the result of the decrease in entrained small bubbles at lower oil viscosities.

Experimental data for slug liquid holdup was compared against TUFFP unified model (2003), Gregory et al. (1978), Andreussi and Bendiksen (1989), Gomez et al. (2000), Barnea and Brauner (1985), Abdul-Majeed (2000), PDVSA (2010) and Kora (2010) correlation. For both upward and downward inclination, Kora (2010) correlation performed well even with the lack of term to explicitly consider the effect of inclination

Liquid Film holdup

A slight increase in liquid film holdup was observed with increasing liquid viscosity within 0.587 Pa·s to

0.181 Pa·s range. The liquid film holdup was higher in upward inclined pipe compared to the downward inclined pipe owing to slippage effects. At high superficial gas velocities, no significant effect of oil viscosity on liquid film holdup was observed.

Conclusions

Experimentation in -2° and +2° inclined two phase flow is completed. Existing instrumentation was used to observe and record the flow characteristics such as flow pattern, slug length, slug frequency, slug liquid holdup, translational velocity.

Nomenclature

D= internal diameter of the pipe [m]
v = velocity [m/s]
L = length [m]

Subscripts

G = gas phase
L = liquid phase
S = superficial, slug
M= mixture

References

Abdul-Majeed, G.: "Liquid Slug Holdup in Horizontal and Slightly Inclined Two-Phase Slug Flow," Journal of Petroleum Science and Engineering, 27, pp. 27-32 (2000).

Abduvayt, P., Arihara, N., Sharma, Y., and Yoshida, Y.: "A Mechanistic Model for Gas liquid Two-phase Flow in Slightly Inclined Pipes: To Improve Predictions of Flow Patterns and Pressure Drops," Japan Pet. Inst., Vol. 45, pp. 175-186 (2002).

Andreussi, P., Minervini, A., and Paglianti, A.: "Mechanistic Model of Slug Flow in Near-Horizontal Pipes," AIChE J., Vol.39, pp. 1281-1291 (1993).

Andritsos, N., Williams, L., and Hanratty, J.: "Effect of Liquid Viscosity on the Stratified-Slug Transition in Horizontal Pipe Flow," Int. J. Multiphase Flow, Vol. 15, pp. 877-892 (1989).

Barnea, D., Shoham, O., and Taitel, Y.: "Flow Pattern Transition for Gas-Liquid Flow in Horizontal and Inclined Pipes - Comparison of Experimental Data with Theory," Int.J. Multiphase Flow, Vol. 6, pp. 217-225 (1980).

Barnea, D.: "A Unified Model for Predicting Flow Pattern Transitions for The Whole Range of Inclinations," Int. J. Multiphase Flow, Vol. 13, pp. 1-12 (1987).

Barnea, D., and Taitel, Y.: "A Model for Slug Length Distribution in Gas-Liquid Slug Flow," Int. J. Multiphase Flow, Vol. 19, No. 5, pp. 829-838 (1993).

Gokcal, B., Wang, Q., Zhang, H. Q., and Sarica, C., 2006. 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.

Gokcal, B, Al-Sarkhi, A.S., and Sarica, C., 2008. Effects of High Oil Viscosity on Drift Velocity for Horizontal Pipes, Presented at BHRg Conference of Multiphase Production Technology, Banff, June 4-6.

Gomez, L.E., Shoham, O., Taitel, Y.: "Prediction of Slug Liquid Holdup: Horizontal to Upward Vertical Flow," Int. J. Multiphase Flow 26, 517–521 (2000).

Kora, Y. "Effects of high oil viscosity on slug liquid holdup in horizontal pipes," Ms Thesis, The University of Tulsa, Tulsa, OK. (2010).

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

Nadler, M., and Mewes, D.: "Effects of the Liquid Viscosity on the Phase Distributions in Horizontal Gas-Liquid Slug Flow," Int. J. Multiphase Flow, Vol. 21, No. 2, pp. 253-266 (1995).

Nydal, O. "An Experimental Investigation of Slug Flow" PhD Dissertation, University of Oslo. (1991).

Petalas, N., and Aziz, K.: "A Mechanistic Model for Multiphase Flow in Pipes," Presented at 49th Annual Technical Meeting of Petroleum Society of the Canadian Institute of Mining, Metallurgy and Petroleum, Paper 98-39, Calgary, Alberta, June 8-10, 1998.

Rosa, E.S., and Netto, J.R.F.: "Viscosity Effect and Flow Development in Horizontal Slug Flows," Paper No.306, Presented at 5th International Conference on Multiphase Flow, Yokohama, Japan, May 20-June 4, 2004.

Scott, S. L., Shoham, O., and Brill, J. P.: "Modelling Slug Growth in Large Pipe Diameter Pipes," Paper B2, Presented at 3rd International Conference on Multiphase Flow, The Hague, May 18-20, 1987.

Fluid Flow Projects

Downward Two-Phase Stratified Flow for Highly Viscous Oils

R. Brito, E. Pereyra and C. Sarica

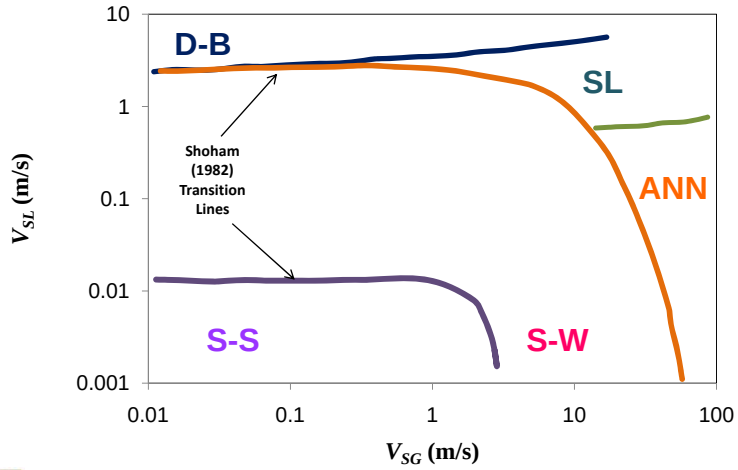
Advisory Board Meeting, October 26, 2011

Outline

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

Introduction

- Observed Flow Pattern vs. Shoham (1982) Data

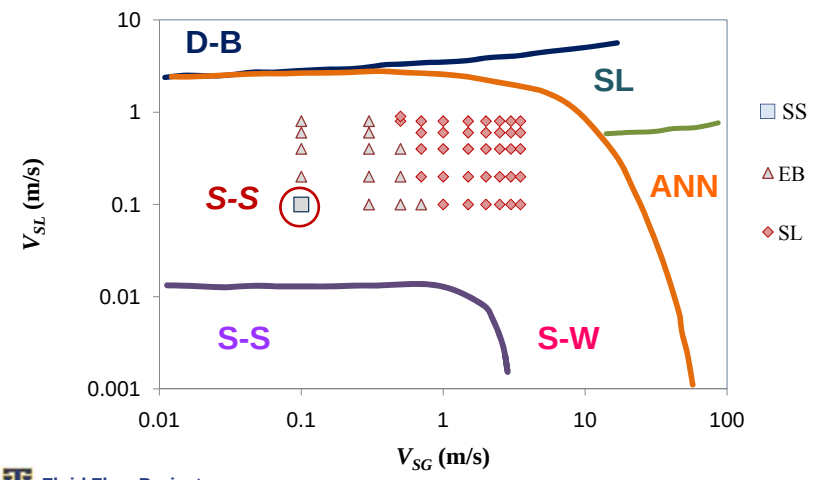


Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

Introduction

- Observed Flow Pattern vs. Shoham (1982) Data



Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

Objective

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

Outline

- Introduction
- Objective
- *Experimental Program and Results*

Experimental Program

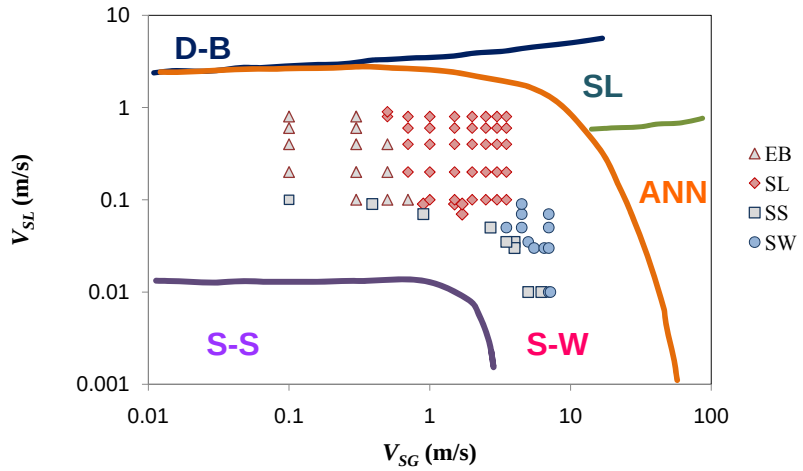
- 2-in ID High Viscosity Indoor Facility
- Superficial Liquid Velocity
  - 0.01 – 0.8 m/s
- Superficial Gas Velocity
  - 0 – 7.2 m/s
- Inclination
  - Downward (-2°)

Experimental Program …

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

Experimental Results

- Observed Flow Pattern vs. Shoham (1982) Data



Outline

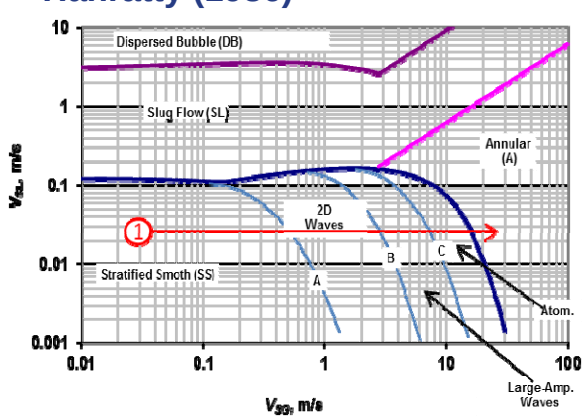
- Introduction
- Objective
- Experimental Program and Results
- ***Wave Pattern for Stratified Region***

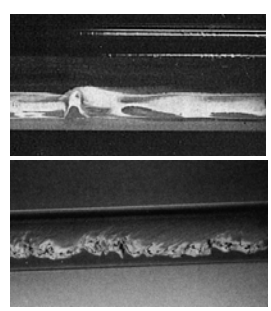
Wave Pattern

- Andritsos and Hanratty (1986)
  - Studied the Interfacial Instability of Stratified Horizontal Flow
  - μ_o= 1 cP – 70 cP
  - Three Types of Instabilities has been Observed
    - 2-D Small Amplitude Waves
    - Irregular Large Amplitude Waves
    - Atomization
  - 2-D Waves Region Attenuates as Liquid Viscosity Increases

Wave Pattern…

- Interfacial Instabilities after Andritsos and Hanratty (1986)

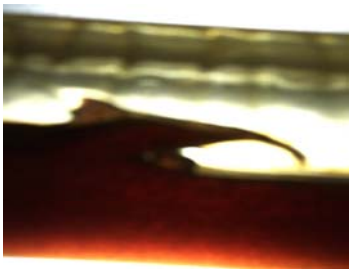




Wave Pattern…

- **Large Amplitude Waves**

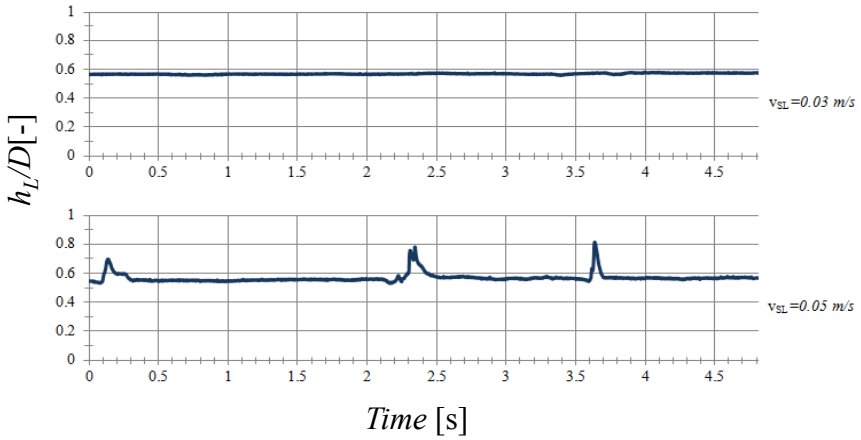
Long Waves
v_{SG}=5.5 m/s and v_{SL}=0.03 m/s



Breaking Waves
v_{SG}=4.5 m/s and v_{SL}=0.09 m/s

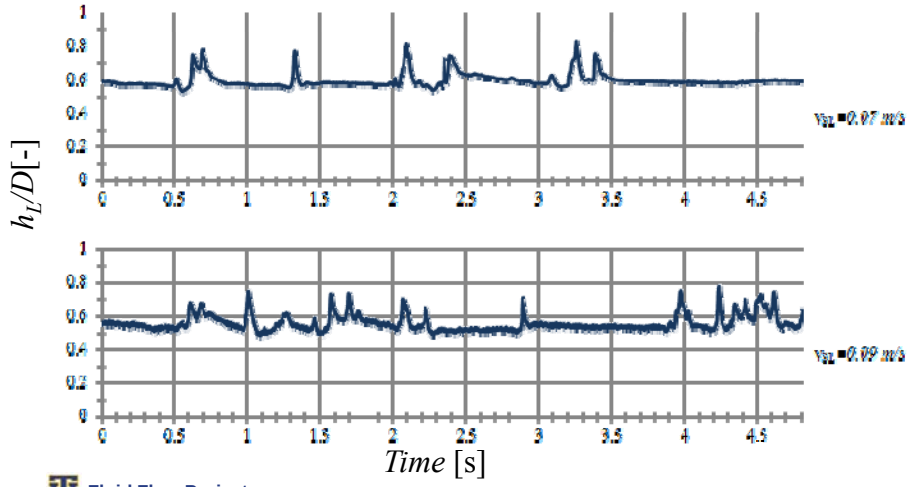
Wave Pattern…

- **Film Thickness Time Traces for v_{SG}=4.5 m/s**



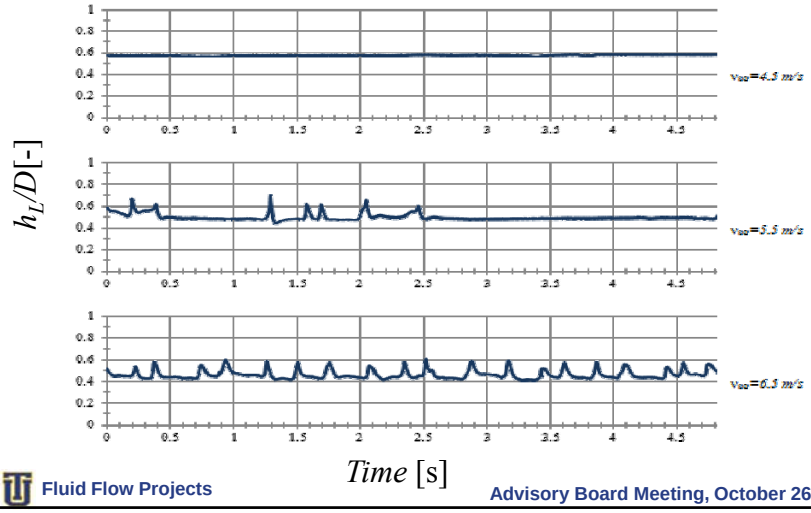
Wave Pattern…

- Film Thickness Time Traces for v_{SG}=4.5 m/s



Wave Pattern…

- Film Thickness Time Traces for v_{SL}=0.03 m/s

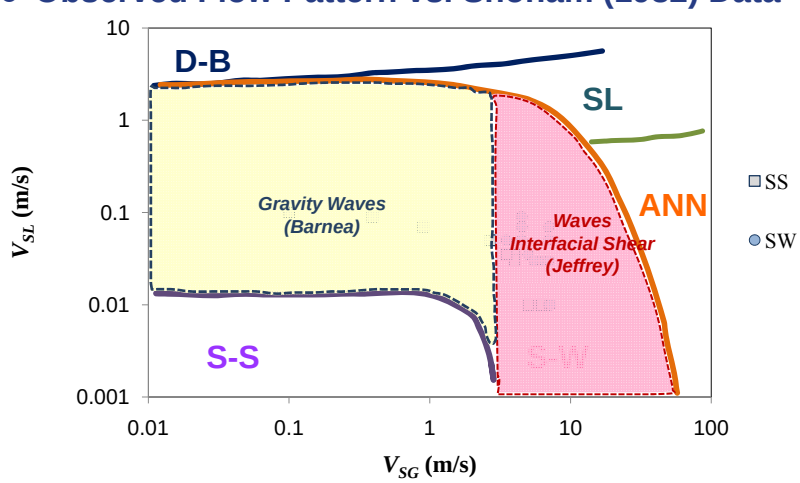


Outline

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

Stratified Smooth – Stratified Wavy

- **Observed Flow Pattern vs. Shoham (1982) Data**



Stratified Smooth – Stratified Wavy…

- Jeffrey's Theory

Potential Flow Field

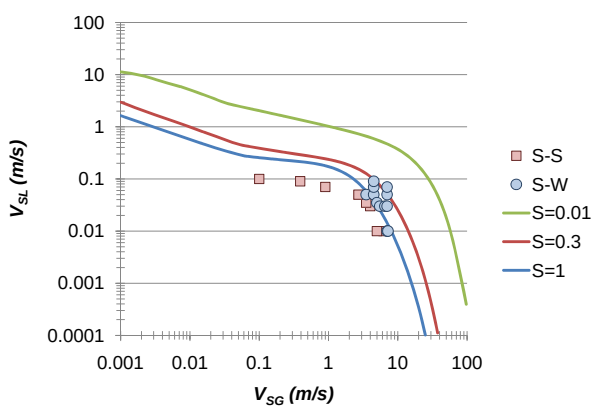
Pressure and Shear Forces > Viscous Dissipation of Waves

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

s: fraction of wave exposed to the action of the wind

Stratified Smooth – Stratified Wavy …

- Sheltering Coefficient Sensitivity



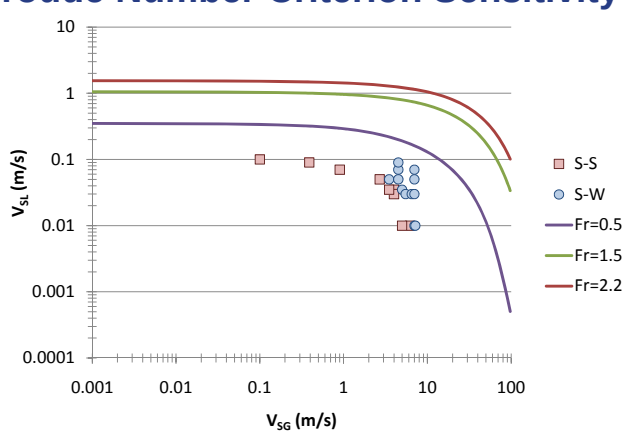
Stratified Smooth – Stratified Wavy …

- Barnea *et al.* (1982)
  - Waves Generated by Gravity in Downward Flow

$$Fr = \frac{v_L}{\sqrt{g\,h_L}} \geq 1.5$$

Stratified Smooth – Stratified Wavy …

- Froude Number Criterion Sensitivity

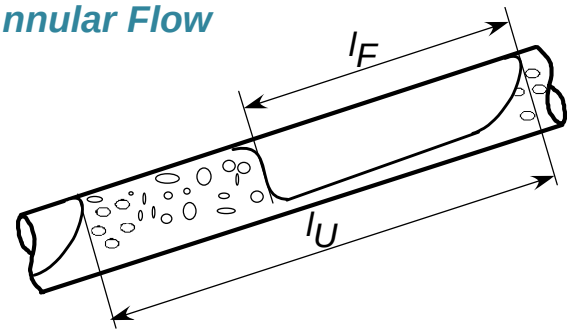


Outline

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

Stratified – Non-Stratified

- **Slug Flow Stability Analysis (Zhang *et al.*, 2003)**
  - $l_F / l_U > 1$ ***Transition to Stratified or Annular Flow***

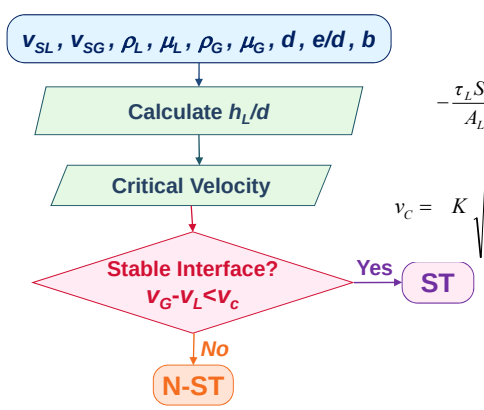


Stratified – Non-Stratified …

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

Stratified – Non-Stratified …

- Stability of the Gas-Liquid Interface



$$-\frac{\tau_L S_L}{A_L}+\frac{\tau_G S_G}{A_G}+\tau_i S_i\left(\frac{1}{A_L}+\frac{1}{A_G}\right)-(\rho_L-\rho_G)g\ \sin\beta=0$$

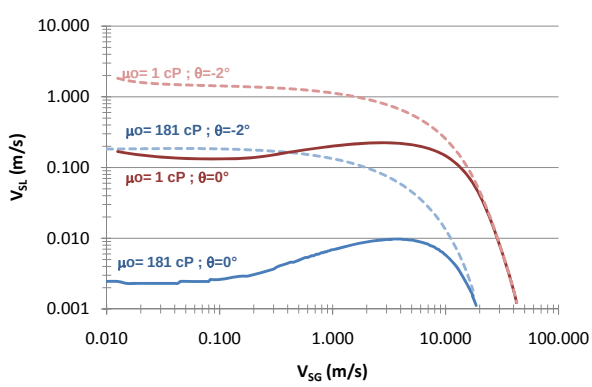
$$v_C = K\sqrt{(\rho_L(1-H_L)+\rho_G H_L)\left[\frac{(\rho_L-\rho_G)}{\rho_L\rho_G}g\cos(\theta)\frac{A}{dA_L/dh_L}\right]}$$

Stability Analysis Models

Model	Considerations	*K*
Taitel &Dukler (1976)	Suction force ≥ Gravity Force	$K = \left(1 - \frac{h_L}{d}\right)$
IKH **Barnea (1991)**	Do not consider viscous effect on stability analysis.	$K=1$
VKH **Barnea (1991)**	Consider the viscous effect using the shear stresses between the wall and each phase.	$K = \sqrt{1 - \frac{(C_V - C_W)^2}{\frac{(\rho_L - \rho_G)}{\rho}} g\cos(\theta) \frac{A}{dA_L / dh_L}}$

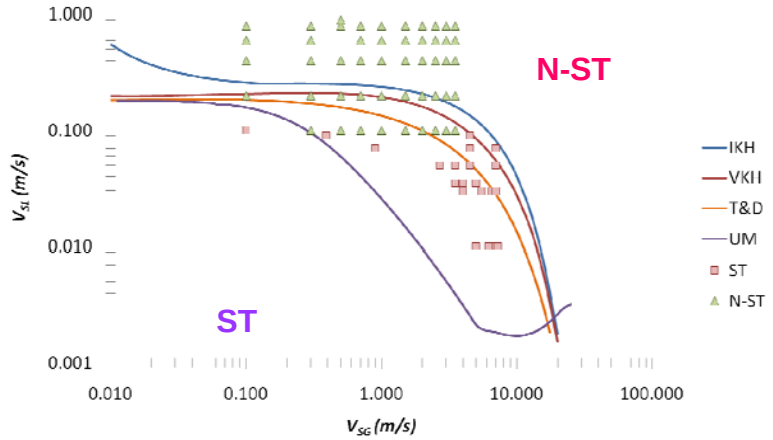
Stability Analysis Model …

- **Taitel and Dukler (1976) Sensitivity Analysis**



Stratified – Non-Stratified …

- Model Comparison



Outline

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

Conclusions

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

Conclusions …

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

Future Tasks

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

Thanks …

Questions

Downward Two-Phase Stratified Flow for Highly Viscous Oils

Brito, R., Pereyra, E., and Sarica, C.

Objective

The objective of this study is to investigate experimentally and theoretically the transition boundary from Stratified-Smooth (SS) to other flow patterns during the flow of highly viscous oil -gas two phase flow in downward pipe.

Introduction

For stratified region, depending on the interaction between the gas and liquid, different types of waves are formed at the interface affecting the pressure drop and liquid holdup. Andritsos and Hanratty (1986) experimentally observed three types of instability occurring within the stratified flow region, namely, 2D waves, large amplitude waves and atomization of the liquid. For stratified smooth conditions, a flat interface is observed, any disturbance wave attenuates and disappears. Small-amplitude 2D waves occur at medium gas velocities. For higher gas flow rates, irregular large-amplitude waves can be present. With the large-amplitude waves, droplets or liquid filaments are sheared out of the wave crest and deposited on the pipe walls. The initiation of the atomization is defined as the gas velocity at which droplets start hitting the top of the pipe.

As liquid viscosity increases, Andritsos and Hanratty (1986) observed that the transition from stratified smooth to 2D waves shift towards the right (transition occurs at higher superficial liquid velocities) reducing the occurrence of small amplitude waves. The effect of the viscosity on the two other transitions (large-amplitude waves and atomization) is negligible.

This summary describes the experimental and modeling study to evaluate the phenomenon of stratified flow for downward highly viscous two-phase flow.

Experimental Program

The indoor high viscosity test facility is comprised of an 18.9-m long, 50.8-mm ID pipe with a 9.15-m long transparent acrylic pipe section to visually observe the flow. The test section was inclined -2° from horizontal. Prior to each test, the temperature of the oil tank is set to the desired temperature. Air and viscous mineral oil were used as test fluids. The fluids were combined at the mixing tee, flowed through the test section and returned to the oil storage tank.

Transparency of the acrylic pipe allows visual observations of the flow behavior. A high speed video system is used to observe the transition from Stratified Smooth to Stratified Wavy.

The acrylic test section is instrumented with pressure and differential pressure transducers, thermocouples, capacitance sensors and quick closing valves. A two wire capacitance sensor was installed ahead of the new quick-closing valve system.

Superficial liquid and gas velocities range from 0.01 m/s to 0.8 m/s and from 0 to 7.2 m/s, respectively. The experiments were performed at temperature 100 °F. The oil viscosity corresponding to the above temperature is 0.181 Pa·s.

A two-wire capacitance sensor was installed close to the quick closing valve system, to determine the liquid holdup. Capacitance sensor works on the principle of difference in dielectric values between two different phases.

Experimental Results

The flow pattern characterization was carried out by visual observation, high speed videos and time traces from the capacitances sensors. The observed flow patterns were compared with the transitions lines reported by Shoham (1982) for air-water flows in a -2° downward inclined 2-in pipe.

For low superficial velocities, the liquid phase travels at the bottom of the pipe and the gas phase on top generating a flat interface free of any disturbance wave. As the gas velocity increases, the formation of long solitary waves has been observed, namely, stratified wavy. For high viscosity oil, small-amplitude 2D waves have not been observed and a direct transition from stratified smooth to long-amplitude wave occurs. This result is in agreement with Andritsos and Hanratty (1986) observation that the small-amplitude wave region reduces as the liquid viscosity increases.

For air-water (Shoham, 1982) the downward inclination promotes wave formation at the interface increasing stratified wavy region. For this case the transition occurs from stratified wavy to slug or elongated bubble flow. For the high viscosity liquid, a transition from stratified smooth to intermittent

flow occurs at low gas velocities. The small-amplitude waves generated by the gravity effects are attenuated by the large liquid viscosity. Additionally, the air-water data shows a direct transition from stratified wavy to dispersed bubble flow, which is not seen in the high viscosity liquid case.

Analysis of the dimensionless film thickness traces indicates that the wave frequency increases as the liquid and gas superficial velocity increases.

Breaking waves have been observed for the largest gas and liquid superficial velocity. For these conditions, the gas shears off liquid lumps form the crest of the wave, which falls back on the side walls of the pipe. This liquid drains back to bottom of the pipe creating a film similar to that of annular flow. The gas does not have enough energy to break the lump of liquid in such small droplets, which can reach the top of the pipe. Thus, the film does not cover the entire perimeter and the axial velocity of the liquid is negligible. This region corresponds to the initiation of the atomization region described by Andritsos and Hanratty (1986). Increasing the gas superficial velocity provide enough turbulent kinetic energy to break the lumps of liquid into small droplets, which can be transported to the top of the pipe. Further increase of gas flow rate promotes the droplet deposition at the top of the pipe, increasing the film thickness around the wall resulting in annular flow. In this study neither atomization nor annular flow region has been observed.

Stratified Smooth- Stratified Wavy

Jeffreys (1926) theory establishes a criterion to determine the transition between stratified-smooth to stratified-wavy, where a sheltering coefficient, *s*, expresses the amount of a wave that is exposed to the action of the wind, and this means that *s* value should be lower than or equal to one.

Different sensitivities in the sheltering coefficient were performed in order to match the experimental data and Jeffrey's (1926) criterion, the obtained *s* value was 1.0, this criterion assumes that waves are generated by the interfacial shear stress between phases.

For downward inclined flow, Barnea *et al.* (1982) proposed a critical Froude number criterion to account for gravity waves induced by the inclination. When compared with the experimental data, it can be concluded that any gravity wave is attenuated by the viscosity. Therefore, Barnea *et al.* (1982) criterion is not required for the viscosity and inclination angle considered in this study.

Stratified – Non Stratified

The occurrence of stratified flow can be predicted either by analyzing the stability of the slug flow or the gas-liquid interface. Zhang *et al.* (2003) proposed a slug flow stability analysis which can be utilized to describe the transition between slug and stratified flow. On the other hand, the stability of the gas-liquid interface can be determined by Kelvin-Helmholtz analysis. This analysis begins with a linearization of the two-fluid model combined momentum equation. After perturbing the linear model with a monochromatic wave, the relation for stratified to non-stratified flow is defined by the marginal stability.

Taitel and Dukler (1976) presented a simplified approach to the Kelvin-Helmholtz analysis, where the effect of the surface tension is neglected. The condition for wave growth, leading to instability of the stratified configuration, is when the suction force is greater than the gravity force.

Later, Barnea and Taitel (1993) solved the marginal stability for two cases, the first one neglecting the viscous effect (IKH) and the second one considering viscous effect (VKH).

Comparing with the experimental data, Taitel and Dukler (1976) model presents the best performance, followed by the viscous and inviscid analyses, respectively. Zhang *et al.* (2003) under predicts this transition owing to the slug length closure relationship which is independent of the liquid viscosity.

Conclusions

For the liquid viscosity of 181 cP and inclination angle of -2° considered in this study, no gravity waves have been observed. Any instability caused by the pipe inclination is attenuated by the large liquid viscosity yielding in a flat interface. Based on this, Barnea *et al.* (1982) criterion does not apply for these conditions, and Jeffreys (1926) model requires a sheltering coefficient equal to 1 to match the experimental data.

Taitel and Dukler (1976) model shows the best performance predicting the stratified to non-stratified transition. Transition from Stratified to Dispersed Bubble has not been observed as compare with downward air-water two-phase flow. Further experimental studies are required at medium liquid viscosities to analyze the gradual effect of the viscosity over the parameters considered in this study.

References

Andritsos, N., Hanratty, T.: "Interfacial Instabilities for Horizontal Gas-Liquid Flows in Pipelines". Int. J. Multiphase Flow. v 13. n 50. pp. 583-603. (1986).

Barnea, D., Shoham, O., and Taitel, Y.: “Flow-Pattern Transition for Downward Inclined Two-Phase Flow; Horizontal to Vertical”. Chem. Eng. Sci. 37, 735. (1982).

Barnea, D. and Taitel, Y.: "Kelvin-Helmholtz Stability Criteria for Stratified Flow, Viscous Versus Non-Viscous (Inviscid) Approaches". Int. J. Multiphase flow, Vol. 19, pp. 639-649.(1993).

Jeffreys, H.: “On the Formation of Water Waves by Wind”. Proc., IBID Royal Soc., London, Great Britain A110, 241.(1926).

Shoham, O.: “Flow-Pattern Transition and Characterization in Gas-Liquid Two-Phase Flow in Inclined Pipes”. PhD dissertation, Tel-Aviv University, Israel.(1982).

Taitel, Y. and Dukler, A.: "A Model for Predicting Flow Regime Transitions in Horizontal and near Horizontal Gas-Liquid Flow". AIChE J., Vol. 22, pp. 47-55. (1976).

Zhang, G., Wang, Q., Sarica, C., Brill, J.: "Unified Model for Gas-Liquid Pipe Flow via Slug Dynamics—Part 1: Model Development". JERT. Volume 125, Issue 4, pp.266-273. (2003).

Fluid Flow Projects

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

Rosmer Brito

Advisory Board Meeting, October 26, 2011

Outline

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

General Objective

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

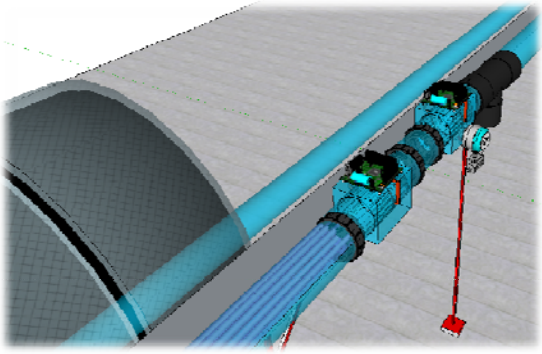
Specific Objective

- Data Analysis Process

Specific Objectives …

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

Fluid Flow Projects



Experimental Program

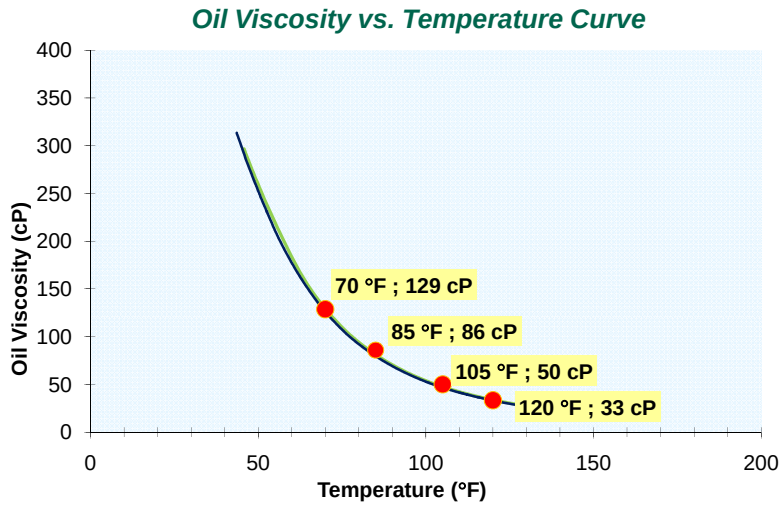
Experimental Facility

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

Test Oil Characteristics

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

Test Oil Characteristics …

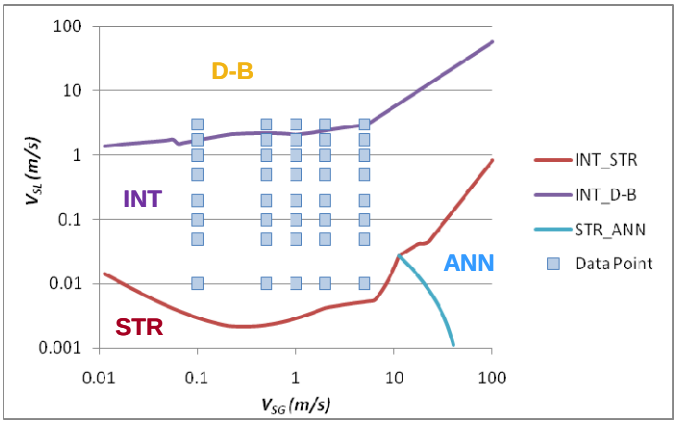


Experimental Matrix

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

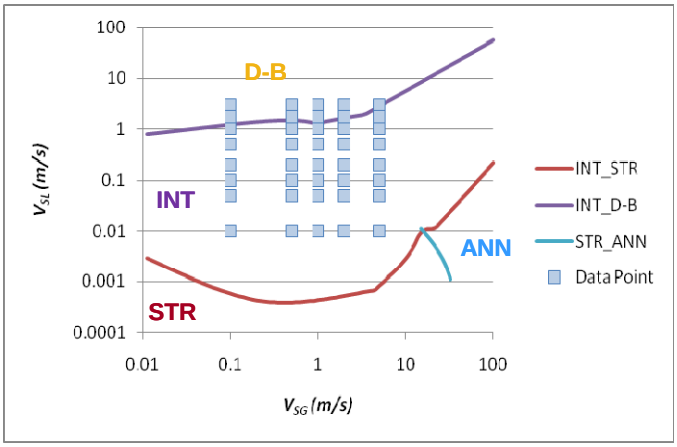
Experimental Matrix …

Flow Pattern Map 33 cP. TUFFP Unified Model



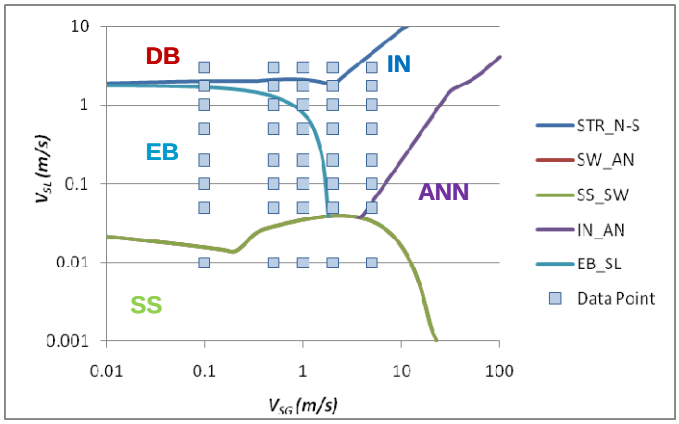
Experimental Matrix …

Flow Pattern Map 129 cP. TUFFP Unified Model



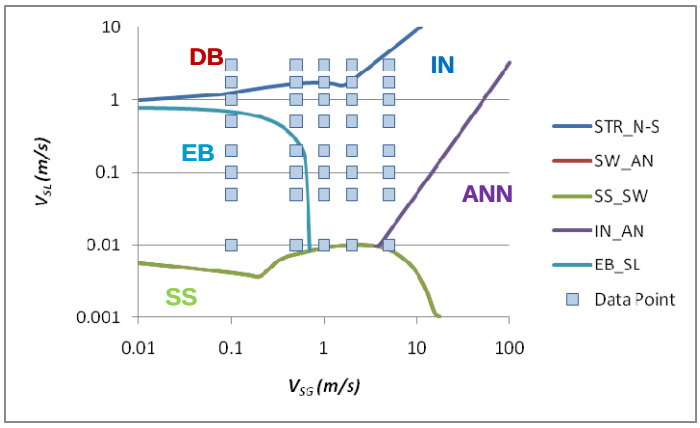
Experimental Matrix …

Flow Pattern Map 33 cP. Barnea Model

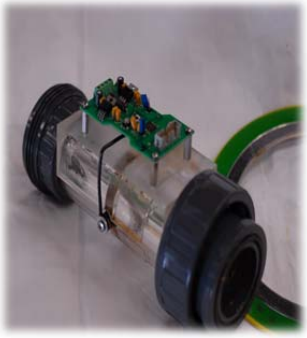


Experimental Matrix …

Flow Pattern Map 129 cP. Barnea Model



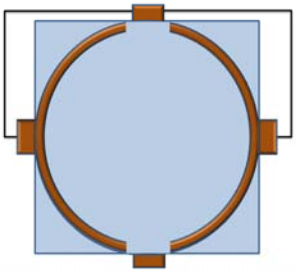
Fluid Flow Projects



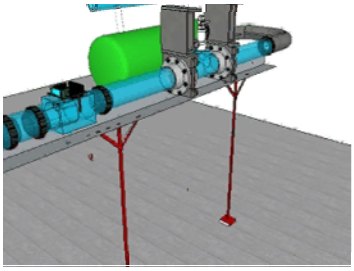
Capacitance Sensor

Advisory Board Meeting, October 26, 2011

Capacitance Sensor



Ring Type Capacitance Sensor



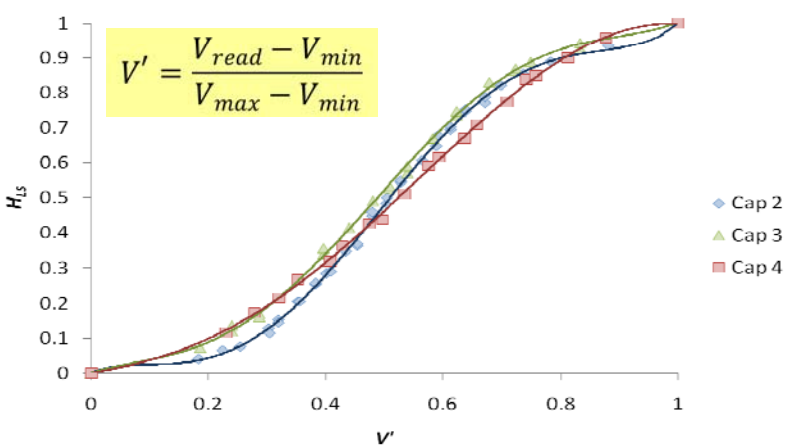
Capacitance Sensors Location

Capacitance Sensor Static Calibration

Static Calibration

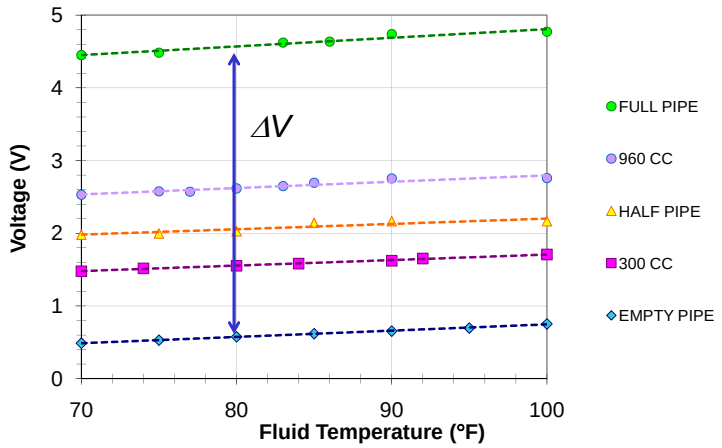
Capacitance Sensor Static Calibration …

Static Calibration Curve



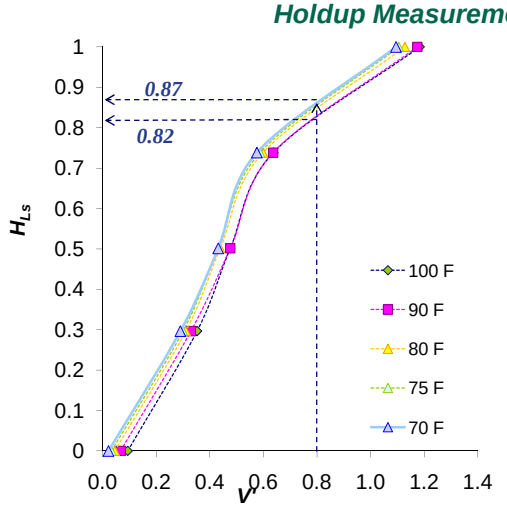
Fluid Temperature Effect

Output Voltage vs. Fluid Temperature Curve



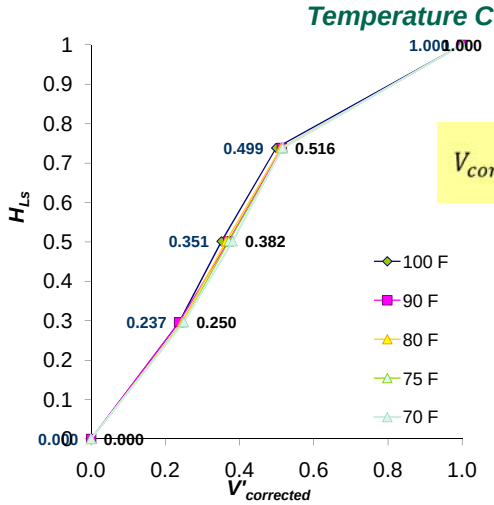
Fluid Temperature Effect …

Holdup Measurement Discrepancy



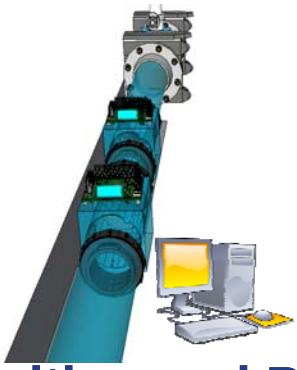
$$V' = \frac{V_{read} - V_{\min @ 70^\circ F}}{V_{max @ 70^\circ F} - V_{\min @ 70^\circ F}}$$

Fluid Temperature Effect ...



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

Fluid Flow Projects



Data Acquisition and Processing

Input Data
Quality Validation and Setup

Test Name:
Test Description:

Signal	Max	Min	Length (m)
Cap 1	4.7	2.4	0.3
Cap 2	5	3.9	0.35
Cap 3	4.7	2.4	10
Cap 4	5	3.9	10.5
Cap 5	4.7	2.4	20
Cap 6	5	3.9	20.5
Laser 1	4.7	2.4	
Laser 2	5	3.9	

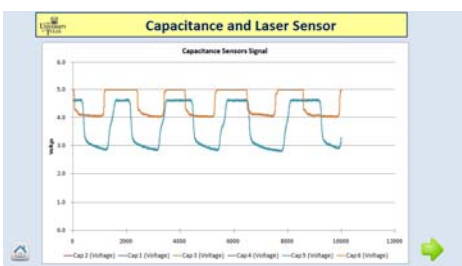
Pipe ID (m)	0.0508
Time Delay	0.001
L1-L2 (m)	0.2794
Cap 1-2 (m)	0.2794
Cap 3-4 (m)	0.2794
Cap 5-6 (m)	0.2794

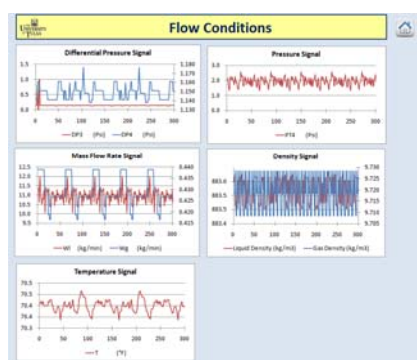
SETUP
IMPORT DATA
CAPACITANCE AND LASER SIGNAL
FLOW CONDITIONS
THRESHOLD ANALISYS
AIR PROPERTIES UNCERTAINTY
CLEAR

Input Data

Row	Time	DP3 (Psi)	DP4 (Psi)	PT4 (Psi)	T (°F)	Wl (kg/min)	Wg (kg/min)	ρl (kg/m3)	ρg (kg/m3)	Cap 2 (Voltage)	Laser 1 (Voltage)	Laser 2 (Voltage)	Cap 1 (Voltage)	Cap 3 (Voltage)	Cap 4 (Voltage)	Cap 5 (Voltage)	Cap 6 (Voltage)
1	13:43:0	0.134	1.14084	2.12064	70.4083	11.3456	0.43885	883.549	9.71851	4.98286	4.59941	4.98286	4.59941	4.59941	4.98286	4.59941	4.98286
2	13:43:0	0.151	1.14084	2.15579	70.4183	11.3772	0.43885	883.564	9.71851	4.98286	4.60705	4.98286	4.60705	4.60705	4.98286	4.60705	4.98286
3	13:43:0	0.150	1.14084	1.77869	70.4183	10.6272	0.43885	883.574	9.71851	4.98477	4.61087	4.98477	4.61087	4.61087	4.98477	4.61087	4.98477
4	13:43:0	0.803	1.15444	1.56579	70.4183	11.3916	0.43885	883.464	9.72851	4.98095	4.58859	4.98095	4.58859	4.58859	4.98095	4.58859	4.98095
5	13:43:0	0.364	1.16084	1.33579	70.4083	11.9972	0.43885	883.464	9.71351	4.98286	4.60195	4.98286	4.60195	4.60195	4.98286	4.60195	4.98286
6	13:43:0	0.011	1.16084	1.49579	70.4083	11.3972	0.43885	883.48	9.70851	4.98286	4.62423	4.98286	4.62423	4.62423	4.98286	4.62423	4.98286
7	13:43:0	0.00023	1.16084	2.12001	70.4183	10.9872	0.43885	883.454	9.70851	4.98413	4.62742	4.98413	4.62742	4.62742	4.98413	4.62742	4.98413
8	13:43:0	1.0044	1.16084	2.28579	70.4183	10.6457	0.43885	883.454	9.70851	4.98222	4.62233	4.98222	4.62233	4.62233	4.98222	4.62233	4.98222
9	13:43:0	1.00011	1.15084	2.18914	70.4044	10.5272	0.43885	883.454	9.72851	4.98413	4.61023	4.98413	4.61023	4.61023	4.98413	4.61023	4.98413
10	13:43:0	0.1439	1.15084	2.05579	70.3983	10.6172	0.43885	883.454	9.71851	4.98286	4.60259	4.98286	4.60259	4.60259	4.98286	4.60259	4.98286
11	13:43:0	0.1439	1.15084	2.20329	70.3983	10.8772	0.43885	883.554	9.71851	4.98413	4.61341	4.98413	4.61341	4.61341	4.98413	4.61341	4.98413
12	13:43:0	0.1439	1.15084	2.00704	70.3983	10.757	0.43885	883.554	9.71851	4.98286	4.62614	4.98286	4.62614	4.62614	4.98286	4.62614	4.98286
13	13:43:0	0.1439	1.15084	1.98579	70.3983	11.0872	0.43885	883.474	9.72851	4.98286	4.57522	4.98286	4.57522	4.57522	4.98286	4.57522	4.98286
14	13:43:0	0.1439	1.15084	1.78499	70.3983	11.3172	0.43885	883.564	9.71351	4.98477	4.60959	4.98477	4.60959	4.60959	4.98477	4.60959	4.98477
15	13:43:0	0.1439	1.15084	1.73579	70.3983	11.1372	0.42885	883.564	9.70851	4.98413	4.6166	4.98413	4.6166	4.6166	4.98413	4.6166	4.98413
16	13:43:0	0.1439	1.15084	2.10539	70.3983	10.0772	0.42885	883.564	9.70851	4.98159	4.6045	4.98159	4.6045	4.6045	4.98159	4.6045	4.98159
17	13:43:0	0.1439	1.15084	2.28579	70.3983	10.8082	0.42885	883.474	9.70851	4.98413	4.61278	4.98413	4.61278	4.61278	4.98413	4.61278	4.98413
18	13:43:0	0.1439	1.15084	1.89579	70.4187	11.4172	0.42885	883.464	9.72851	4.9835	4.61787	4.9835	4.61787	4.61787	4.9835	4.61787	4.9835
19	13:43:0	0.1439	1.15084	1.87649	70.4159	11.3372	0.42885	883.554	9.71851	4.98413	4.62296	4.98413	4.62296	4.62296	4.98413	4.62296	4.98413
20	13:43:0	0.1439	1.15084	1.93579	70.4159	11.241	0.42885	883.574	9.71851	4.98286	4.63824	4.98286	4.63824	4.63824	4.98286	4.63824	4.98286

Input Data
Quality Validation and Setup …



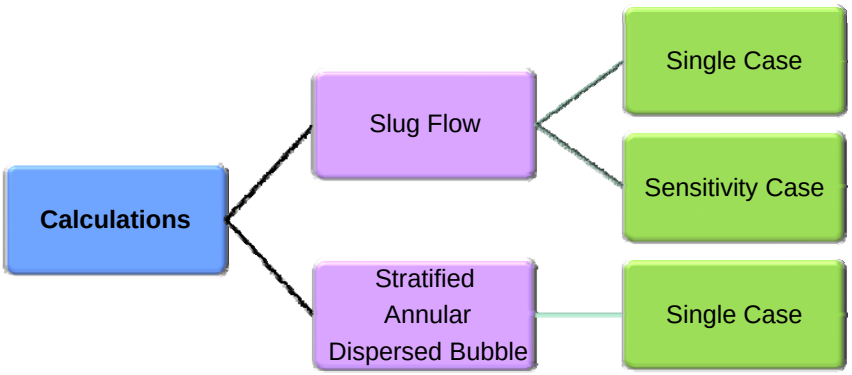


Fluid Flow Projects

Input Data

Advisory Board Meeting, October 26, 2011

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**

	Mean	Uncertainty
DP3 (Psi , %)	0.072	20.988
DP4 (Psi , %)	0.574	1.825
PT4 (Psi , Psi)	1.944	1.387
T (°F, °F)	70.400	0.068
Wl (kg/s, kg/s)	0.183	0.042
Wg (kg/s, kg/s)	0.007	4.000E-02
ρl_m (kg/m3)	883.515	0.102
ρg_m (kg/m3)	9.717	0.016
ρl_c (kg/m3, kg/m3)	887.856	1.765
ρg_c (kg/m3, kg/m3)	1.351	0.113
µL (cP, cP)	137.233	1.618
µG (cP, cP)	0.009	1.499E-06
vsl (m/s, m/s)	0.102	2.312E-02
vsg (m/s, m/s)	2.609	1.461E+01
Vm (m/s , m/s)	2.711	1.487E+00
Rem	801.890	439.865

Calculations

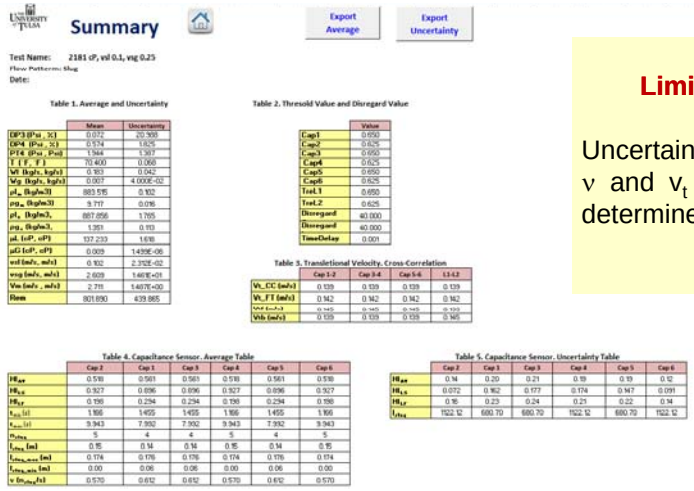
(Single Case – Slug Flow)

Average and Uncertainty

- $H_{L,\,av}$, $H_{L,\,LS}$ (Dynamic Calibration), $H_{L,\,LF}$ (Static Calibration)
- n_{slug}
- Slug Length Distribution
- Slug Frequency
- Translational Velocity
  - Cross-Correlation
  - Time of Flight (v_t, v_{tf}, v_{tb})
- L_{slug_CC}, L_{slug_FT}
- $L_{slug_max_CC}$, $L_{slug_max_FT}$
- $L_{slug_min_CC}$, $L_{slug_min_FT}$

Calculations

(Single Case – Slug Flow)



Summary

Export Average | Export Uncertainty

Test Name: 2181 cP, vsl 0.1, vsg 0.25
Flow Pattern: Slug
Date:

Table 1. Average and Uncertainty

	Mean	Uncertainty
DP3 (Pa , %)	0.072	20.900
DP4 (Pa , %)	0.574	1.625
PT4 (Pa , Pa)	1.364	1.317
T (°F , °F)	70.400	0.068
Wl (kg/s , kg/s)	0.183	0.042
Wg (kg/s , kg/s)	0.007	4.000E-02
ρl, (kg/m3)	883.595	0.102
ρg, (kg/m3)	9.717	0.016
ρl, (kg/m3),	887.856	1.765
ρg, (kg/m3),	1.351	0.113
μl, (cP, cP)	137.233	1.618
μG (cP, cP)	0.009	1.439E-06
vsl (m/s , m/s)	0.102	2.392E-02
vsg (m/s , m/s)	2.609	1.461E+01
Vm (m/s , m/s)	2.711	1.467E+00
Rem	801.890	439.865

Table 2. Thresold Value and Disregard Value

	Value
Cap1	0.650
Cap2	0.625
Cap3	0.650
Cap4	0.625
Cap5	0.650
Cap6	0.625
TwL1	0.650
TwL2	0.625
Disregard	40.000
Disregard	40.000
TimeDelay	0.001

Table 3. Transletional Velocity. Cross-Correlation

	Cap 1-2	Cap 3-4	Cap 5-6	L1-L2
Vt_CC (m/s)	0.139	0.139	0.139	0.139
Vt_FT (m/s)	0.142	0.142	0.142	0.142
[illegible]	0.145	0.145	0.145	0.139
Vtb (m/s)	0.139	0.139	0.139	0.145

Table 4. Capacitance Sensor. Average Table

	Cap 2	Cap 1	Cap 3	Cap 4	Cap 5	Cap 6
H_{LAV}	0.518	0.561	0.561	0.518	0.561	0.518
H_{LLS}	0.327	0.696	0.696	0.327	0.696	0.327
H_{LLF}	0.198	0.294	0.294	0.198	0.294	0.198
t_{slug} (s)	1.166	1.455	1.455	1.166	1.455	1.166
t_{slug} (s)	3.943	7.932	7.932	3.943	7.932	3.943
n_{slug}	5	4	4	5	4	5
L_{slug} (m)	0.15	0.14	0.14	0.15	0.14	0.15
L_{slug_max} (m)	0.174	0.176	0.176	0.174	0.176	0.174
L_{slug_min} (m)	0.00	0.06	0.06	0.00	0.06	0.00
v (v_{slug}) (s)	0.570	0.612	0.612	0.570	0.612	0.570

Table 5. Capacitance Sensor. Uncertainty Table

	Cap 2	Cap 1	Cap 3	Cap 4	Cap 5	Cap 6
H_{LAV}	0.14	0.20	0.21	0.19	0.19	0.12
H_{LLS}	0.072	0.162	0.177	0.174	0.147	0.091
H_{LLF}	0.16	0.23	0.24	0.21	0.22	0.14
t_{slug}	1122.12	680.70	680.70	1122.12	680.70	1122.12

Limitation

Uncertainty for n_{slug}, ν and v_t cannot be determined

Calculations

(Threshold Sensitivity Case – Slug Flow)

Average and Uncertainty

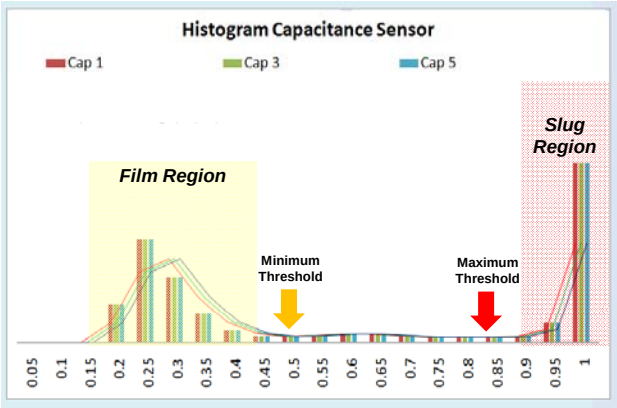
- $H_{L, av}$, $H_{L, LS}$, $H_{L, LF}$
- n_{slug}
- **Slug Length Distribution**
- **Slug Frequency**
- **Translational Velocity**
  - **Cross-Correlation**
  - **Time of Flight (v_t, v_{tf}, v_{tb})**
- L_{slug_CC}, L_{slug_FT}
- $L_{slug_max_CC}$, $L_{slug_max_FT}$
- $L_{slug_min_CC}$, $L_{slug_min_FT}$

✖ 30

Threshold Values

Min ≤ Threshold≤ Max
(Monte Carlo)

Threshold Value Selection



Single Case

Threshold Value and Disregard Value

TreL1	0.65
TreL2	0.625
DisregardCap	40
Cap1	0.65
Cap2	0.625
Cap3	0.65
Cap4	0.625
Cap5	0.65
Cap6	0.625
DisregardLaser	40

Threshold Sensitivity Case

Maximum Threshold Value

TreL1_Max	0.8
TreL2_Max	0.8
Cap1_Max	0.8
Cap2_Max	0.8
Cap3_Max	0.8
Cap4_Max	0.8
Cap5_Max	0.8
Cap6_Max	0.8

Minimum Threshold Value

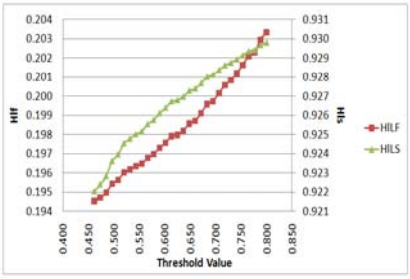
TreL1_Min	0.5
TreL2_Min	0.45
Cap1_Min	0.5
Cap2_Min	0.45
Cap3_Min	0.5
Cap4_Min	0.45
Cap5_Min	0.5
Cap6_Min	0.45

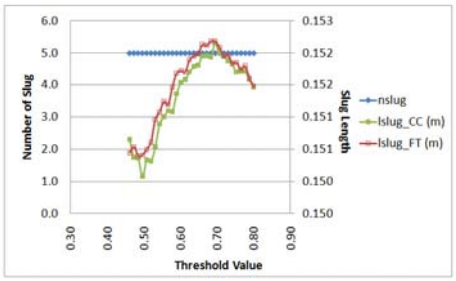
Fluid Flow Projects

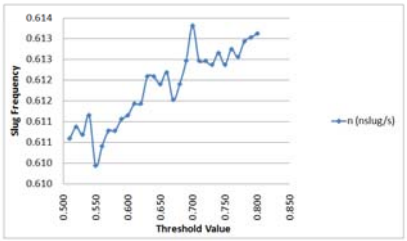
Advisory Board Meeting, October 26, 2011

Calculations

(Threshold Sensitivity Case. Slug Flow) …





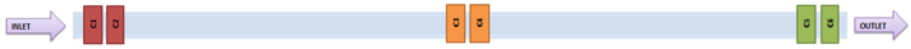


Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

Calculations

Flow Behavior Evolution



P05

Sensor	Length (m)	Threshold	Hl_{cc}	Hl_{cf}	Hl_{cd}	n_{avg}	L_{avg_cc} (m/s)	$L_{avg_max_cc}$ (m/s)	$L_{avg_min_cc}$ (m/s)	v (n_{avg}/s)	vt_FT (m/s)	vtf_FT (m/s)	vtb_FT (m/s)	L_{avg_ff} (m/s)	$L_{avg_max_ff}$ (m/s)	$L_{avg_min_ff}$ (m/s)	L/D_CC	L/D_FT
Cap 1	0.30	0.468	0.5175	0.1946	0.9222	5	1.502E-01	1.753E-01	-1.435E-04	0.570	1.394E-01	1.390E-01	1.382E-01	1.504E-01	1.755E-01	-1.436E-04	2.9567	2.9607
Cap 2	0.35	0.515	0.5600	0.2719	0.8713	4	1.345E-01	1.720E-01	5.561E-02	0.610	1.394E-01	1.390E-01	1.382E-01	1.345E-01	1.720E-01	5.563E-02	2.6475	2.6479
Cap 3	10.00	0.515	0.5600	0.2719	0.8713	4	1.345E-01	1.720E-01	5.561E-02	0.610	1.394E-01	1.390E-01	1.382E-01	1.345E-01	1.720E-01	5.563E-02	2.6475	2.6479
Cap 4	10.50	0.468	0.5175	0.1946	0.9222	5	1.502E-01	1.753E-01	-1.435E-04	0.570	1.394E-01	1.390E-01	1.382E-01	1.504E-01	1.755E-01	-1.436E-04	2.9567	2.9607
Cap 5	20.00	0.515	0.5600	0.2719	0.8713	4	1.345E-01	1.720E-01	5.561E-02	0.610	1.394E-01	1.390E-01	1.382E-01	1.345E-01	1.720E-01	5.563E-02	2.6475	2.6479
Cap 6	20.50	0.468	0.5175	0.1946	0.9222	5	1.502E-01	1.753E-01	-1.435E-04	0.570	1.394E-01	1.390E-01	1.382E-01	1.504E-01	1.755E-01	-1.436E-04	2.9567	2.9607

P50

Sensor	Length (m)	Threshold	Hl_{cc}	Hl_{cf}	Hl_{cd}	n_{avg}	L_{avg_cc} (m/s)	$L_{avg_max_cc}$ (m/s)	$L_{avg_min_cc}$ (m/s)	v (n_{avg}/s)	vt_FT (m/s)	vtf_FT (m/s)	vtb_FT (m/s)	L_{avg_ff} (m/s)	$L_{avg_max_ff}$ (m/s)	$L_{avg_min_ff}$ (m/s)	L/D_CC	L/D_FT
Cap 1	0.30	0.625	0.5177	0.1980	0.9268	5	1.516E-01	1.771E-01	-1.420E-04	0.570	1.422E-01	1.453E-01	1.390E-01	1.517E-01	1.773E-01	-1.422E-04	2.9839	2.9863
Cap 2	0.35	0.650	0.5611	0.2942	0.8960	4	1.427E-01	1.796E-01	5.751E-02	0.612	1.422E-01	1.453E-01	1.390E-01	1.428E-01	1.799E-01	5.759E-02	2.8088	2.8119
Cap 3	10.00	0.650	0.5611	0.2942	0.8960	4	1.427E-01	1.796E-01	5.751E-02	0.612	1.422E-01	1.453E-01	1.390E-01	1.428E-01	1.799E-01	5.759E-02	2.8088	2.8119
Cap 4	10.50	0.625	0.5177	0.1980	0.9268	5	1.516E-01	1.771E-01	-1.420E-04	0.570	1.422E-01	1.453E-01	1.390E-01	1.517E-01	1.773E-01	-1.422E-04	2.9839	2.9863
Cap 5	20.00	0.650	0.5611	0.2942	0.8960	4	1.427E-01	1.796E-01	5.751E-02	0.612	1.422E-01	1.453E-01	1.390E-01	1.428E-01	1.799E-01	5.759E-02	2.8088	2.8119
Cap 6	20.50	0.625	0.5177	0.1980	0.9268	5	1.516E-01	1.771E-01	-1.420E-04	0.570	1.422E-01	1.453E-01	1.390E-01	1.517E-01	1.773E-01	-1.422E-04	2.9839	2.9863

P95

Sensor	Length (m)	Threshold	Hl_{cc}	Hl_{cf}	Hl_{cd}	n_{avg}	L_{avg_cc} (m/s)	$L_{avg_max_cc}$ (m/s)	$L_{avg_min_cc}$ (m/s)	v (n_{avg}/s)	vt_FT (m/s)	vtf_FT (m/s)	vtb_FT (m/s)	L_{avg_ff} (m/s)	$L_{avg_max_ff}$ (m/s)	$L_{avg_min_ff}$ (m/s)	L/D_CC	L/D_FT
Cap 1	0.30	0.783	0.5181	0.2026	0.9296	5	1.520E-01	1.777E-01	-1.394E-04	0.570	1.436E-01	1.488E-01	1.397E-01	1.522E-01	1.778E-01	-1.394E-04	2.9918	2.9953
Cap 2	0.35	0.785	0.5632	0.3128	0.9081	4	1.540E-01	1.875E-01	5.854E-02	0.613	1.436E-01	1.488E-01	1.397E-01	1.541E-01	1.876E-01	5.857E-02	3.0309	3.0329
Cap 3	10.00	0.785	0.5632	0.3128	0.9081	4	1.540E-01	1.875E-01	5.854E-02	0.613	1.436E-01	1.488E-01	1.397E-01	1.541E-01	1.876E-01	5.857E-02	3.0309	3.0329
Cap 4	10.50	0.783	0.5181	0.2026	0.9296	5	1.520E-01	1.777E-01	-1.394E-04	0.570	1.436E-01	1.488E-01	1.397E-01	1.522E-01	1.778E-01	-1.394E-04	2.9918	2.9953
Cap 5	20.00	0.785	0.5632	0.3128	0.9081	4	1.540E-01	1.875E-01	5.854E-02	0.613	1.436E-01	1.488E-01	1.397E-01	1.541E-01	1.876E-01	5.857E-02	3.0309	3.0329
Cap 6	20.50	0.783	0.5181	0.2026	0.9296	5	1.520E-01	1.777E-01	-1.394E-04	0.570	1.436E-01	1.488E-01	1.397E-01	1.522E-01	1.778E-01	-1.394E-04	2.9918	2.9953

Fluid Flow Projects

Uncertainty Analysis

Uncertainty Analysis

Uncertainty Model

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

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

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

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

$$S_{\bar{X},R} = \left[\sum_{i=1}^{N_i}\left(S_{\bar{X},i}\right)^2\right]^{1/2}$$

Uncertainty Analysis…

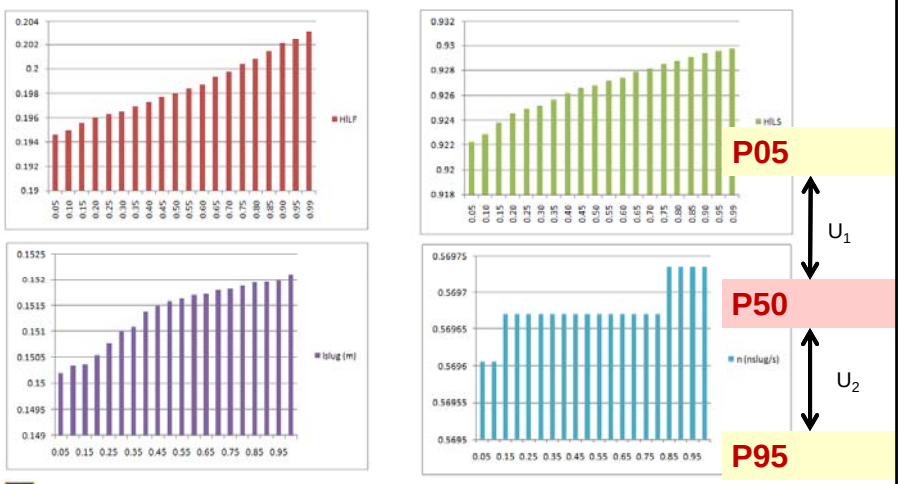
Uncertainty Propagation

$$U = \sqrt{\left(\frac{\partial F}{\partial Y}\right)^2 (\Delta Y)^2 + \left(\frac{\partial F}{\partial Z}\right)^2 (\Delta Z)^2 + \cdots}$$

- Fluid Properties:
  - Density
  - Viscosity
- Superficial Velocities
- Mixed Velocity
- Mixed Reynolds Number

Uncertainty Analysis ...

Slug Characterization



Output Data

Quality Validation

High U

- Repeat Point
- Check Instrumentation

Low U

- Export Data point to the Macro Data Base Excel File

Future Tasks

Evaluate the Effect of the Inlet Geometry on the Flow Behavior	October 2011
Experimental Program Execution for Medium Oil Viscosity	February 2011
Data Analysis	April 2011
Model Verification or Develop New Ones (if Necessary)	May 2012
Write Thesis	Jun 2012

Thanks …

Questions

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

Rosmer Brito

Project Completion Dates

Evaluate the Effect of the Inlet Geometry on the Flow Behavior (Phase 1)	October 2011
Evaluate the Effect of the Inlet Geometry on the Flow Behavior (Phase 2)	October 2011
Experimental Program Execution for Medium Oil Viscosity	February 2011
Data Analysis	March 2011
Model Verification or Develop New Ones (if Necessary)	May 2012
Write Thesis	June 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 behaviors 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) has been published in the literature. Thus, there is a need of experimental investigation for 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 with medium liquid viscosity experimental results.

An appropriate experimental procedure and data acquisition and analysis is required in order to reduce the uncertainty in the acquired data, this will increase the data consistency and quality reducing data processing time and the probability of human error that could affect the experimental results. This executive summary describes the experimental procedure developed to assure a high quality data acquisition and analysis.

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.

Oil Selection

Four mineral oils were characterized to determine the oil viscosity change with temperature, and select the mineral oil that will allow the viscosity range from 20 cP to 200 cP. The four mineral oil were Lubspar 110, ND-20, ND-30 and Citgo Sentry 220. The mineral oil selected was ND-20, which will allow covering a viscosity range from 33 cP (70 °F) to 129 cP (120 °F).

Data Acquisition

Sensor calibration and verification is required for proper data acquisition. This section presents the procedure for proper calibration that has been considered in this study.

Capacitance Sensor

Capacitance sensor works on the principle of difference in dielectric values between two different phases. The ring type sensors comprises of two concave half rings which are fitted onto the inner circumference of the pipe.

Six capacitance sensors are installed along the flow loop, two at the entrance, two at the middle and two 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.

Static Calibration

Static calibration is required for proper holdup measurements. Different volumes of liquid were placed in an acrylic pipe with the capacitance sensor in the middle to perform the static calibration. The temperature and height (h_L) of the fluid in the pipe is measured, and compared with output voltage of the circuit. The voltage reading is converted to a dimensionless voltage (V'), and the liquid holdup is calculated by the ratio between the area occupied by fluid over the cross sectional area.

The holdup (H_L) vs. dimensionless voltage (V') data is fitted by a fifth or fourth degree polynomials, which were found to be the best fits for the ring type

configuration. The accuracy of each capacitance sensor is calculated using the Basic Calibration Uncertainty Calculation procedure described by Dieck (2007).

Effect of the Oil Temperature on the Output Signal

In addition to the conventional static calibration procedure, the effect on the oil temperature on the capacitance sensor output signal has to be evaluated. For this, first hot air (empty pipe case) is flowed through the capacitance sensor and the voltage and air temperature is recorded. In addition, several oil volumes at different temperatures are placed in an acrylic pipe connected to the capacitance sensor. Output voltage is recorded while the oil temperature is decreasing.

It was observed that output voltage and fluid temperature are directly proportional, when the oil temperature decreases the output voltage decrease with a linear trend. It was observed that span between the lowest voltage (empty pipe case) and highest voltage (liquid full pipe case) remains constant for all fluid temperatures. This justifies the necessity to read the maximum or minimum value for each fluid temperature in order to predict and accurate liquid holdup and exclude the effect of the fluid temperature in the holdup calculations.

Effect of the Ambient Temperature on the Output Signal

The capacitance sensor circuit was exposed to different ambient temperatures to evaluate the effect of the ambient temperature on the output voltage. It was demonstrated that the ambient temperature does not affect the output signal obtained from the capacitance sensor.

Dynamic Calibration

For slug flow a correction factor is required for the static calibration considering the effect of phase distribution in the slug body. Owing to the static calibration curve, each capacitance sensor has a different fitted dynamic calibration curve.

Data Processing

An excel macro was develop to process the raw data 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, absolute pressure, liquid temperature, mass flow rate, fluid properties (density and viscosity), superficial velocities, mix velocity, mix Reynolds number and average liquid holdup. In addition, if the slug flow is observed, additional parameters are calculated, namely, average liquid holdup in the film region, average liquid holdup in the slug region, number of slugs, slug frequency, translational velocity, slug length and slug length distribution.

Input Data (Quality Validation and Setup)

The raw data will be imported to the Excel macro to verifying the stability of the test and the voltage signal obtained from the capacitance sensors.

Slug Flow Characterization

Starting from the procedure for slug characterization suggested by Gokcal *et al.* (2010) and Alsafran *et al.* (1999) the following methodology is suggested.

For each capacitance sensor, the slug characterization is performed selecting a threshold value to identify the slug region (holdup higher than the selected threshold value) and film region (holdup lower than the selected threshold value). In addition, a disregard value will be defined to eliminate the effect of air bubbles in the slug region, which may create large variations in the output signal. This will generate a vector ($\mathbf{v}$) 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.

To estimate the number of slugs, the algorithm determines when the $\mathbf{v}$ vector changes from zero to one, then looks for further changes from one to zero which represent one slug. The algorithm counts the entire slug's front arriving to the sensor during the recording time. Then, the slug frequency is obtained dividing the number of slugs by the test time.

Two techniques will be used to calculate the translational velocity, namely, cross-correlation and flying time of flight. The last technique calculates the time required (Δt) by the slug front and bubble nose to travel from one sensor to the other. Then, back (v_b) and front (v_f) velocities are calculated dividing the capacitance sensor distance by the time required (Δt).

As two different translational velocities will be obtained for each data point, two slug lengths will be calculated for each capacitance sensor and further analysis will be carried out to select the best result.

Threshold Value Selection

A proper selection of the threshold value is critical for the code to accurately identify slugs and calculate their flow characteristics. For this reason, the

following methodology is proposed to select the threshold value and evaluate its effect on the slug characteristics.

After that liquid holdup is estimated, a liquid holdup histogram is plotted to facilitate the determination of all possible threshold values. The histogram allows the identification of the film and slug regions. The threshold value 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 on slug parameters. At least thirty threshold values are used in the calculations.

Flow Behavior Evolution

The flow behavior evaluation will be performed using the data from six capacitance sensors. The evolution of slug flow parameters along the flow loop will be used to determine if the flow is fully developed.

Uncertainty Analysis

A cautious uncertainty analysis will performed for all measured and calculated parameters. This uncertainty analysis is included on the developed macro to perform the data analysis.

Uncertainty Analysis for Measured Parameters

The U_{ASME} model[1] will be used to calculate parameter uncertainty assuming that the sample rate always is higher than 30. There are two required inputs to determine the uncertainty; these are the systematic error (b_R) and the random error or standard deviation of the average for the results ($S_{\overline{X},R}$). The uncertainty will be calculated as $U_{ASME}=\pm 2(b_R^2+S_{\overline{X},R}^{\ 2})$. This equation will be applied for the pressure gradient, total pressure, oil temperature, gas and liquid mass flow rate.

Uncertainty Analysis for Calculated Parameters

Taylor's Series uncertainty propagation equation [1] will be used to propagate the uncertainty over the calculated parameters. It is necessary to identify all the independent variables that will affect the dependent variable (calculated parameter) and obtain a mathematical expression that will relate both independent and dependent variables.

Slug Flow Uncertainty Analysis

As it was mentioned before, threshold sensitivity will be performed for each data point (v_{SLi}, v_{SGi}). This will allow to obtained 30 different values of film region holdup, slug region holdup, number of slug, slug frequency, translational velocity and slug length. Then, the uncertainty for each slug parameter can be obtained with a frequency histogram and the calculation of the percentiles *P5*, *P50* and *P95*. Finally, the uncertainty can be calculated subtracting the *P50* value minus the *P5* value and subtracting the *P95* value minus the *P50* value.

Project Plan

The project plan is divided into experimental program and modeling.

Experimental Program

The experiments will be run using air and mineral oil as the two phases 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. A limited number of tests with the high viscosity oil (181 cP < μ_O < 587 cP) and horizontal pipe are considered to compare the new inlet configuration with previous data.

The final set of experiments will be run viscosities from 33 to 129 cP. These results will be used to validate the performance of existing flow pattern, pressure gradient and holdup prediction models.

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.

References

Dieck. R.: "Measurement Uncertainty Method and Applications". Fourth Edition. (2007).

Hernandez. V.: "Gas-liquid two-phase flow in inclined pipes". The University of Nottingham, School of Chemical, Environmental and Mining Engineering. (2007).

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

Gokcal .B., et al:, "Prediction of Slug Frequency for High-Viscosity Oils in Horizontal Pipes". SPE Projects, Facilities & Construction, vol. 5. (2010).

Fluid Flow Projects

Characterization of High Viscosity Slug Flow in Horizontal Pipes

Eissa Al-safran (KU/KOC)

Advisory Board Meeting, October 26, 2011

Outline

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

Introduction

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

Objectives

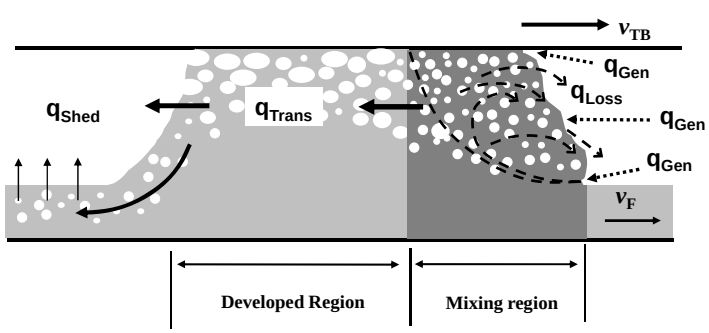
- Understand and Model High Viscosity Effect on Slug Liquid Holdup in Horizontal Pipes
- Develop a Physical Model to Explain Slug Flow Characteristics Interaction under the Condition of High Viscosity Flow

Slug Liquid Holdup

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

Slug Liquid Holdup . . .

- Gas Entrainment and Transport in Low Liquid Viscosity Slug



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

Slug Liquid Holdup . . .

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

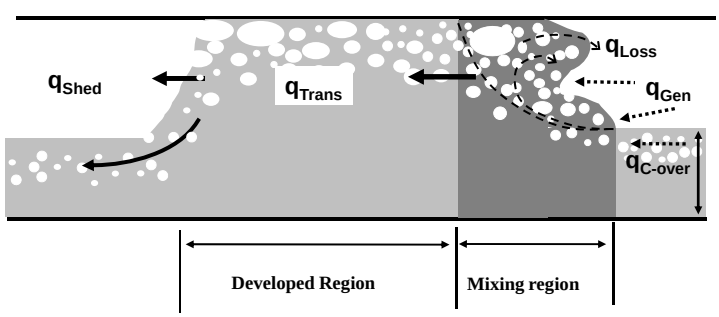
Slug Liquid Holdup . . .

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

Slug Liquid Holdup . . .

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

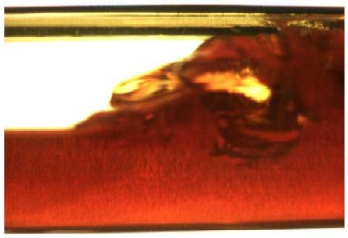
Slug Liquid Holdup . . .



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

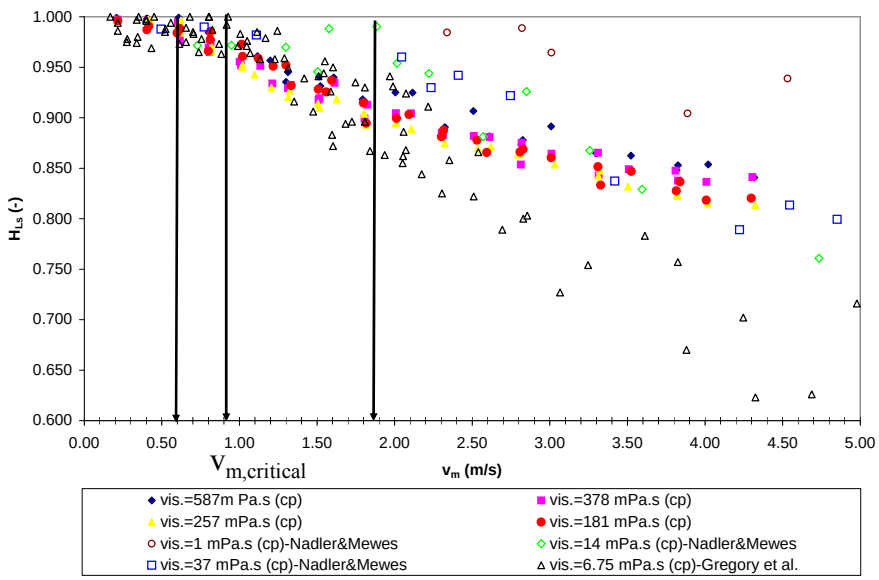
Slug Liquid Holdup . . .

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



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

Slug Liquid Holdup . . .

- Medium Viscosity Oil
  - Moderate Aeration Critical Mixture Velocity (v_m=1.8 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

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 $0.15 < N_{Fr} N_{\mu} 0.2 < 1.5$

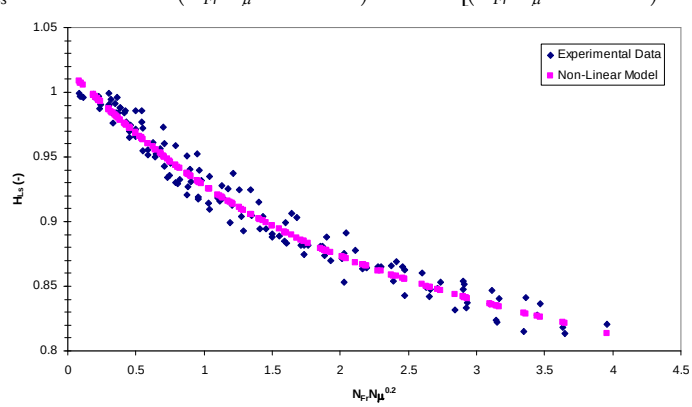
$$H_{Ls} = 0.9473\, e^{(-0.041\, F_r N_{\mu}^{0.2})}$$ For $N_{Fr} N_{\mu} 0.2 \geq 1.5$

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

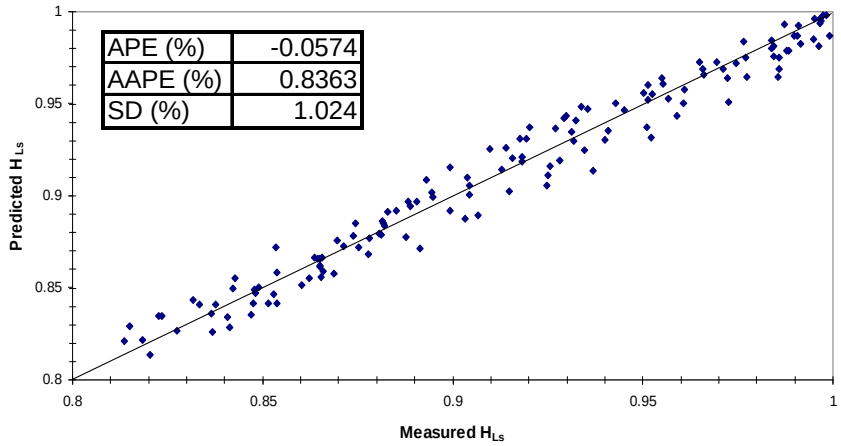
Modeling Slug Liquid Holdup . . .

- **Non-Linear Modeling**

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



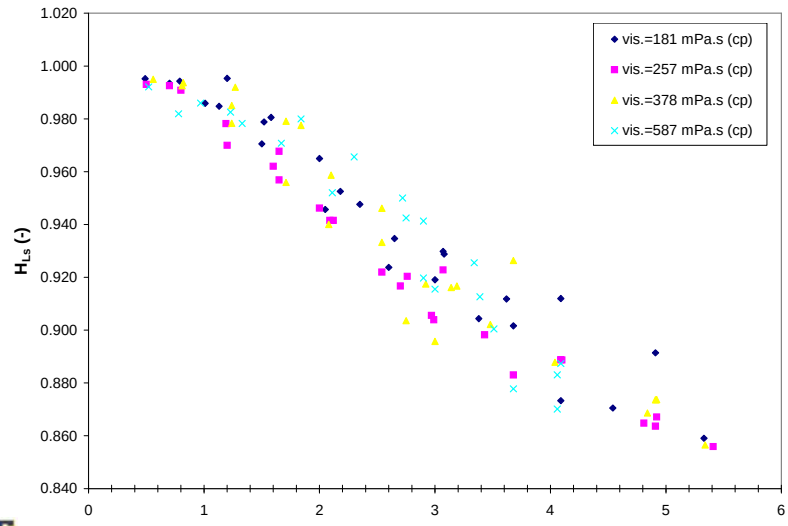
Modeling Slug Liquid Holdup . . .



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

Slug Characteristics Interaction . . .

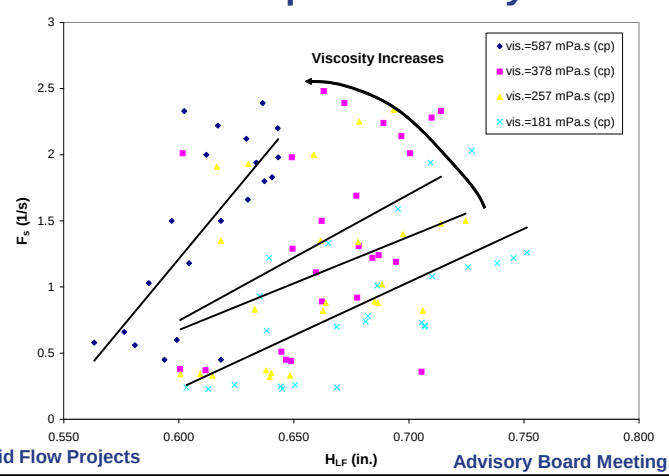


Fluid Flow Projects

Advisory Board Meeting, Oct. 26, 2011

Slug Characteristics Interaction . . .

- Slug Frequency is Proportional to Film Thickness and Liquid Viscosity

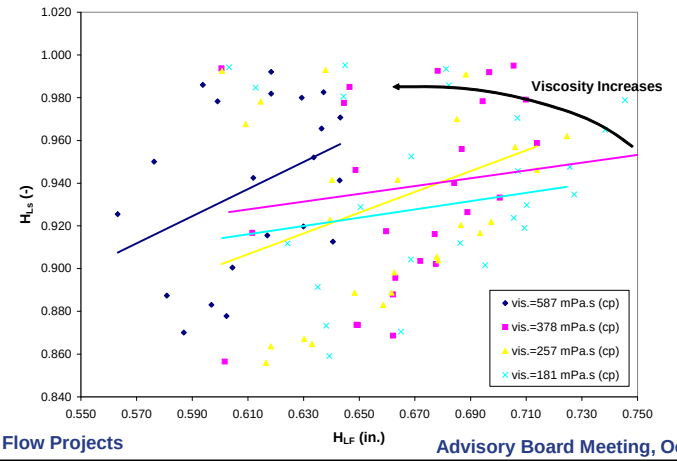


Fluid Flow Projects

Advisory Board Meeting, Oct. 26, 2011

Slug Characteristics Interaction . . .

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



Future Work

- Slug Liquid Holdup Model Uncertainty Analysis
- Slug Liquid Holdup Model Validation and Comparison
- Investigate High Viscosity Slug Characteristics Interactions
- Develop Physical Model for High Viscosity Slug Flow Characteristics

Characterization of High Viscosity Slug Flow in Horizontal Pipes

Eissa Al-safran

Project Completion Dates

Literature Review	Completed
Data Analysis	Ongoing
Physical Modeling	Ongoing
Modeling	Ongoing
Model validation and comparison	April 2012
Final Report	Sep. 2012

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 to a comprehensive understanding of slug flow behavior and characteristics under high viscosity conditions.

Activities Summary

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

Physical Modeling

The basis of a physical model of slug liquid holdup is founded according 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 in 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 important two are given.

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 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. Furthermore, a positive significant correlation between the liquid film height and slug liquid holdup was observed as explained in the above proposed physical modeling. 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.

References

1. Al-Safran, E., Gokcal, B., and Sarica C.: "High Viscosity Liquid Effect on Two-Phase Slug Length in Horizontal Pipes," BHRG 15th International Multiphase Flow Technology Conference, Cannes, France, June 2011.

2. Gokcal, B., Al-Sarkhi, A., Sarica, C. and Al-Safran, E.: "Prediction of Slug Frequency for High-Viscosity Oils in Horizontal Pipes," SPE 124057, *SPE Projects, Facilities & Construction Journal*, September, (2010).

3. Gokcal, B. An Experimental and Theoretical Investigation of Slug Flow for High Oil Viscosity in Horizontal Pipes. Ph.D. Dissertation, The University of Tulsa, Tulsa, OK, 2008.

4. Gregory, G., Nicholson, M. and Aziz, K.: "Correlation of the Liquid Volume Fraction in the Slug for Horizontal Gas-Liquid Slug Flow. *International J. Multiphase Flow*s, 4, 33-39, 1978.

5. Kora, C., Sarica, C., H.-Q Zhang, Al-Sarkhi, A., and Al-Safran, E.: "Effects of High Oil Viscosity on Slug Liquid Holdup in Horizontal Pipes," Accepted for presentation in CSUG/SPE conference, Calgary, Canada, November, 2011.

6. Nadler M. and Mewes D.: "Effect of the Liquid Viscosity on the Phase Distribution in Horizontal Gas-Liquid Slug Flow" *Int. J. of Multiphase Flow*, 21, No. 2, 253-266, (1995).

Fluid Flow Projects

Low Liquid Loading Gas-Oil-Water Flow

Kiran Gawas

Advisory Board Meeting, October 26, 2011

Outline

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

Objectives

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

Introduction

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

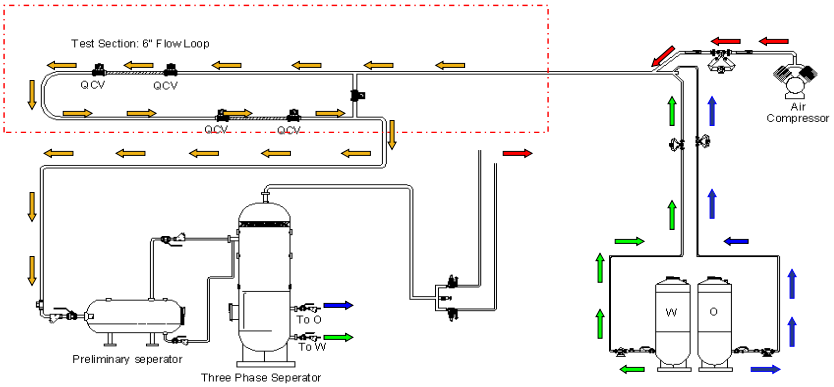
Experimental Overview

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

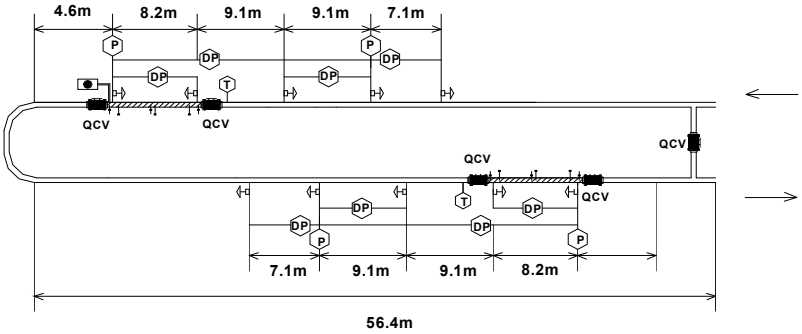
Experimental Study

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

Experimental Facility



Test Section



Test Fluids

- Test Fluid
  - Gas – Air
  - Water – Tap Water

    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

Measurement Techniques

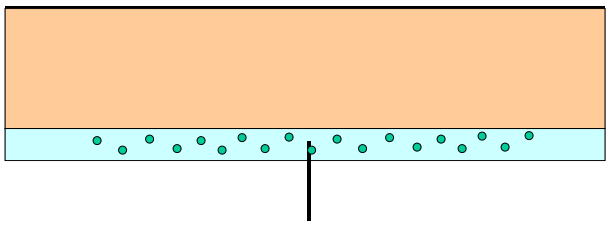
- Pressure and Temperature : PTs And DPs and TTs
- Liquid Film Thickness And Flow Pattern: Conductivity Probes
- Holdup: Quick Closing Valves And Pigging System
- Wetted Wall Perimeter: Scales On Wall

Measurement Techniques …

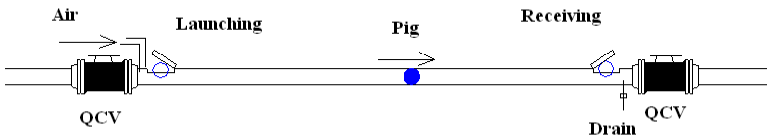
- Droplet Flux: Iso-kinetic Sampling System
- High Speed Imaging : Droplet Size Distribution And Flow Regime
- Wave Characteristics
- Surface Tension And Interfacial Tension
- Data Acquisition: DeltaV

Film Thickness & Flow Pattern: Conductivity Probes

- Principle: Conductivity Difference
- Traverse Across Pipe
- Oil-Water Flow Pattern And Water layer Thickness

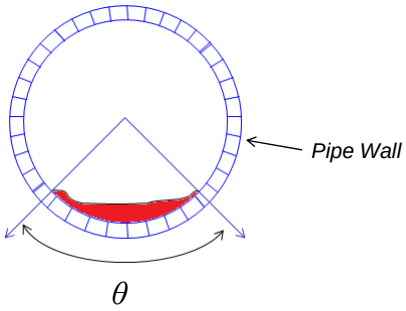


Holdups: QCVs & Pigging System

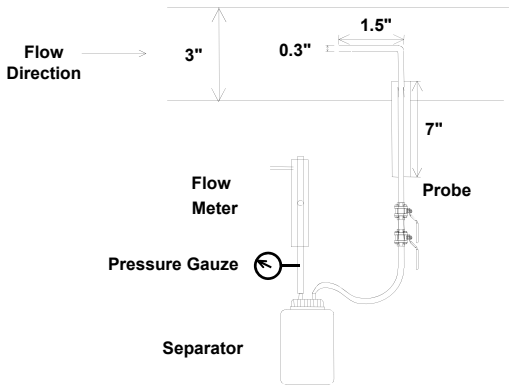


Wetted Perimeter

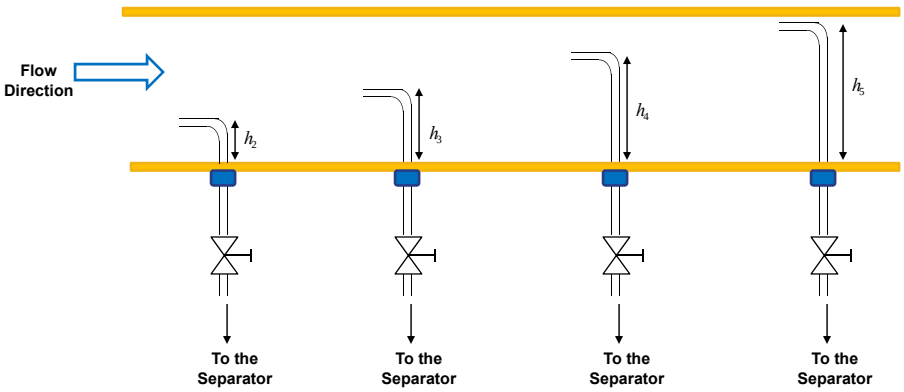
- Scales Attached To The Pipe
- Calibration To Account For Pipe Curvature Effects And Refraction
- At High Gas Flow Rates Large Fluctuations Due To Film Waviness



Droplet Flux : Isokinetic Probe

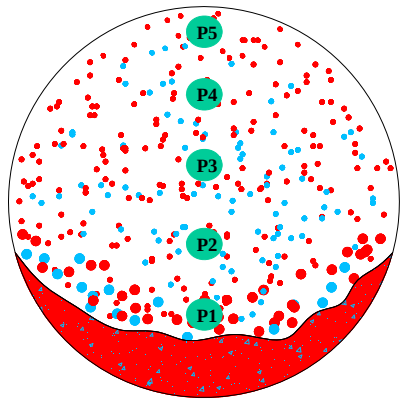


Droplet Flux



Isokinetic Sampling System

Droplet Flux …



$$\frac{h_2}{D} = \frac{1}{4}$$

$$\frac{h_3}{D} = \frac{1}{2}$$

$$\frac{h_4}{D} = \frac{3}{4}$$

$$\frac{h_5}{D} = 1$$

Probe Position

Isokinetic Sampling System : Calibration

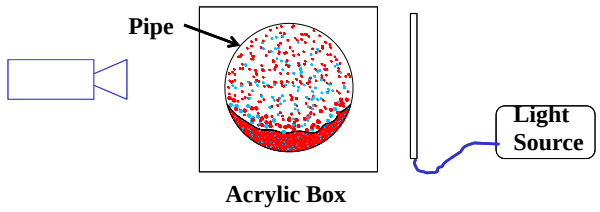
V_{Sg} = 17.75 ± 0.3 m/s

V_{SL} = 0.7 m/s

Upward		Downward	
Probe #	Percentage Error Relative To Mean	Probe #	Percentage Error Relative To Mean
1	5.44	2	8.65
5	4.76	3	1
9	2.04	7	5.77
4	0.23	8	3.85
12	2.49	11	5.77

Droplet Size Distribution …

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



- **High Shutter Speeds**
- **Shadow Of Droplets Registered By The Camera**

Droplet Size Distribution …

Original Image

8-Bit Gray ↓ Background Compensation

Gray Scale Image

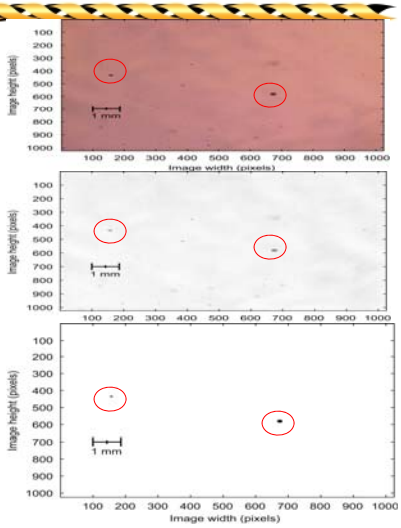
Threshold ↓ Criterion

Binary Image

Edge ↓ Detection

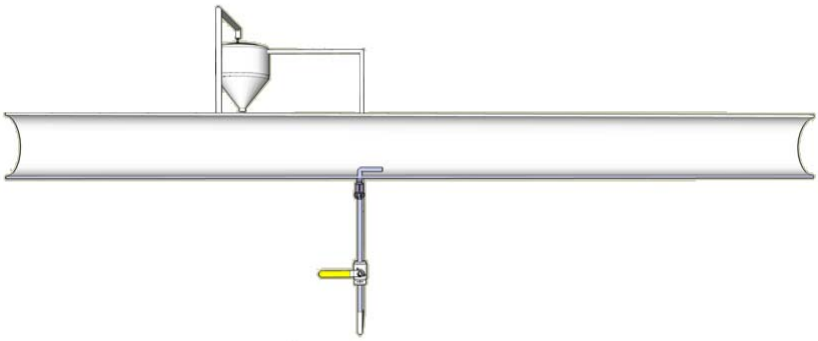
Droplet Diameter

Patruno et al. (2010)



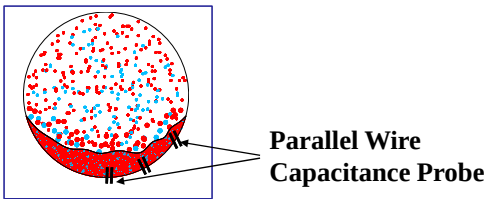
Flow Regime Identification

- Dye Injection Method For Flow Regime Identification In Oil-Water Layer



Wave Characteristics

- Three Parallel Wire Capacitance Probe



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

Experimental Program

- Tests At Low Gas Flow Rates
  - Flow Conditions Used by *Dong (2007)*
- Tests At High Gas Flow Rates
  - Gas-Oil And Gas-Water Two-phase Tests
  - Gas-Oil-Water Three-phase Tests

Experimental Program …

- Test Ranges
  - Superficial Gas Velocity:
    5 to 22.5 m/s
  - Liquid Loading Level :
    50 to 1200 m^3/MMsm^3
  - Water Cut:
    0 to 0.15
  - Inclination Angles:
    0º, +2º, -2º

Low Gas Flow Rate Studies

Test Matrix

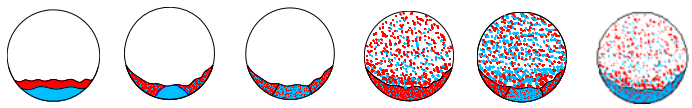
Superficial Gas Velocity (m/s)	Superficial Liquid Velocity (m/s)			
	Water Cuts : 0, 5%, 15 %			
5	0.001	0.004	0.007	0.01
10	0.001	0.004	0.007	0.01
15	0.001	0.004	0.007	0.01

High Gas Flow Rate Studies

Test Matrix

Superficial Gas Velocity (m/s)	Superficial Liquid Velocity (m/s)			
	Water Cuts : 0, 5%, 15%, 100%			
16.5	0.004	0.01	0.02	0.035
18.5	0.004	0.01	0.02	0.035
22.5	0.004	0.01	0.02	0.035

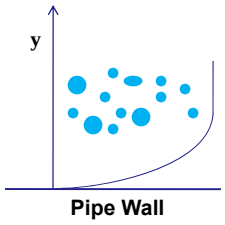
Modeling Framework



- **Modeling Of Liquid-Liquid Flow Pattern**
  - Stratified To Non-Stratified Flow Based On Kelvin-Helmoltz Linear Stability Criterion
  - Semi-Dispersed Flow Or Fully Dispersed Flow Based On Stability Of Dispersed Phase Drops

Modeling Framework …

- **Liquid-Side Friction Factor**
  - Modification Of Fan's Approach
  - Law Of Wall Approach



$$u^+ = 1/\kappa \ln y^+ + \beta$$

$\kappa(d_{mean}, \phi)$ $\beta(d_{mean}, \phi)$

Modeling Framework …

- Droplet Transport
  - Modeling Of Turbulent Diffusion And Trajectory Mechanism
  - Transport Mechanism As Also The Actual Fluxes Depend On Droplet Size
  - Droplet Size Distribution Measured In Current Study
  - Criterion For Droplets To Reach Top Of The Pipe

Timeline

Literature Review	Ongoing
Testing	November 2011
Data Analysis	February 2012
Model Development	May 2012
Final Report	June 2012

Thank You

Low Liquid Loading in Gas-Oil-Water Pipe Flow

Kiran Gawas

Project Completion Dates

Literature Review	Ongoing
Experimentation	November 2011
Data Analysis and Model Comparison	February 2011
Model Validation	April 2012
Final Report	June 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. Therefore, understanding of the flow characteristics of low liquid loading gas-oil-water flow is of great importance in transportation of wet gas. 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 flow pattern, pressure drop, volumetric fractions (of the three phases), liquid film thickness, wetted wall fractions, entrainment fractions and droplet size of entrained liquid will be observed and measured at different flow rates, liquid loading levels and water cuts.

Activities Summary

The following activities have been carried out during this period.

Experiments

Since the last ABM the flow loop has been modified for experiments on inclined pipe flow. Both the upward and downward runs of the test section are inclined at 2° from the horizontal. New flow visualization sections were installed on both the runs of the loop. Details of the flow loop and test sections can be found in previous ABM reports.

The 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. The flow meters are calibrated by the manufacturer and have a mass flow rate and density uncertainty of ±0.1% and ±0.5% respectively. Pressure, temperature and pressure gradients are measured using Rosemount pressure and temperature transmitters and Rosemount differential pressure transducers, respectively. Liquid holdup is measured by trapping liquid between the two quick-closing valves (QCV) and then pigging out the entrapped liquid into graduated cylinders. Wetted wall perimeter is measured using grades on pipe circumference. 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. This device employs the Du-Nuoy's ring method for direct determination of the surface tension and interfacial tension. Currently, an iso-kinetic sampling system is used for determination of entrainment fraction. 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 one location does not influence the reading of probe at another location. Probe located closest to the gas-liquid interface is also provided with pressure gauge at outlet of its separator. This helps to determine location of the gas-liquid interface. Two such sampling systems were built, one each for the upward and downward test sections.

Size of drops influences the droplet transport mechanism and thus influences deposition rates. A new high speed imaging technique was 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 200 which produces a diffuse white light is used for illumination from back of the pipe so that the light source and camera face each other. The camera and the light assembly are enclosed in a special enclosure to cut out surrounding light. The images generated by the high speed camera will be edited using ImageJ software. Algorithm for image processing that will be used for determination of droplet size from raw images can be found in Hay *et al.* (1998).

Parallel-wire conductivity probes are installed for determination of oil-water flow pattern. This probe can traverse vertically through the pipe cross-section and is also used for determination of water film thickness at bottom of the pipe.

Dye-injection technique is used for determination of flow regime in the liquid phase.

Wave characteristics will be measured using a two-wire capacitance probe assembly. The probe assembly consists of two probes placed one foot apart. Each probe consists of a set of two-wire probes placed at different locations along the circumference of the pipe.

Modeling

The modeling of low liquid loading three phase flow phenomenon is divided into three sub-models, namely, oil-water flow, gas-liquid flow and entrainment fraction model.

Torres-Monzon (2006) presented the most recent study for flow pattern identification in oil-water pipe flow. This model can be adapted for the case of low liquid loading flow by considering the flow of oil and water in channel.

The gas-liquid flow patterns observed in the current experimental range are stratified smooth and stratified wavy flow. As proposed by Fan (2005), a model for liquid friction factor and interfacial friction factor will be developed using the law of wall in turbulent boundary layer. The effect of the immiscible liquid phases will be accounted for by modifying the velocity profile for the law of wall approach. In the past, Troshko and Hassan (2001) and Vielma (2006) showed that the law of wall can be used for dispersed liquid-liquid flow by modifying the von-Karman coefficient and the integration coefficient. These parameters are functions of dispersed phase, droplet diameter and volume fraction. A similar approach will be adopted for the case of gas-liquid-liquid flow.

Future Work

- Complete testing of proposed test matrix.
- Analyze experimental data.
- Carry out comparison with existing models.
- Development of new model.

References

Fan, Y.: “An Investigation of Low-Liquid Loading Gas-Liquid Stratified Flow in Near Horizontal Pipes”, PhD Dissertation, The University of Tulsa, (2005).

Hay, K.J., Liu, Z.C., Hanratty, T.J.: "A backlighted imaging technique for particle size measurements in two-phase flows", *Expt. in Fluids*, 25, 226-232, 1998.

Torress-Monzon, C. F.: “Modeling of Oil-Water Flow in Horizontal and Near Horizontal and Near Horizontal Pipes,” PhD Dissertation, The University of Tulsa, (2006).

Troshko, A. A., & Hassan, Y. A.: “Law of the Wall for Two-phase Turbulent Boundary Layers,” International Journal of Heat and Mass Transfer, 44(4), 871-875, (2001).

Vielma, J. C.:“Rheological Behavior of Oil-Water Dispersion Flow in Horizontal Pipes,” MS Thesis, The University of Tulsa, (2006).

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 Documented
- Need to Generate Datasets and Improve Model Predictions

Objectives

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

Literature Review

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

Literature Review …

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

Literature Review …

- Wilson *et al*. (2004)
  - Multiphase Flow Modeling Verification for
    - Gas + Condensate + Fresh Water
    - Gas + Condensate + Water (50 wt% MEG)
    - Gas + Condensate + Water (42 wt% MeOH)
  - No Significant Difference in Flow Behavior for Three Different Cases
  - No Data Presented

Literature Review …

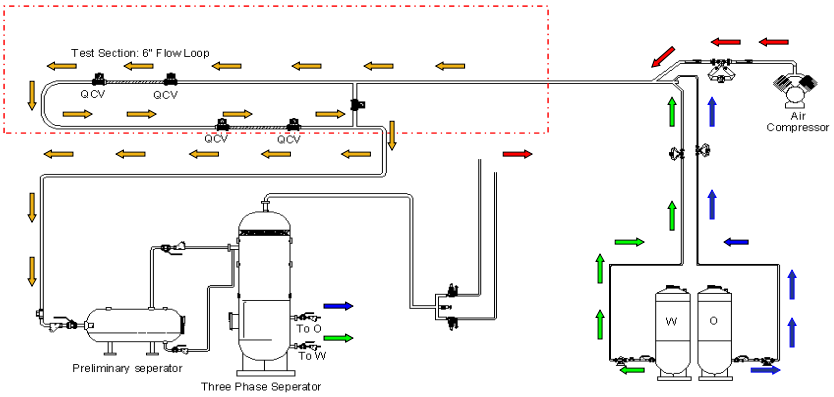
- Manfield *et al*. (2007)
  - Coulomb Field
    - Two-Well Gas/Condensate Development in Gulf of Mexico
    - Two Wells: C2 and C3
    - Well C3 Contains Higher Wax Content
    - Large Emulsion Viscosities When C3 is Produced

Experimental Program

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

Experimental Facility

6-in ID Low Liquid Loading Facility

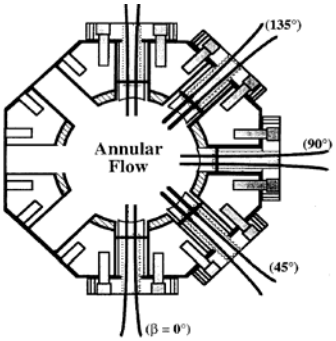


Measurement Techniques

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

Measurement Techniques …

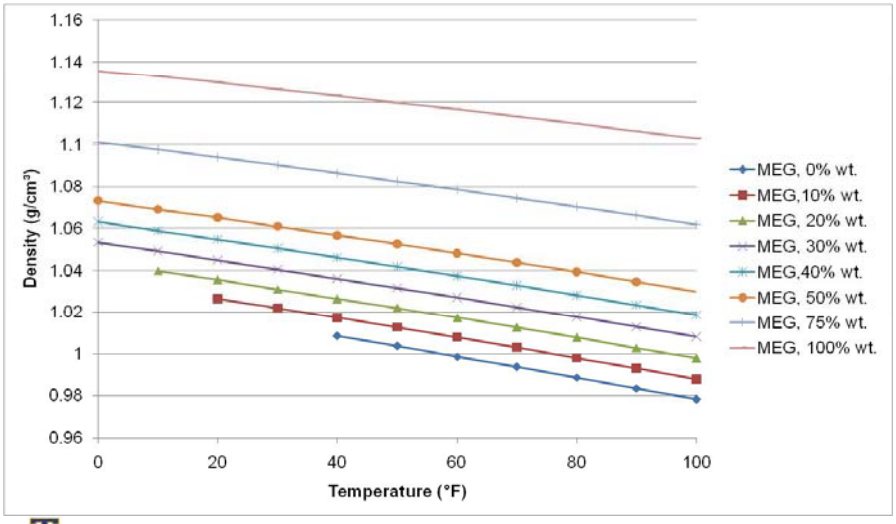
- Capacitance Probes
  - Multiple Probes Around Pipe Periphery



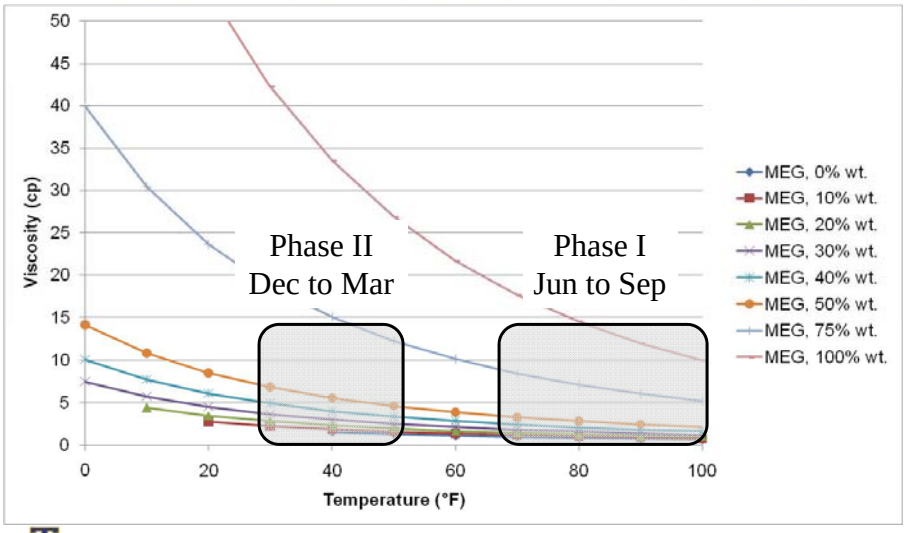
Measurement Techniques …

- Densito 30PX

Water+MEG Densities



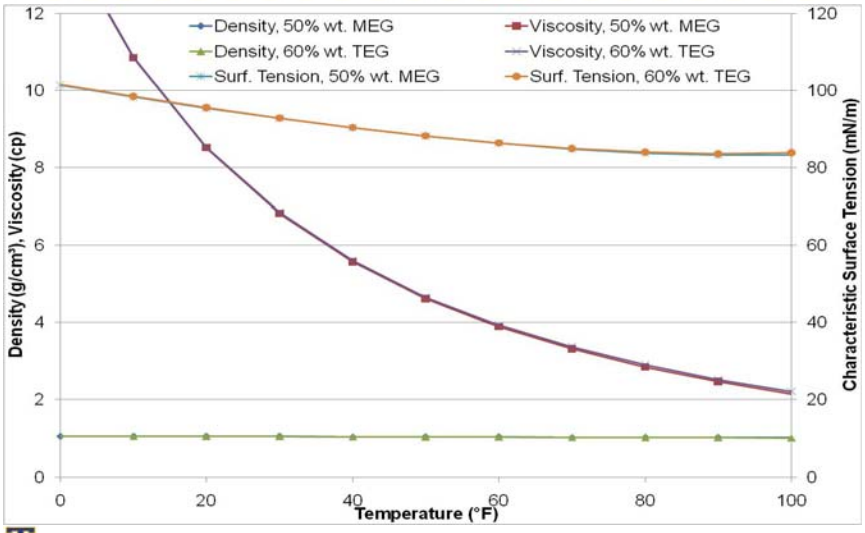
Testing Range



Fluid Flow Projects

Advisory Board Meeting, Oct 26, 2011

TEG Instead of MEG ?



Fluid Flow Projects

Advisory Board Meeting, Oct 26, 2011

Future Activities

- Project Definition
  - Preliminary Discussions (Fall 2011)
  - Test Matrix (January 2012)
- Flow Loop Modification (Spring 2012)
- Data Acquisition (Starting Summer 2012)
- Model Comparison and Development (Starting Spring 2013)

Questions and Comments

?

Effects of MEG on Multiphase Flow Behavior

Hamidreza Karami Mirazizi

Project Completion Dates

Literature Review	Ongoing
Test Matrix Design	Winter 2011
Flow Loop Modification	Spring 2012
Data Acquisition	Summer 2013
Model Comparison and Development	Fall 2013

Objectives

The specific objectives of this study are:

- Collect Flow Pattern, Holdup, Pressure Drop and Entrainment Data on a 6" Pipe With and Without MEG under Steady State, Developing and Start up-Shut Down Condition;
- 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 in order to allow predictions of MEG concentration in the different phases. Some work has been done at Tulsa and SWRI on settling and effectiveness of MEG injection under quiescent conditions 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. The scopes of these systems are real time virtual metering, pressure drop calculations, liquid holdup predictions, MEG tracking, ramp up/turn down scenario modeling, 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 and address scale-up in this area that can be used by model developers, current and future.

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 or modeling studies for three-phase gas-oil-water flow. Among these studies, few of them are investigating low liquid loading flow. Reliable works for the low liquid loading range are important for calculating flow rates of natural gas, containing traces of condensate.

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. It is also important to predict the flow pattern and wetted wall fraction by liquid phases, under different rates of MEG injection. Only few studies have investigated the effect of MEG on multiphase flow parameters. No experimental data or comprehensive analysis has been reported. 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 coefficients, the ratio of gas and liquid densities and superficial velocities. One of the coefficients takes into account the effect of MEG concentration on liquid holdup.

Later, Hamersma & Hart (1989) conducted a new study on air-water two-phase flow by adding different glycol concentrations and a detergent (Tween). By decreasing the interfacial tension, resulted from adding these additives, they observed no effect on the value of liquid holdup and the wetted wall fraction. However, by decreasing the interfacial tension, 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 and benchmarked OLGA2000. They described the flow assurance challenges and technical solutions selected for the harsh environmental condition of Ormen Lange field. The experimental work was conducted in four different campaigns: gas-condensate, gas-condensate-fresh water, gas-condensate-fresh water including 50 wt% MEG, gas-condensate-fresh water including 42 wt% MeOH. The OLGA2000 model was modified according to

the conducted experimental work. Using three different water phases, they observed no major differences in flow behavior between them. However, no data was presented in the paper.

Manfield *et al.* (2007) investigated the performance of the two gas-condensate wells in Coulomb field in Gulf of Mexico. In this field, one of the wells had higher wax content and while operating that well, large emulsion viscosities were observed. They concluded that MEG used for hydrate inhibition promotes emulsion formation when combined with condensate. This emulsion affects pressure drop values of the well caused by wax deposition.

Experimental Program

For this study, the 6 in. ID low liquid loading facility will be utilized. The current measurement techniques, along with some new instrumentation will be used. Pressure and temperature will be measured 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. New capacitance system, including multiple probes around the pipe periphery, will be used to estimate wave characteristics. Finally, a portable densitometer, Densito 30PX, is considered to monitor MEG concentration for different experiments.

Adding MEG to the aqueous phase changes its characteristics. The phase density increases slightly by 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 onset of entrainment. Experiments are planned to be conducted in two phases. Phase-1 will be conducted at high temperature range of 70-90 °F, from July to September. Phase-2 will be conducted at low temperature range of 40-60 °F, from November to March. Simulation results obtained from PVTsim show that at summer temperatures (70-90 °F), triethylene glycol (TEG) presents similar properties as MEG at low temperatures (40-60 °F). Thus, TEG may be utilized to study the effect of MEG at low temperatures avoiding winter conditions.

Different MEG concentrations from 10 wt% to 100 wt% will be used for experiments. Inclination angles of 0° and ±2° are the experimental values selected. The design of the test matrix will be confirmed in near future. First set of the experiments will be conducted with fully mixed liquid phases. Water and MEG will be mixed in the tank and keeping the MEG concentration constant. The resulting values of pressure drop, holdup, and entrainment rate will be compared for the effects of different concentration. Second set of experiments will be conducted under developing conditions. For this case water and glycol will be kept at different tanks. The evolution of the air-water-MEG mixture will be analyzed along the flow loop. Third set of experiments will investigate the effect of start-up and shut-down conditions on the controlled parameters.

References

Hamersma, P.J., and Hart, J., “A Pressure Drop Correlation for Gas/Liquid Pipe Flow with a Small Liquid Holdup”, Chem. Engng Sci. 42 (1987), pp. 1187-1196.

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.

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

Manfield, P., Nisbet, W., Balius, J., Broze, G., Vreenegoor, L., “Wax-On, Wax-Off: Understanding and Mitigating Wax Deposition in a Deepwater Subsea Gas/Condensate Flowline”, Offshore Technology Conference, Paper # 18834 (2007).

Fluid Flow Projects

Modeling of Droplet Entrainment in Co-current Annular Two-Phase Flow: A New Approach

Abdel Al-Sarkhi

Advisory Board Meeting, October 26, 2011

Outline

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

Objective

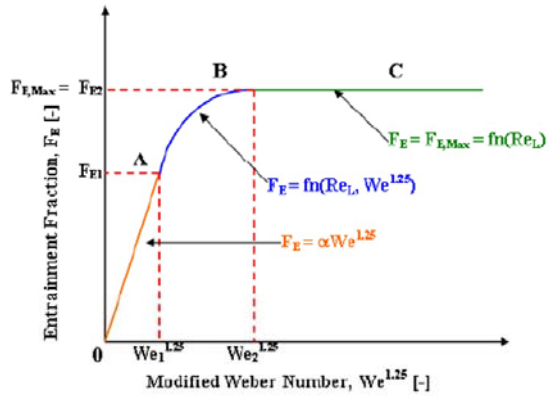
- Develop a Simple, Explicit and Accurate Entrainment Model With a Wide Range of Applicability
  - The Model Should not Allow Negative Entrainment Values or a Very Large Value That Exceeds the Maximum Possible Value

Introduction

- Annular Flow, Occurs in Many Industries and Processes
  - Steam Generation and Power Plants
  - Heating and Refrigeration Equipment
  - Transportation of Crude Oil and Natural Gas
- In Annular Flow, Entrainment Fraction Prediction is Important for the Estimation of Pressure Drop, Flow Rate, Liquid Holdup, Dry-out

Entrainment Modeling

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



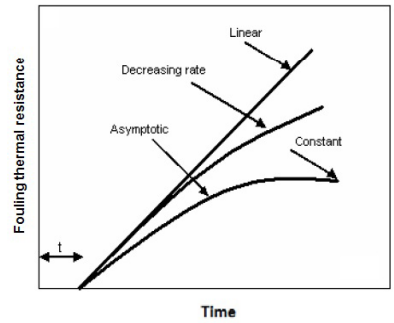
(Sawant *et al.* (2008))

Entrainment Modeling …

- The Trend Observed in Previous Figure has also been Seen in Many Other Processes
  - Step Response of Electrical Systems (Start-up of an Electric Motor (Ogata (2003))
  - Charging of a Capacitor in Resistance-Capacitance (RC) Circuit
  - Fouling of Heat Exchangers (Bott (1995))

Entrainment Modeling …

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



Various fouling models(Bott (1995))

Entrainment Modeling …

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

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

Where:

R_f : the fouling resistance (common units are m^2K/W)

t: time

R_f^* : the **asymptotic** value of the fouling resistance

τ_c : the time constant, which is the time when fouling resistance reaches 63.2% of the asymptotic value

Entrainment Modeling …

- **With the Analogy for the Entrainment Fraction, the Work of Sawant *et al.* (2008) Leads to the Following Model**

$$F_E = \boxed{F_{E,max}}(1 - exp(-We_{SG} / \boxed{We^*_{SG}}))$$

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

Where

We_{SG} : Superficial Gas Weber Number

$F_{E,max}$: Asymptotic Value of Entrainment Fraction

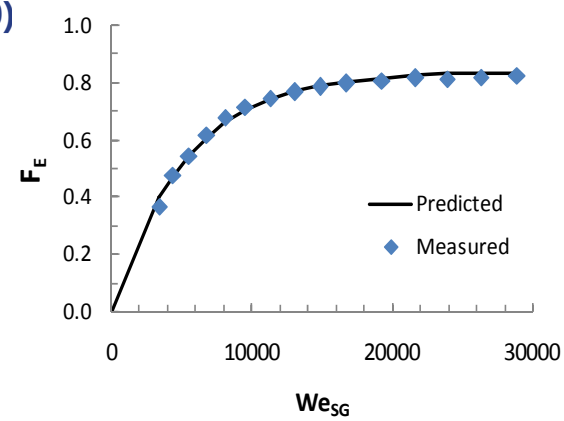
We_{SG}^* : Analogous Time Constant, Dimensionless and the Weber Number When Entrainment Fraction is 63.2% of Its Asymptote

Entrainment Modeling …

- **Model Validation**
  - **Model Contains Two Constants i.e., $F_{E,max}$ and We_{SG}^***
  - **Two Constants are Currently Determined from the Available Experimental Data**
  - **Responses of Several Data Sets Representing Different Operational Conditions, Pipe Diameters and Orientations are Tested**

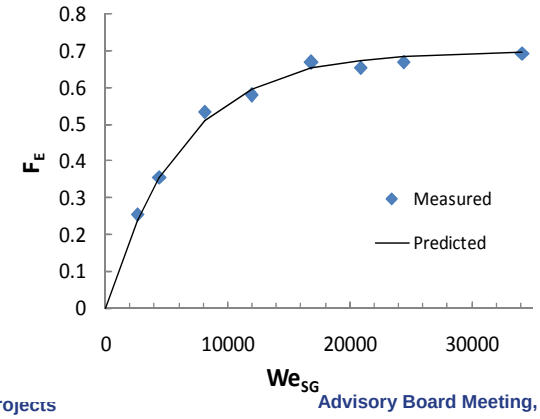
Model Validation

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



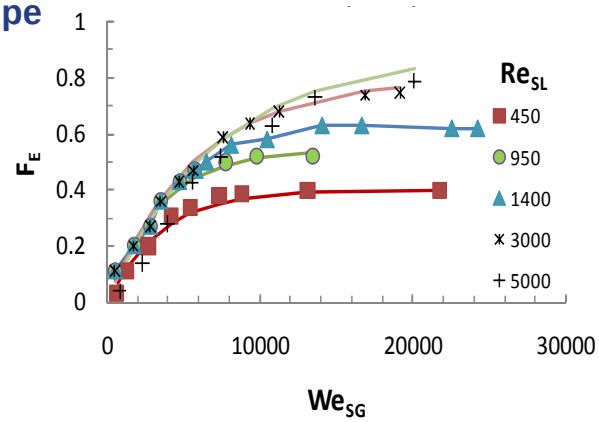
Model Validation…

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



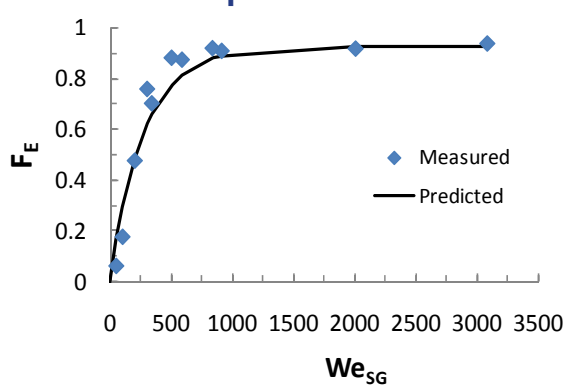
Model Validation …

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



Model Validation …

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



Model Validation …

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

Modeling of $F_{E,max}$

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

Modeling of $F_{E,max}$ …

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

$$F_{E,max} = 1 - \frac{13N_{\mu f}^{-0.5} + 0.3(Re_{SL} - 13N_{\mu f}^{-0.5})^{0.95}}{Re_{SL}}$$

$$N_{\mu f} = \frac{\mu_f}{\left(\rho_f \sigma \sqrt{\frac{\sigma}{g\Delta\rho}}\right)^{1/2}}$$ Viscosity Number

$$Re_{SL} = \frac{\rho_f V_{SL} D}{\mu_f}$$ Superficial Liquid Reynolds Number

Modeling of $F_{E,max}$ …

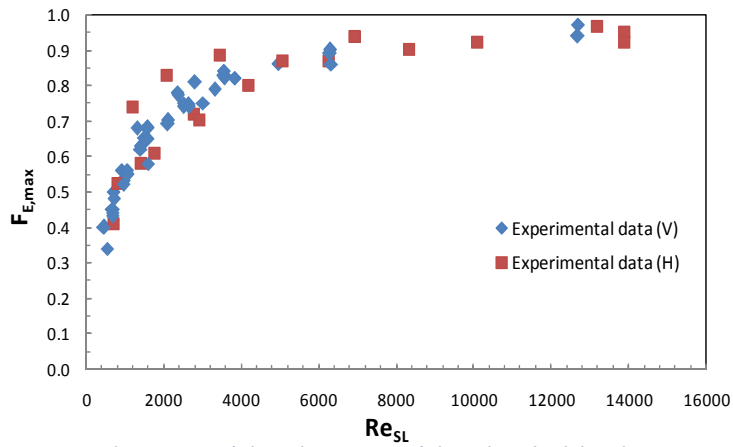
- **Sawant *et al.* (2009)**

$$F_{E,max} = 1 - \frac{13N_{\mu f}^{-0.5} + 0.3(Re_{SL} - 13N_{\mu f}^{-0.5})^{0.95}}{Re_{SL}}$$

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

$$\mathrm{Re}_f < 13N_{\mu f}^{-0.5} \quad \text{OR} \quad (\mathrm{Re}_{SL} - 13N_{\mu f}^{-0.5}) < 0$$

Variation of $F_{E,\,max}$ vs. Re_{SL} (Vertical (V) and Horizontal (H) Pipes)



Exp. Data: (Sawant *et al.* (2008); Owen *et al.* (1985), Schadel and Hanratty (1989); Deryabina *et al.* (1989), Magrini (2009); Assad *et al.* (1998); Mantilla (2008); Dallman (1978), Laurinat (1982) and Williams (1990))

Modeling of $F_{E,max}$ …

- **Following Closure Relationship is Proposed**

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

Where

Re_{SL} : Superficial Liquid Reynolds Number

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

Re_{SL}^{*} : Analogous Time Constant in the Form of a Reynolds Number When Maximum Entrainment Fraction Reaches 63.2% of Its Limiting Value

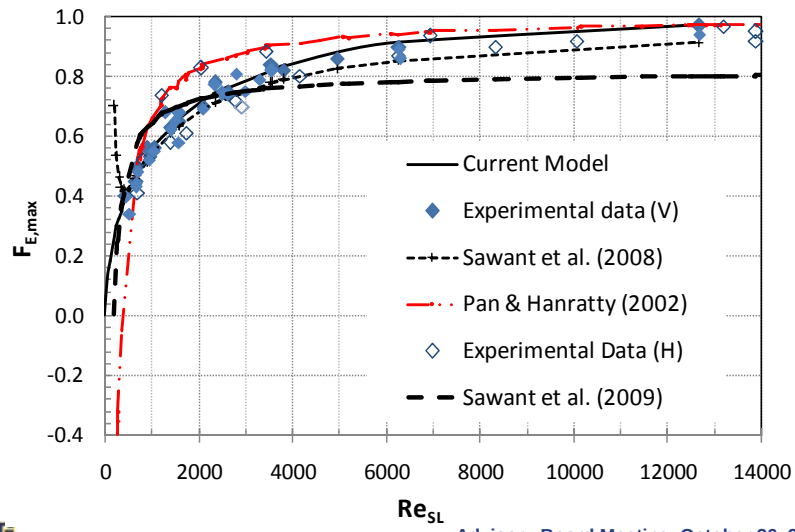
$F_{E,max}$ Closure Relationship

- Two Constants
  - Can be Determined Based on the Experimental Data Shown in the Previous Figure
- If All Thermo-physical Properties Remain Constant in the Reynolds Numbers, the Superficial Liquid Velocity, v_{SL}, can be Used Instead of Re_{SL}

$F_{E,max}$ Closure Relationship …

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

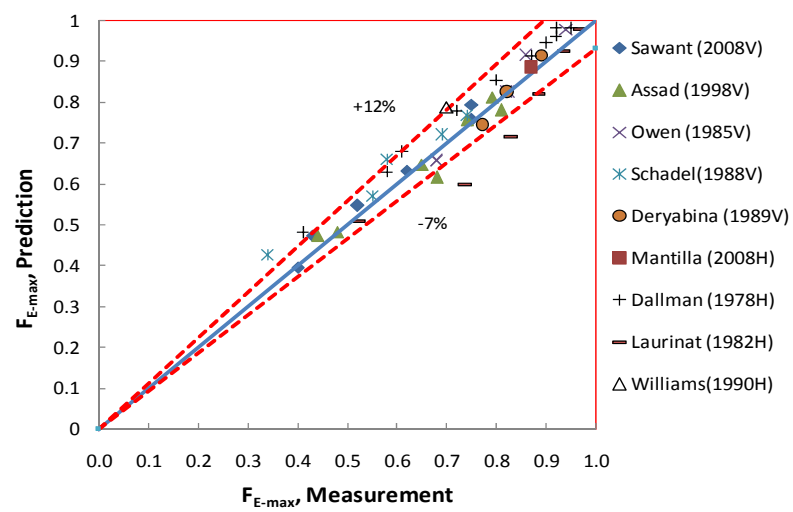
Validation of $F_{E,max}$ Closure Relationship



Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

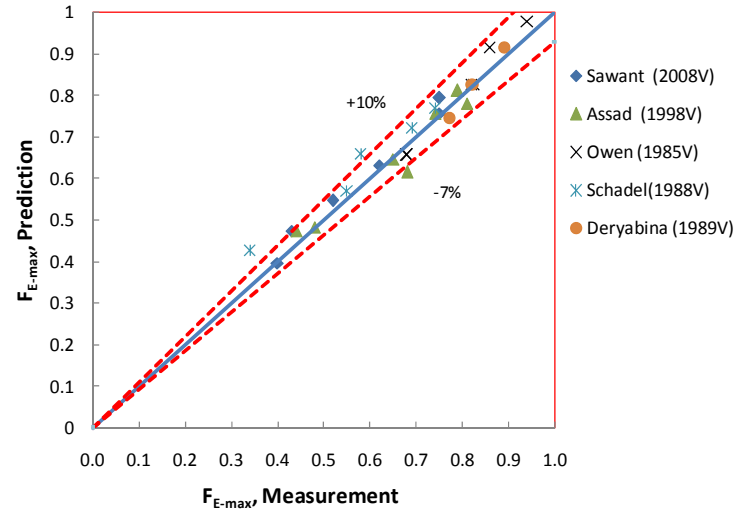
Validation of $F_{E,max}$ Closure Relationship …



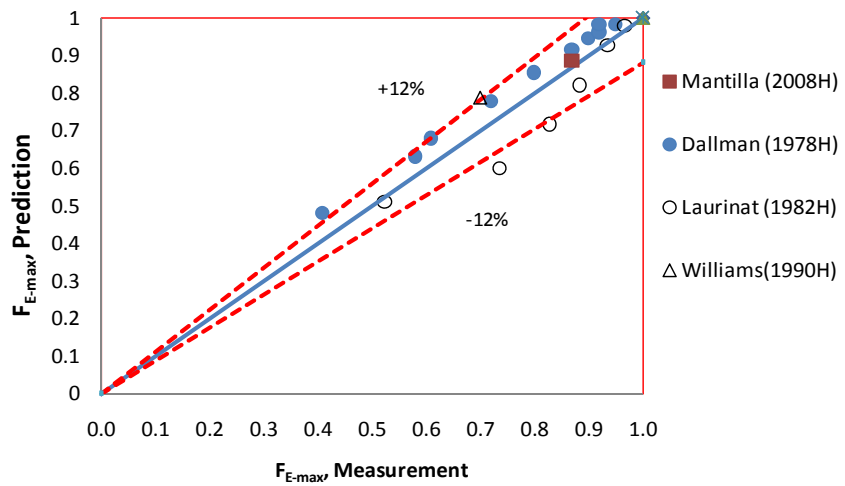
Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

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



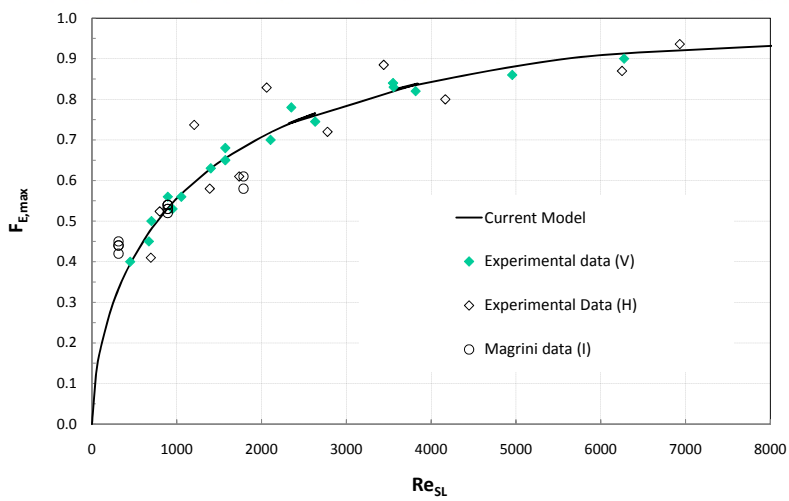
Validation of $F_{E,max}$ Closure Relationship …



Comparison With Others

- Pan and Hanratty (2002) Over Predicts While Sawant *et al.* (2008) Under Predicts
- Sawant *et al.* (2009) Under Predicts at High Re_{SL} and Over Predicts at Low Re_{SL}
- Sawant *et al.* (2008) and Pan and Hanratty (2002) Cannot Predict Maximum Entrainment Fraction at Very Low Liquid Reynolds Numbers (~ Re_{SL} < 400)
- Sawant *et al.* (2009) also has Similar Problems at Low Re_{SL}
- Proposed Equation Predicts the Experimental Data Very Well

Effect of Inclination Angle on $F_{E,\,max}$



Conclusions

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

Recommendations

- More Investigation is Needed for the Second Constant, We_{SG}^*
- Significant Experimental Work Still Need to Be Performed for Very High ($F_{E,max}$ > 0.85) and Low ($F_{E,max}$ < 0.5) Maximum Entrainment Fraction Region Using Air-water Two-phase Flow and Other Two-phase Fluid Flow Combinations

Modeling of Droplet Entrainment in Co-current Annular Two-Phase Flow: A New Approach

Abdel Alsarkhi

Abstract

Entrainment fraction is one of the key parameters in many applications including wellbore and flow line design, separator design and wellbore loading and many others. Entrainment fraction in annular flow is defined as the fraction of the total liquid flow in the form of droplets in the gas core. Its prediction is important for the estimation of pressure drop, liquid holdup and dry-out in annular flow. Recently, Al-sarkhi and Sarica (2011 a, b) explained how the models of Pan and Hanratty (2002) and Sawant *et al.* (2008) have failed to predict the maximum entrainment fraction at low liquid Reynolds number. A new methodology of modeling the entrainment fraction, containing only two constants, is proposed. The model was found to predict the experimental data available in the literature very well. Furthermore, an equation for the maximum fraction of entrainment was developed. The proposed maximum entrainment fraction equation predicted more accurately than the equations found in the literature.

Introduction

Annular flow occurs in many industrial processes, and is characterized by high gas flow at the center of the pipe and liquid film flow around the pipe wall. Due to the high gas velocity, large shear velocities are induced that result in high interfacial shear stress causing continuous entrainment of liquid droplets into the gas core from the liquid film. Entrainment fraction results from a dynamic equilibrium between the rate of deposition of drops from the gas core to the liquid film and the rate of droplet formation (also called Atomization) at the gas-liquid interface from waves occurring on the film surface (Pan and Hanratty (2002), Mantilla *et al.* (2008), Al-sarkhi *et al.* (2011)). There are immense amount of data and correlations available in the literature for vertical flow to predict entrainment fractions; the most well-known of which are by Wallis (1969), Oliemans *et al.* (1986), Ishii and Mishima (1989), Pan and Hanratty (2002a), and most recently by Sawant *et al.* (2008) and Schubring and Shedd (2011). Many of these authors (Pan and Hanratty (2002a), Sawant *et al.* (2008), Wallis (1969), and Ishii and Mishima (1989)) used the exponent type of functions in one form or another in their correlation or model. All these correlations vary in their prediction of entrainment fraction resulting in high uncertainty and lower confidence in design.

The objective of this project is to develop an equation for maximum fraction of entrainment and an entrainment model that is simple and explicit yet accurate with a wide range of applicability. Furthermore, it is understood that the model should not allow negative entrainment values or a very large value that exceed the maximum possible value.

Entrainment Modeling

From the onset of entrainment to the asymptotic condition, the complete process, according to Sawant *et al.* (2008), can be divided into three parts (See Fig. 1).

The trend observed in Fig. 1 has also been seen in many other processes such as step response of electrical systems (e.g. start-up of an electric motor (Ogata (2003)), charging of a capacitor in Resistance-Capacitance (RC) circuit and fouling of heat exchangers (Bott (1995)).

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

$$R_f = R_f^*(1-\exp(-t/\tau_c)), \qquad (1)$$

where R_f is the fouling resistance (common units are m^2-K/W), t is time, R_f* is the asymptotic value of the fouling resistance, and τ is the time constant. The time constant has units of seconds and is the time when fouling resistance reaches 63.2% of the asymptotic value.

Similarly, if an analogy is made for the entrainment fraction, then the work of Sawant *et al.* (2008) leads to the following model:

$$F_E = F_{E,max}(1-exp(-We_{SG}/We_{SG}^*)). \qquad (2)$$

Where F_E is the entrainment fraction, We_{SG} is the superficial gas Weber number, $F_{E,max}$ is the asymptotic value of the entrainment fraction, and We_{SG}* is the analogous time constant. The time constant, in this case is dimensionless and is the Weber number when entrainment fraction reaches 63.2% of its asymptotic value. Sawant *et al.* (2008) defined a modified Weber number as follows:

$$We_{SG} = \frac{\rho_G v_{SG}^2 D}{\sigma}\left(\frac{\rho_L - \rho_G}{\rho_G}\right)^{1/4}. \quad (3)$$

Where v_{SG} is the superficial gas velocity, D is the pipe diameter, ρ is density of either gas (G) or liquid (L) and σ is the surface tension. Equation (3) contains two constants i.e. $F_{E,max}$ and We_{SG}*. The responses of several data sets representing different operational conditions, pipe diameters and orientations are shown in Figures 2(a) and 2(b). In Figure 2(a) the average absolute error was calculated as 1.76%.

An assessment of Figs. 2(a) and 2(b) illustrates that the proposed model has a strong and clear potential to predict entrainment fractions in two-phase vertical and horizontal annular flow. The model is not complex and, the only information required, besides the two constants, is the superficial gas velocity.

Modeling of Maximum Entrainment Fraction ($F_{E,max}$)

The literature was searched for data from which maximum entrainment fraction values (asymptotic values) could be extracted. The experimental data from many sources (Sawant *et al.* (2008); Owen *et al.* (1985), Schadel and Hanratty (1989); Deryabina *et al.* (1989), Magrini (2009); Assad *et al.* (1998); Mantilla (2008); Dallman (1978), Laurinat (1982) and Williams (1990)) such that the maximum entrainment fraction is shown as a function of the superficial liquid Reynolds number, in accordance with the explanation provided by *Sawant et al.* (2008).

As the behavior is asymptotic, the following equation, which is similar to the overall model equation, is proposed.

$$F_{E,max} = F_{E,max,lim}\left[1 - exp\left(-\left(\frac{Re_{SL}}{Re_{SL}^*}\right)^{0.6}\right)\right]. \quad (4)$$

Where $F_{E,max}$ is the maximum entrainment fraction, Re_{SL} is the superficial liquid Reynolds number, $F_{E,max,lim}$ is the asymptotic or limiting value of the maximum entrainment fraction and Re_{SL}* is the analogous time constant in the form of a Reynolds number. The time constant, in this case is the Reynolds number when maximum entrainment fraction reaches 63.2% of its limiting value. Since Eq. (4) represents a closure relationship, the two constants can be determined based on the experimental data shown in Figure 3 and, thus, no further equations are required. The limiting value of the maximum entrainment fraction, $F_{E,max,lim}$, has been discussed in the literature, and is known to have a value of little less than one (Assad *et al.* (1998), Sawant *et al.* (2008)). However, the limiting value would be very close to one, and a good a reasonable value would be just one.

The comparison of the experimental data with the above proposed equation as well as the models of Pan and Hanratty (2002 a) and Sawant *et al.* (2008) is shown in Figure 4 below. It should be noted that a value of 1400 was determined for Re_{SL}* (the Reynolds number when maximum entrainment fraction reaches 63.2% of its limiting value of 1). It is clear from the figure that, in general, Pan and Hanratty (2002 a) over-predicts the maximum entrainment fraction while Sawant *et al.* (2008) under-predicts. More recent model of Sawant *et al.* (2009) under-predicts at high Re_{SL} and over-predicts at low Re_{SL}. Furthermore, Sawant *et al.* (2008) and Pan and Hanratty (2002) cannot predict maximum entrainment fraction at very low liquid Reynolds numbers (~ Re < 400). Sawant *et al.* (2009) also has similar problem at low Re_{SL} when $\mathrm{Re}_f < 13N_{\mu f}^{-0.5}$. The proposed equation goes to zero at Re_{SL} = 0 and the others do not. The proposed equation predicts the experimental data very well.

Figure 5 show the model performance in graphical format, it can be concluded that the model consistently provides good prediction.

Effect of Inclination Angle on Maximum Entrainment Fraction, $F_{E,\,max}$

Magrini (2009) data for the lowest three values of Re_{SL} have been used to investigate the effect of the pipe inclination angles on the maximum fraction of entrainment, $F_{E,\,max}$. As shown in Fig. 6, it seems that there is no inclination effect on the maximum fraction of entrainment. More data for $F_{E,\,max}$ are needed at higher Re_{SL} to verify with certainty that there is no effect of pipe inclination angles.

Conclusions and Recommendations

The entrainment fraction was successfully modeled using experimental data from various sources in the literature. The only information model requires are the superficial liquid and gas velocities.

The model of Sawant *et al.* (2008) for maximum entrainment fraction does not predict very well at high (Re_{SL} > 4000) or very low liquid Reynolds numbers (Re_{SL} < 400). Model of Sawant *et al.* (2009) for maximum entrainment fraction does not predict very well at high superficial liquid Reynolds numbers Re_{SL} > 4000) and has strange behavior for the asymptotic value which barely fluctuate around 0.8. Model of Pan and Hanratty (2002) for maximum entrainment fraction does not predict very well at low superficial liquid Reynolds numbers (Re_{SL} < 400).

The proposed maximum entrainment fraction prediction equation provide the best results compared with any equation in the literature and, thus, should be used with the model of Sawant *et al.* (2008) for now by replacing their maximum entrainment fraction equation with the one proposed in this work.

More investigations are needed for the second constant that was not determined i.e., We_{SG}*. A great deal of experimental work still needs to be performed for the very high ($F_{E,max}$ > 0.85) and low ($F_{E,max}$ < 0.5) maximum entrainment fraction region using air-water two-phase flow and other two-phase fluid flow combinations.

References

Al-sarkhi, A. and Sarica, C. 2011 a. Comment on: "correlation of entrainment for annular flow in horizontal pipes", by Pan, L., Hanratty, T.J., Int. J. multiphase flow, 28(3) (2002), 385-408. International Journal of Multiphase Flow, 37 (5), 535-536.

Al-sarkhi, A. and Sarica, C. 2011 b. Comment on: "Droplet entrainment correlation in vertical upward co-current annular two-phase flow", by Sawant, P., Ishii, M., Mori, M., Nuclear Engineering and Design 238 (2008) 1342-1352. Nuclear Engineering and Design, In press, Corrected Proof, Available online 11 June 2011.

Al-sarkhi, A., Sarica, C. and Magrini, K. (2011), Inclination effects on wave characteristics in annular gas–liquid flows. AIChE Journal, 57: n/a. doi: 10.1002/aic.12653

Andreussi, P., Asali, J.C., Hanratty, T.J., 1985. Initiation of small waves in gas–liquid flows. AIChE Journal 31, 119–126.

Assad, A., Lopez de Bertodano, M., Beus, S., 1998. Scaled entrainment measurements in ripple-annular flow in a small tube. Nucl. Eng. Des. 184, 437–447.

Bott, T.R., Fouling of Heat Exchangers, Chemical Engineering Monographs 26, Elsevier Science B.V., The Netherlands, 1995.

Dallman, J.C., 1978. "Investigation of Separated Flow Model in Annular Gas-Liquid Two-Phase Flow," PhD Dissertation, University of Illinois at Urbana, Champaign.

Deryabina, O.N., Semenenko, V.F., Medvedev, A.E., 1989. Distribution of the liquid phase in dispersed annular flow. Thermal Engineering 36(12), 207-235.

Ishii, M., Mishima, K., 1989. Droplet entrainment correlation in annular two-phase flow. International Journal of Heat and Mass Transfer 32(10), 1835-1846.

Laurinat, J.E., 1982. "Studies on the Effects of Pipe Size on Horizontal Annular Two-Phase Flows," PhD Dissertation, University of Illinois at Urbana, Champaign.

Mantilla, I., 2008. "Mechanistic Modeling of Liquid Entrainment in Gas in Horizontal Pipes," PhD Dissertation, University of Tulsa.

Magrini, K, (2009). Liquid entrainment in annular gas-liquid flow in inclined pipes. M.S. Dissertation, the University of Tulsa.

Ogata, K., System Dynamics, fourth edition, Prentice Hall, 2003.

Oliemans, R.V.A., Pots, B.F.M., Trompe, N., 1986. Modeling of annular dispersed two-phase flow in vertical pipes. International Journal of Multiphase Flow 12(5), 711-732.

Owen, D.G., Hewitt, G.F., Bott, T.R., 1985. Equilibrium annular flows at high mass fluxes; data and interpretation. PCH Physicochem. Hydrodyn. 6, 115–232.

Pan, L., Hanratty, T.J., 2002 a. Correlation of entrainment for annular flow in vertical pipes. International Journal of Multiphase Flow 28, 363–384.

Pan, L., Hanratty, T.J., 2002 b. Correlation of entrainment for annular flow in horizontal pipes. International Journal of Multiphase Flow 28, 385–408.

Sawant, P., Ishii, M., Mori, M. 2009. Prediction of amount of entrained droplets in vertical annular two-phase flow. International journal of heat and fluid flow, 30, 715-728.

Sawant, P., Ishii, M., Mori, M., 2008. Droplet entrainment correlation in vertical upward co-current annular two-phase flow. Nuclear Engineering and Design 238, 1342–1352.

Schadel, S.A., Hanratty, T.J., 1989. Interpretation of atomization rates of the liquid film in gas liquid annular flow. International Journal of Multiphase Flow 15, 893–900.

Schubring, D., Shedd, T.A., 2011. A model for pressure loss, film thickness, and entrained fraction for gas-liquid annular flow. International Journal of Heat and Fluid Flow 32(3), 730-739.

Wallis, G.B., One Dimensional Two-Phase Flow, McGraw-Hill, 1969.

Williams, L.R., 1990. "Effect of Pipe Diameter on Horizontal Annular Two-Phase Flow," PhD Dissertation, University of Illinois at Urbana, Champaign.

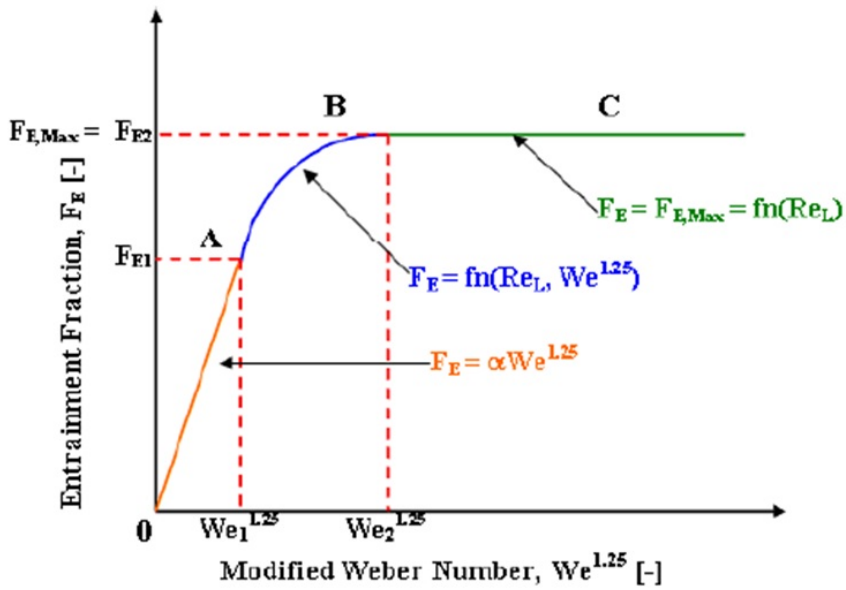


Figure 1: Entrainment process as explained by Sawant *et al.* (2008)

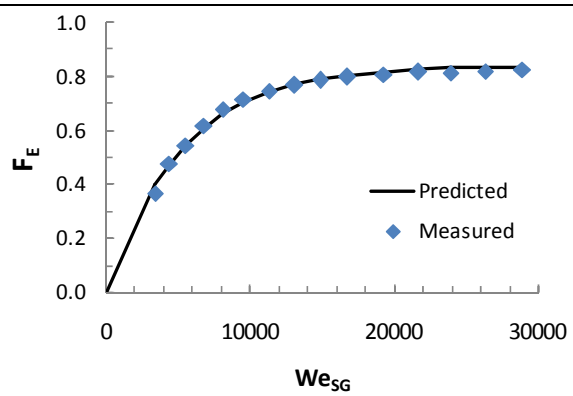


Figure 2(a): Model Comparison with Owen *et al.* (1985) data in vertical 0.0317 m diameter pipe (Re_{SL} =3550)

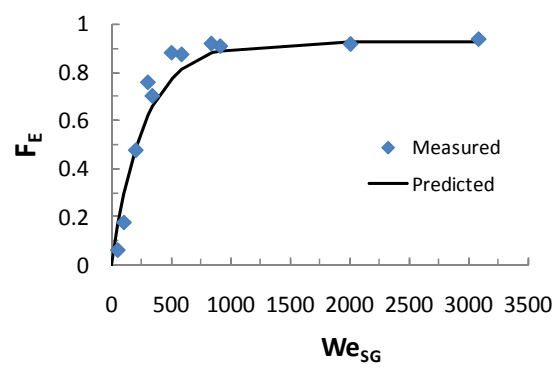


Figure 2(b): Comparison of proposed model with the data of Laurinat (1982) at Re_{SL} = 6905 in a horizontal 0.0508 m diameter pipe

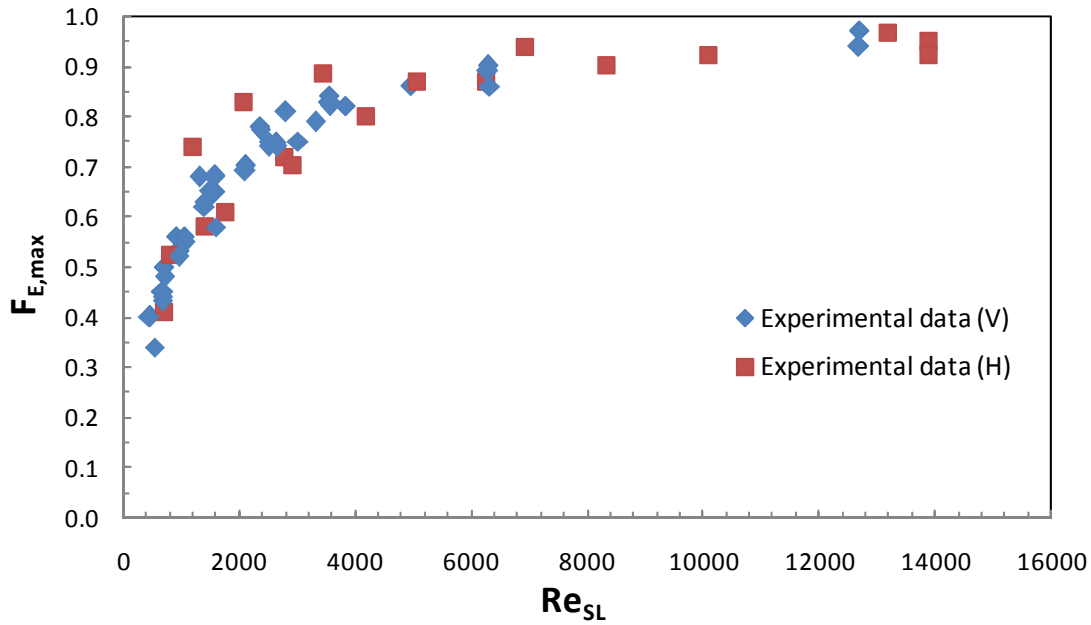


Figure 3: Variation of maximum entrainment fraction with superficial liquid Reynolds number (experimental data in vertical (V) and horizontal (H) pipes)

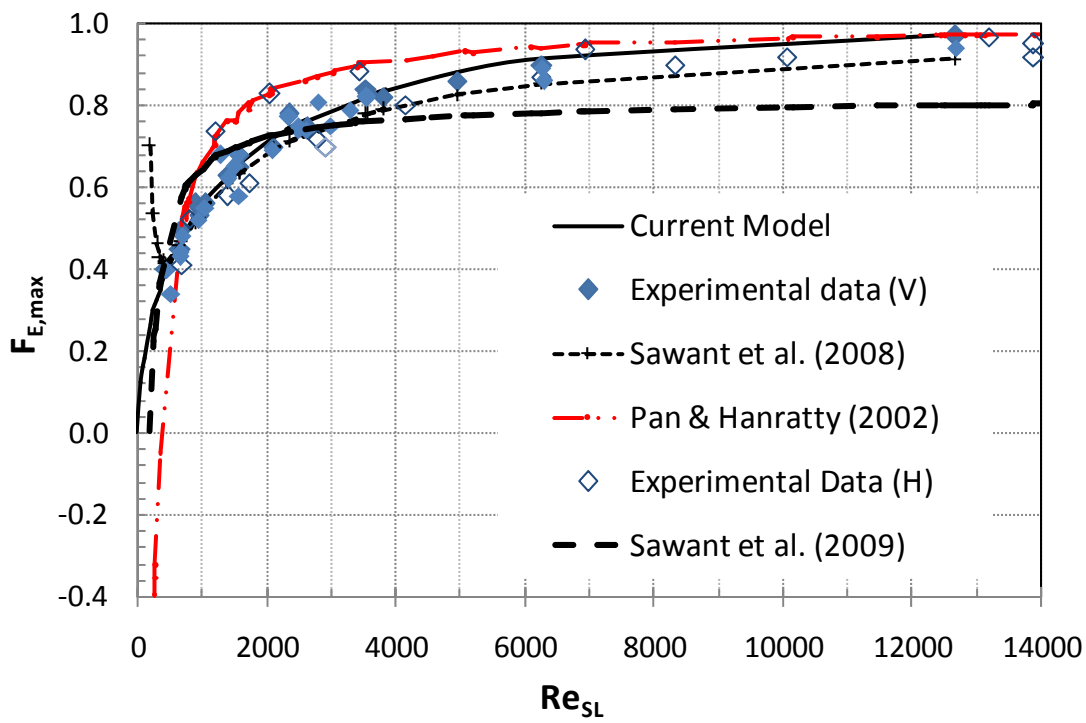


Figure 4: Comparison of proposed equation to predict maximum entrainment fraction

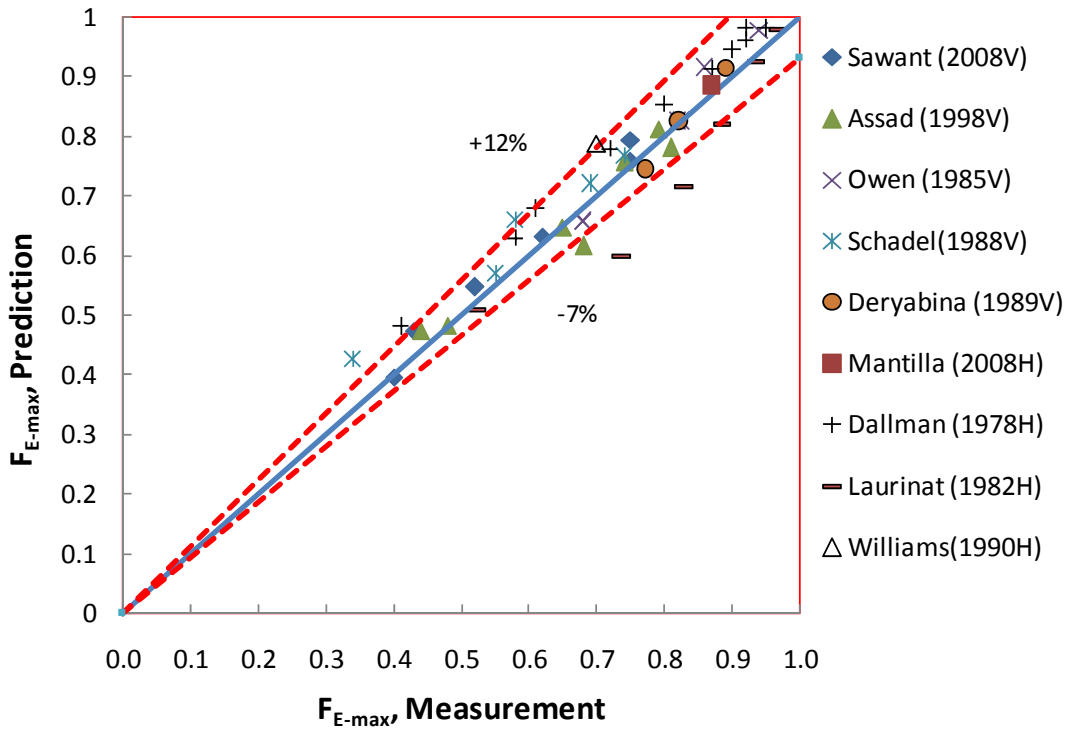


Figure 5: Comparison of proposed model with experimental data

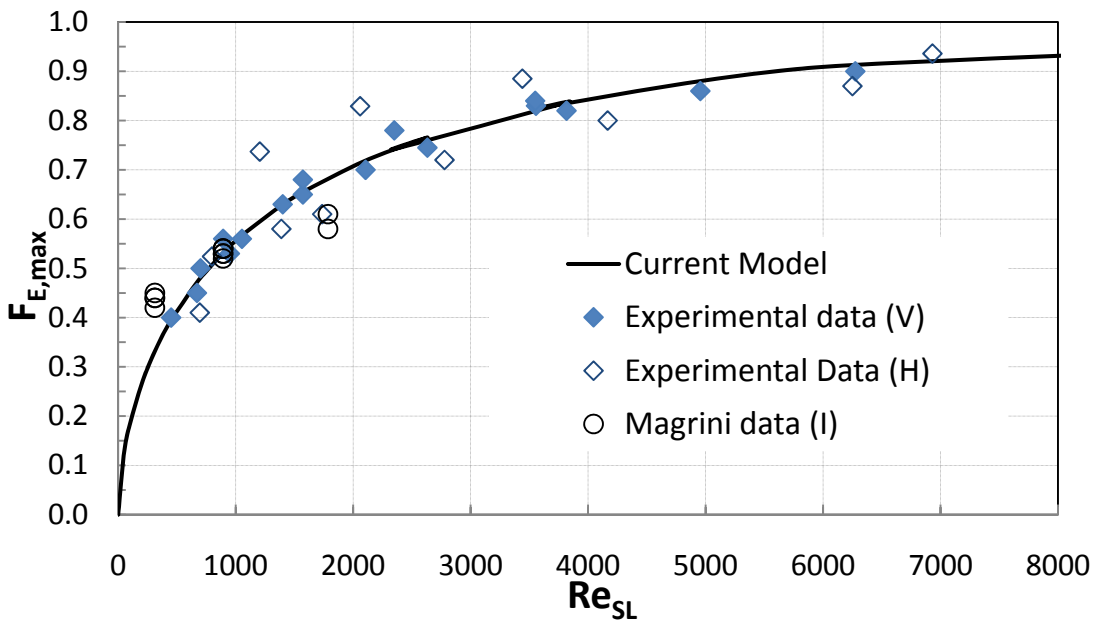


Figure 6: Comparison of proposed equation to predict maximum entrainment fraction

Fluid Flow Projects

High Pressure Test Facility Construction Update

Eduardo Pereyra and
Abdel Al-Sarkhi

Advisory Board Meeting, October 26, 2011

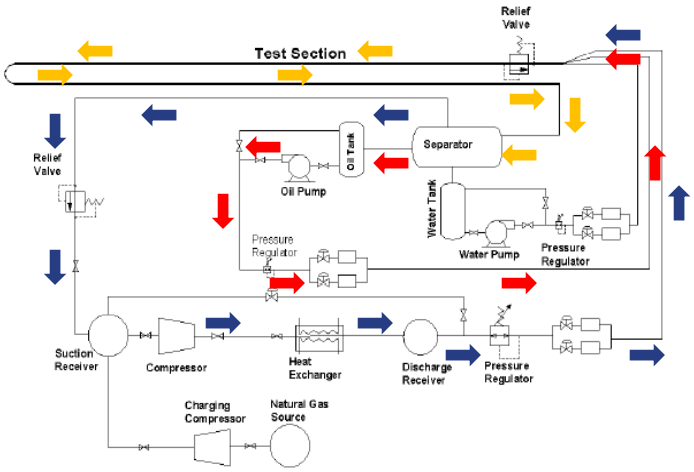
Outline

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

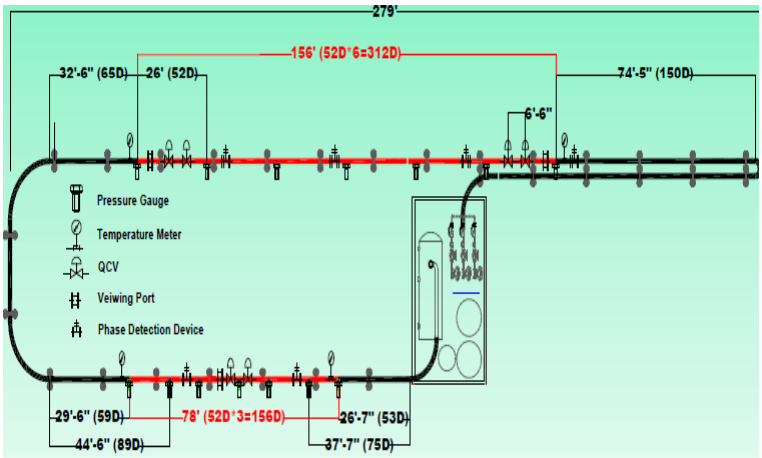
Objectives

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

Facility



Facility …



Test Fluids

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

Basic Instrumentation

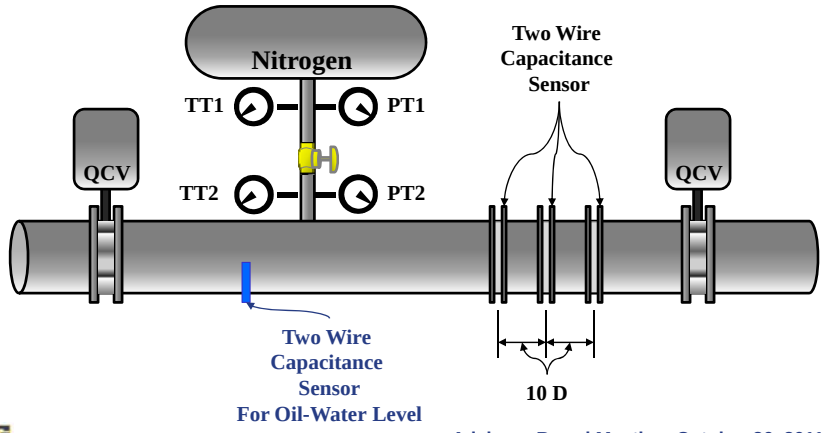
	Pressure (psig)	Capacity
Gas Flow Rate	600	18 MMSCFD
Water Flow Rate	600	200 GPM
Oil Flow Rate	600	200 GPM
Differential Pressure	500	0 – 50 in H_2O
Pressure	600	0 – 800 psi
Temperature	500	0-100 ° C
Quick Closing Valves	600	6 in. ID

Specialty Instrumentation

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

Quick Closing Valves

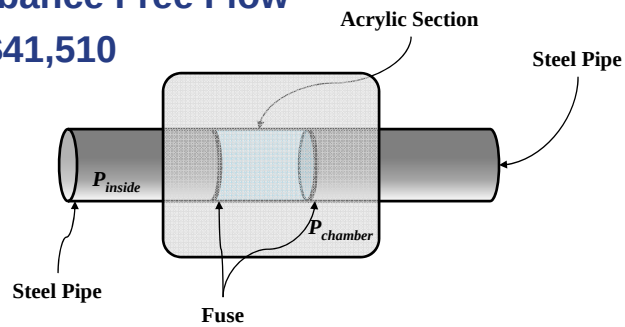
Two and Three Phase Flow



Visual Observation

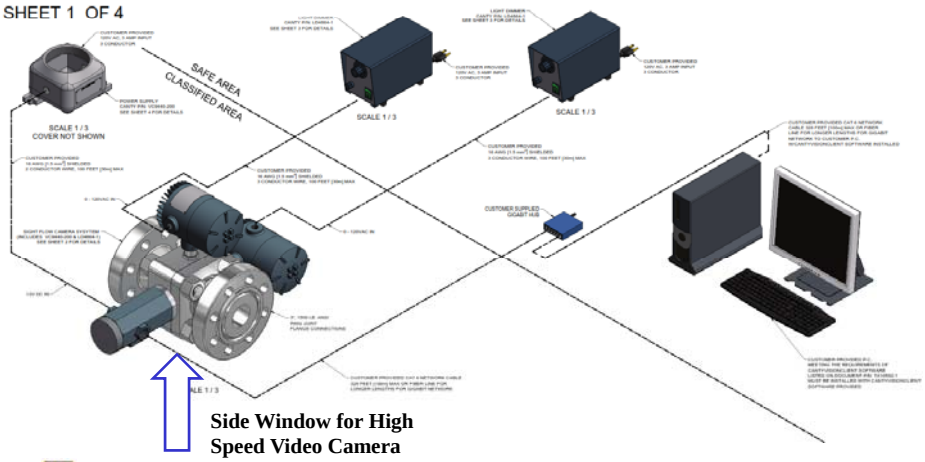
Custom Made High Pressure Sight Flow (Canty)

- Integral Light and Camera
- Disturbance Free Flow
- Cost $41,510



Visual Observation …

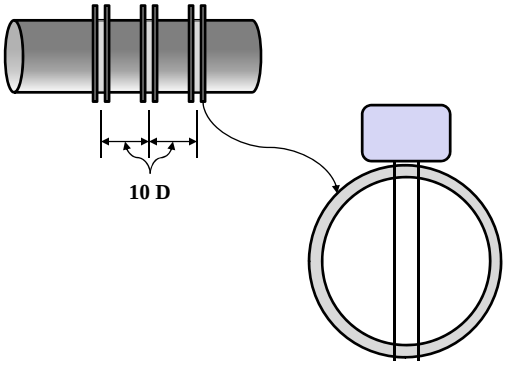
Custom Made High Pressure Sight Flow (Canty)



Capacitance Sensors

Two Wires

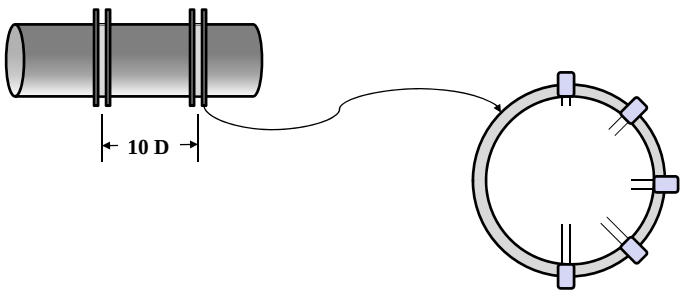
- Waves Characteristics
  - Length
  - Celerity
  - Frequency
  - Amplitude



Capacitance Sensors …

Film Distribution

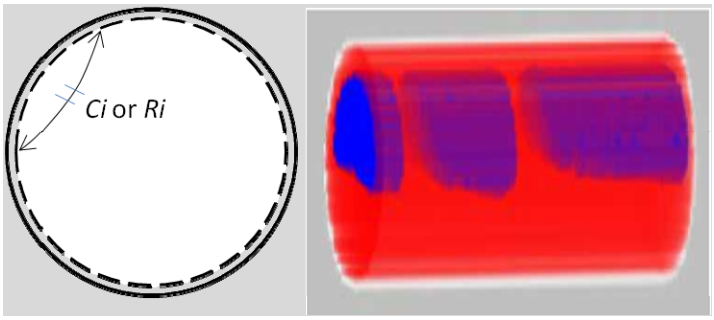
- Film thickness distribution



Capacitance Sensors …

Capacitance and Resistance Tomography

- Film Thickness Distribution
- Gas-Oil-Water (Water Continuous Only)



Capacitance Sensors …

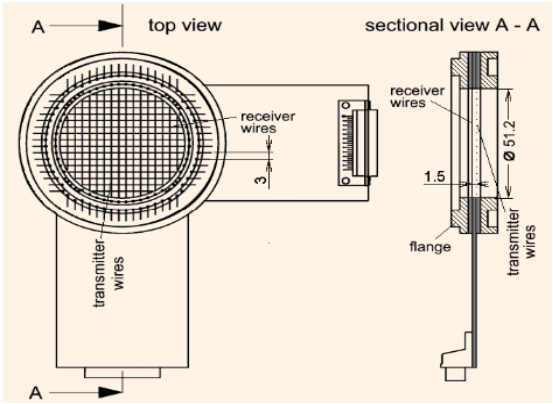
Capacitance and Resistance Tomography

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

Capacitance Sensors …

Wire Mesh Sensor

- Film thickness distribution



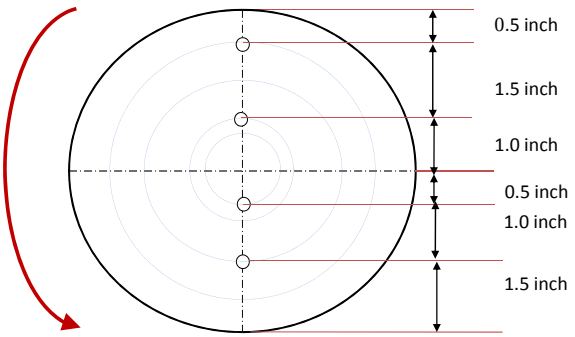
Capacitance Sensors …

Wire Mesh Sensor

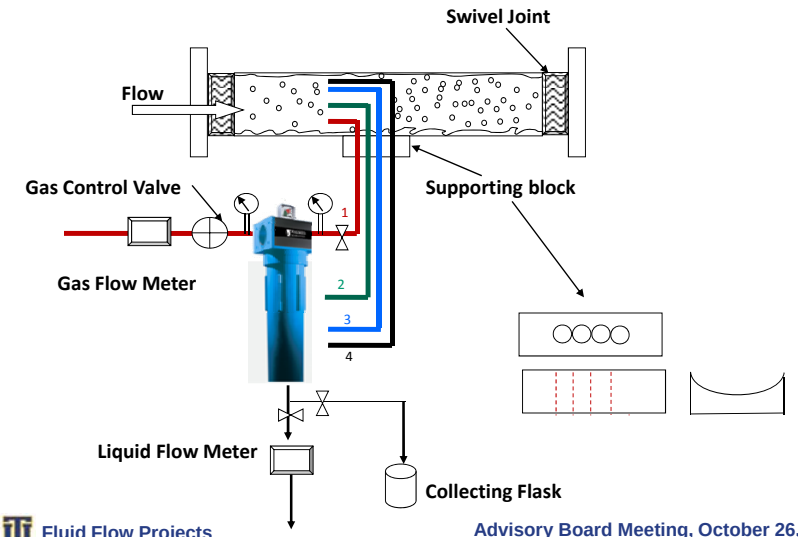
- GWT-TUD
  - Cost = $ 85,645.00 (32 by 32 Wires)
  - Include Software and Electronics
  - Rental Option

Iso-kinetic Sampling

Multiple Probe Design



Iso-kinetic Sampling …

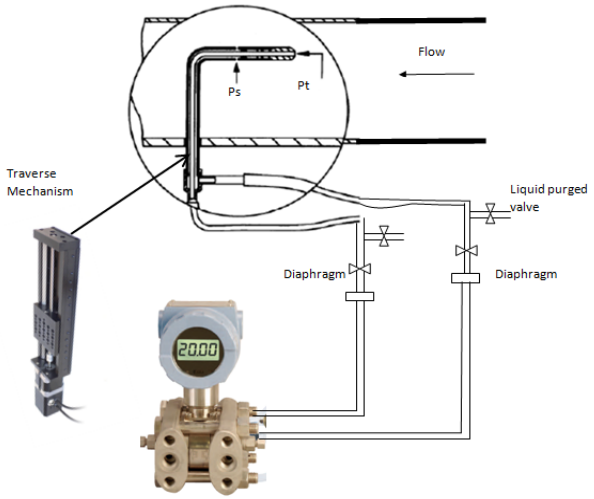


Pitot Tube

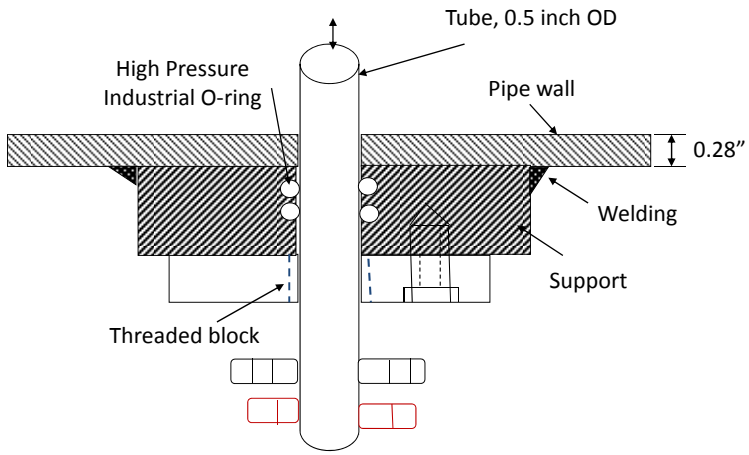
- Previously Used
  - Gas-Liquid Flow : Kawaji *et al.* (1987) and Andreussi *et al.* (1986)
  - Liquid-Liquid: Hamad and He (2010)
- Static and Dynamic Lines Filled with Liquid

Omega High Accuracy Pitot Tube

Pitot Tube …



Pitot Tube …



Construction Schedule

Completion Dates

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

Construction Schedule

HAZOP by COGNASCENTS

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

Construction Schedule …

HAZOP by COGNASCENTS

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

Questions/Comments

High Pressure Test Facility Construction Update

Eduardo Pereyra and Abdel Al-Sarkhi

Project Completion Dates

HAZOP	January 2012
Electrical, Data Acquisition and Control Systems	April 2012
Facility Commissioning	May 2012
Preliminary Test (Special Instrumentation Installed)	October 2011

Objective

The main objective is to construct a high pressure - large diameter multiphase flow facility to conduct up-scaling studies in multiphase flow.

Introduction

Gas-liquid pipe flow characteristics, such as flow patterns, pressure drop and liquid holdup, have been mostly investigated with small diameter pipes (2 or 3 in.) and low pressure conditions (lower than 100 psig). Two-phase flow behavior at high pressure and large pipe diameter may differ from that of at low pressure and small pipe diameters. Thus, validation and improvement for high pressure conditions is required.

Tulsa University Fluid Flow Project (TUFFP) has been constructing a newly high pressure and large pipe diameter facility. Experimental results from this facility can be used to evaluate and improve the available models and correlation.

This report presents the progress made in construction of the facility since the last Advisory Board meeting.

Facility Description

The facility is designed for gas-oil-water three-phase flow. Mineral oil (Isopar L) and distilled water are the liquid phases. The facilities, equipment and instrumentation are designed to work on either Natural gas (The Tulsa City Natural gas) or Nitrogen. Initially, Nitrogen is planned to be used due to its relatively low safety risk. Later, the gas phase will be switched to natural gas with no additional equipment required except a connection to the north campus flare system. Several quick closing valves will be used to isolate the sections of the facility in case of an emergency or leakage in some part of the flow loop. The current flare system will be checked before switching to the natural gas in terms of capacity, and flaring duration.

This facility is subdivided into two sections, namely, low pressure and high pressure side. The low pressure side includes the three-phase separator, oil and water tank. Two progressive cavity pumps and a turbine compressor boost the pressure of the single phases, which flows through the metering system before they mix at the inlet of the flow loop.

The stainless steel Schedule 40 test section has a length of 523 ft and internal diameter of 6 in.. The last section can be inclined 3° downward. For upward flow studies, the direction of the flow will be reversed. Thus, the fluid can circulate clock and counter-clock wise.

The inclinable section length is 279 ft (558xD). In counter-clock direction, the developing region is 410xD, test section is 52xD long and 65xD are considered before the first sharp bend. In clock wise direction, the developing region is 351xD, test section 52xD and 74xD before the first bend. These distances are expected to facilitate fully developed flow.

The maximum operating pressure is 500 psi and the loop operates at ambient temperature. The compressor nominal flow rate, discharge and suction pressures are 18 MMSCFD, 500 psig and 400 psig, respectively. The pumps are able to deliver 200 GPM with the same discharge and suction pressures (500 psig and 400 psig). Temperature and pressure transducer are installed to operate under the given conditions. Coriollis flow meters are used for gas and liquid flow rate measurements.

Specialty Instrumentation

This facility has been design initially for Low-Liquid Loading studies. Special instrumentation required to analyze the multiphase flow behavior under this conditions is presented in this section.

Quick Closing Valves

Two quick closing valves are used to trap the gas and liquid flows to measure the average holdup. For low liquid loading flows, in comparison to the size of the section, the liquid inventory is small. Thus, the calculation of the gas-liquid ratio by the draining the

liquid may result in a large uncertainty. Therefore, the measurement technique used by Kora (2010) is suggested for this application. This approach is based on equalizing pressure with a known reservoir. When the sample is trapped, the pressure and temperature of the section is recorded. A valve connected to a nitrogen recipient (with known volume, pressure and temperature) is opened. The gas-liquid ratio is obtained by measuring the final pressure and temperature and comparing with a calibration curve. For three-phase flow, a two-wire capacitance will be utilized to measure the oil-water interface and the oil-water fractions will be calculated from the geometrical relationships. This system requires prior calibration and verification to ensure low uncertainty in the gas-liquid ratio.

Visual Observation

A free disturbance flow and custom made visualization system has been proposed by JmCanty. An acrylic section is fused with two steel pipe pieces. A chamber surrounds the acrylic section and welded to the steel pipe pieces. The chamber is pressurized keeping the stress over the acrylic section below a critical value. Lights and cameras are located around the circumference of the pipe. The two light sources (HYL 250 Watt) are located at a 90° angle from each other. A JmCanty still picture process camera is located at 90° from the lights. The system is equipped with a side window located at 90° from the camera, where the actual high speed video system (Ultima 120kc) can be connected.

The total cost of the system is $41,510, which also includes Canty Vision Client Software for analysis.

Capacitance Sensor

Capacitance sensor is proposed to measured wave characteristics and phase distribution in the cross sectional area. Four different options have been identified and their description is presented next.

Two-Wire Sensor

The sensor consists of two parallel copper wires positioned perpendicular to the flow at a distance of 0.25 in. An electronic circuit filter, amplify and convert the measured capacitance to a voltage. A calibration process is required to relate the output voltage with liquid level.

Three consecutive two-wire sensors will be installed 10xD apart (as suggested by Johnson, 2005). This will allow the characterization of wave length, amplitude, frequency and celerity at the center of the pipe. The capacitance sensors will be installed between two closing valve to facilitate the dynamic calibration and verification.

Film Distribution Sensor

Similar to Paz (1993), each sensor will consist of five two-wire capacitance sensors installed at every 45° along the pipe circumference. After proper calibration, each sensor will provide the film thickness at each location. Two sensors will be installed 10xD apart allowing wave characterization along the pipe circumference.

Capacitance and Resistance Tomography

Electrical capacitance and resistance tomography can be utilized to measure the phase distributions and liquid holdup. This non invasive method consists of measurement of the capacitance and conductivity of a region in a pipe interior. The permittivity and conductivity distribution is reconstructed by sophisticated algorithm. The advantage of the dual modality (resistance and capacitance) provides with the possibility of measurement of the phase distribution in a gas-oil-water system.

Preliminary quote, by Industrial Tomography System (ITS) has been received. The cost of a capacitance and resistance tomography system is $ 236,870 including sensor, electronic and software.

Wire Mesh Sensor

Wire mesh sensor consists of a grid of wire electrodes stretched across a flow cross section. For a wire mesh sensor operated in a pipe, the wire grid is mounted on a pressure-tight circular frame which is sandwiched between two flanges. Typical wire separation is 2.3 mm in-plane, and 1.5 mm between planes. Fast electronics interrogates the electrical properties of the medium in the cross-section at all wire crossings. Electrical conductivity or relative electrical permittivity can be measured. Both give a phase indicator for multiphase flow. The sensor securely discriminates gas from oil, gas from water and oil from water.

Wire mesh sensors have been successfully employed in pipe flows, especially fast flows between 1 and 10 m/s mixture velocity. They are well suited to discriminate liquids from gases and liquids with different electrical permittivity. Operating two sensors behind each other can be useful to measure phase velocities.

Preliminary quote for a 32x32 wire mesh sensor system is $85,645. A rental option is available for this option including sensor, electronics and software.

Iso-kinetic Sampling

The droplet entrainment can be measured using the iso-kinetic probe. The iso-kinetic condition can be reached by controlling the gas flow rate, using a control valve mounted at the gas outlet. Iso-kinetic sampling nozzles from Jones Inc. have a pressure rating up to 5000 psig and temperature up to 1200 °F. No traverse mechanism to change the position of the sampling point is considered. For safety and time concerns, four sampling nozzles will be welded at different heights in the pipe. The sampling station will be mounted between two Stainless High Pressure Swivel joints. By rotating the sampling section most of the cross sectional area can be covered getting more accurate entrainment data.

A high efficiency separator is needed, stainless steel high pressure filter (Walker Filtration) is proposed. Gas flow meter is required to assure the iso-kinetic conditions. The liquid can be collected in a bottle. The liquid flow rate at given position is determined by measuring the collecting time.

Pitot Tube

A pitot tube will be used to measure the velocity distribution inside the pipe similar to Kawaji *et al.* (1987) and Andreussi *et al.* (1986) in gas-liquid flow, and Hamad and He (2010) in liquid-liquid flow. The Pitot tube static and dynamic lines will be filled with liquid and connected to a diaphragm pressure line system of Rosemount differential pressure transducer. The average velocity can be calculated from the differential pressure reading and calibration. Two liquid purge valves will be used to fill the system with liquid. The Pitot tube will be mounted on a traverse mechanism with driver which can be controlled either manually or by computer. A high pressure Omega FPT-6260-SS pitot tube is considered.

Construction Schedule

Hazard and operability analysis will be facilitated by an external company, COGNASCENTS. The HAZOP analysis is carried out in three, namely, Preparation, HAZOP session and deliverables. During the preparation stage pertinent documentation (P&IDs, standard operating procedures and project scope documents) is provided to the facilitator. After performing all the preparation work, the facilitator will call for the HAZOP session of the project and generate the final HAZOP report. First stage is planned to be completed by December 2011 and HAZOP session and final report are expected by January 2012.

Completion of instrumentation, electrical, data acquisition and control system is expected by April 2012. Hydrostatic test and circulation of fluid in the facility will be carried out by May 2012. Installation and calibration of special instrumentation will be carried out through June to September 2012 and preliminary test are expected by October 2012.

References

Kora, C.: "Effects of High Oil Viscosity on Slug Liquid Holdup in Horizontal Pipes," Master Thesis, The University of Tulsa, 2010.

Johnson, G.: "A Study of Stratified Gas-Liquid Pipe Flow," Ph.D. Thesis, University of Oslo, Norway, ISSN 1501-7710, n. 448, 2005.

Paz, R.:"Annular Flow in Extended Reach Directional Wells," Master Thesis, The University of Tulsa, (1993).

Kawajl, M., Anoda, Y., Nakamura, H., Tasaka, T.: . "Phase and Velocity Distributions and Holdup in High-Pressure Steam/Water Stratified Flow in a Large Diameter Horizontal Pipe," International Journal of Multiphase Flow, v. 13, I. 2, pp. 145-159, 1987.

Hamad, F., He, S.: "Evaluation of Hot-Film, Dual Optical and Pitot Tube Probes for Liquid-Liquid Two-Phase Flow Measurements," Flow Measurement and Instrumentation, v. 21, pp. 302-311, 2010.

Andreussi, P., Persen, L.: "Stratified Gas-Liquid Flow in Downwardly Inclined Pipes," International Journal of Multiphase Flow, v. 13, I. 4, pp. 565-575, 1986.

Fluid Flow Projects

Liquid Loading of Gas Wells (Part 1)

Ge (Max) Yuan

Advisory Board Meeting, October 26, 2011

Comments from Last ABM …

- Dr. Taras Makogon, BP
  - High Speed Camera to Get Gas Fraction in Liquid Film
  - Response:
    - Limited Focus Depth of the Lens

Comments from Last ABM …

- Mr. Mack Shippen, Schlumberger
  - Adding Tests in Well Deviation Range of 0-15°
  - Response:
    - Limited Time
      - Studies to Be Continued with Another MS Student
    - Mechanism Investigated by Comparing Vertical and 15° Well Deviation Cases

Comments from Last ABM …

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

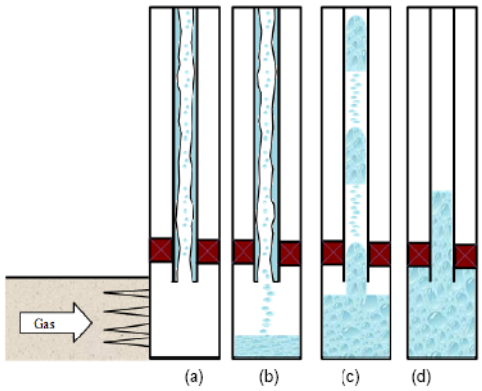
Outline

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

Objectives

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

Introduction



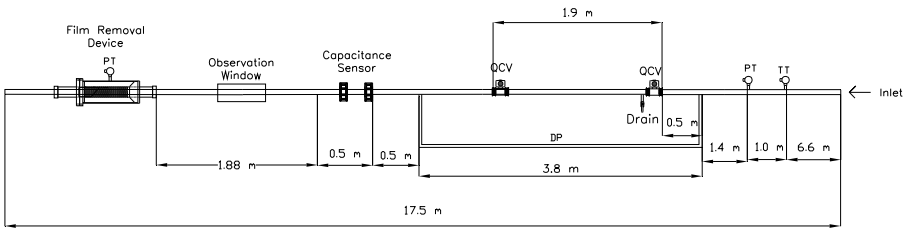
Gas Production Flow Regime Changes from Mist (a) to Annular (b) to Slug/Churn Flow (c) and Eventually Loads up (d).

Introduction …

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

Experimental Program

- Test Section Design



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

Experimental Program …

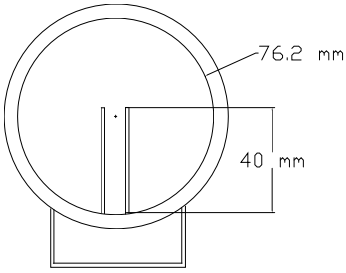
- Test Ranges
  - Superficial Gas Velocity:
    10 to 30 m/s
  - Superficial Liquid Velocity :
    0.005, 0.01, 0.02, 0.05 and 0.1 m/s
  - Well Deviation:
    0º, 15º, 30º, 45º, 60º

Instrumentation

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

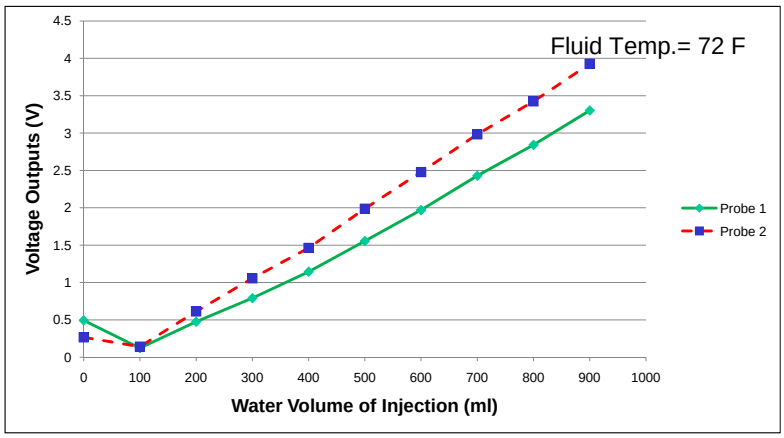
Capacitance Sensor

- Type: Two Parallel Wires
- Range: 5 – 40 mm



Capacitance Sensor …

Static Calibration

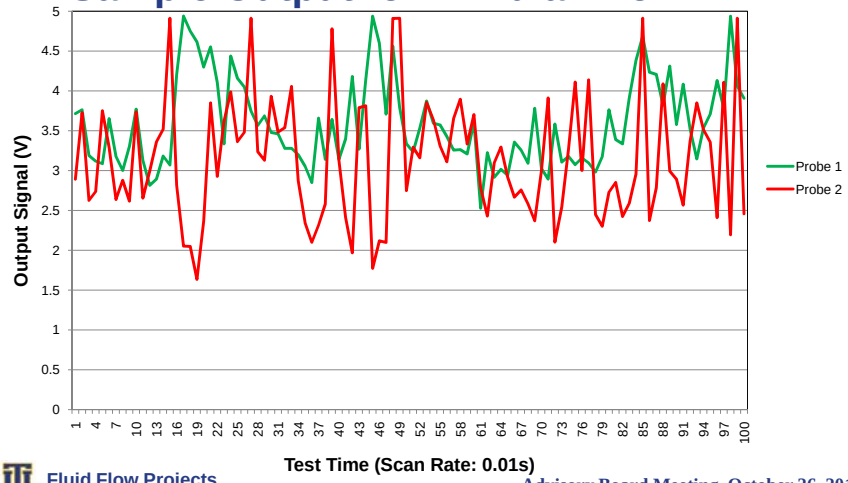


Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

Capacitance Sensor …

Sample Output for Annular Flow



Fluid Flow Projects

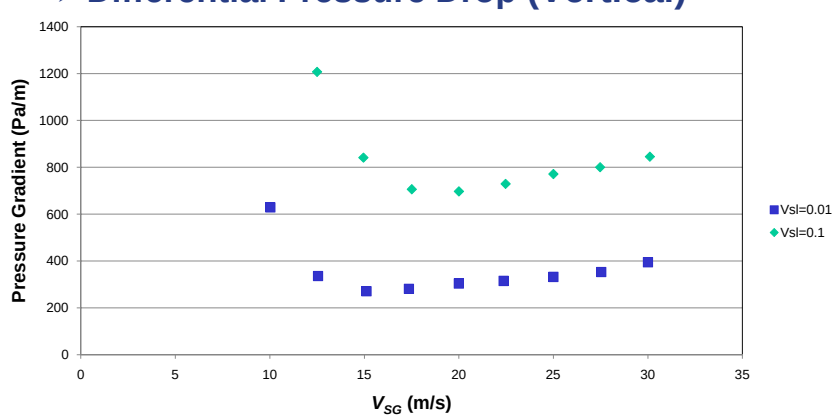
Advisory Board Meeting, October 26, 2011

Experimental Results

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

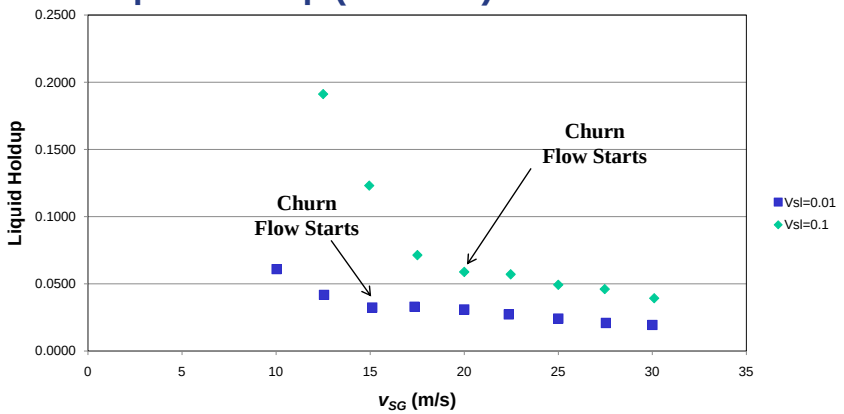
Experimental Results …

- Criteria of Liquid Loading
  - Differential Pressure Drop (Vertical)



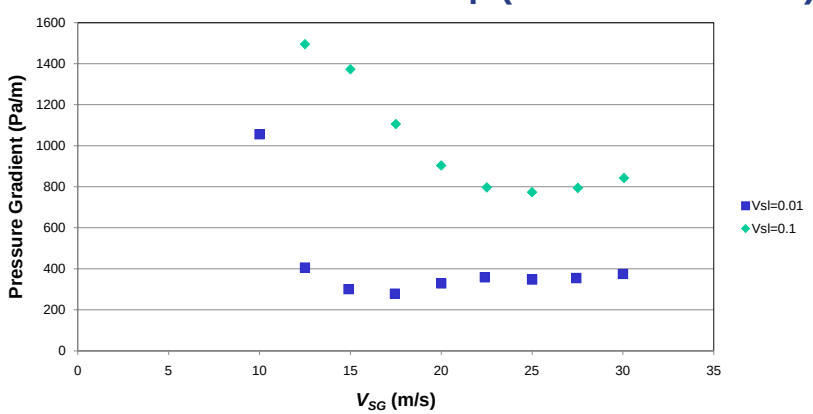
Experimental Results …

- Criteria of Liquid Loading
  - Liquid Holdup (Vertical)



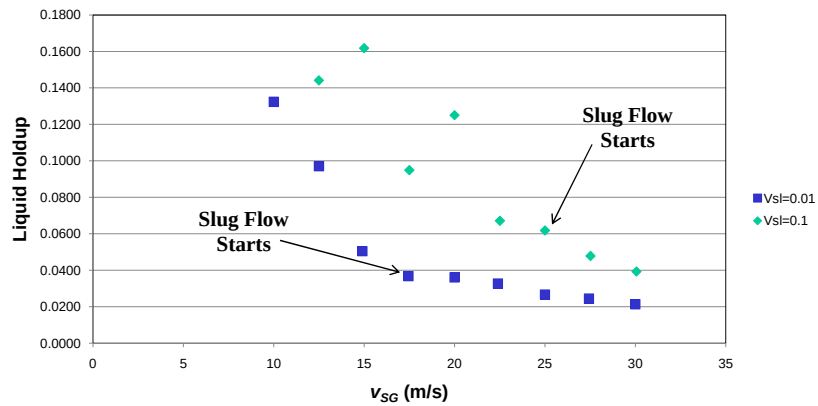
Experimental Results …

- Criteria of Liquid Loading
  - Differential Pressure Drop (15° Well Deviation)



Experimental Results …

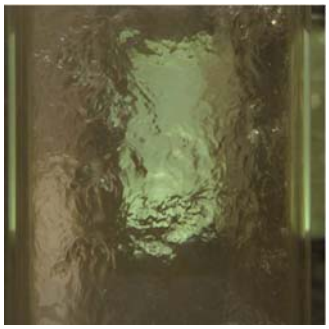
- Criteria of Liquid Loading
  - Liquid Holdup (15° Well Deviation)

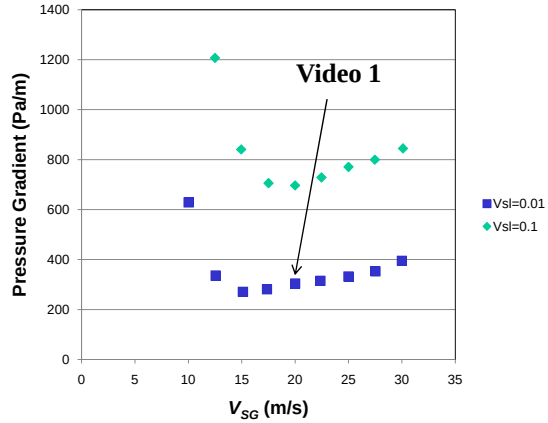


Flow Pattern

- High Speed Videos (Vertical)

Video 1

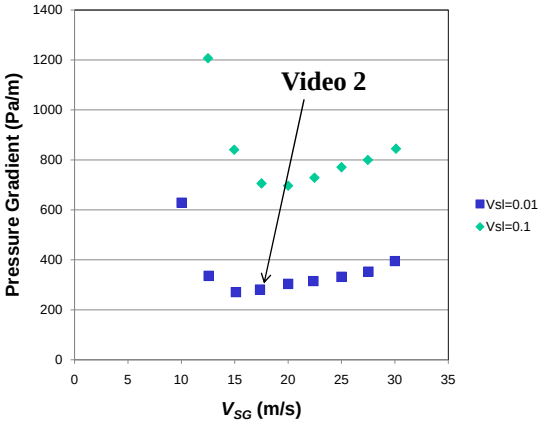




Flow Pattern …

High Speed Videos (Vertical)

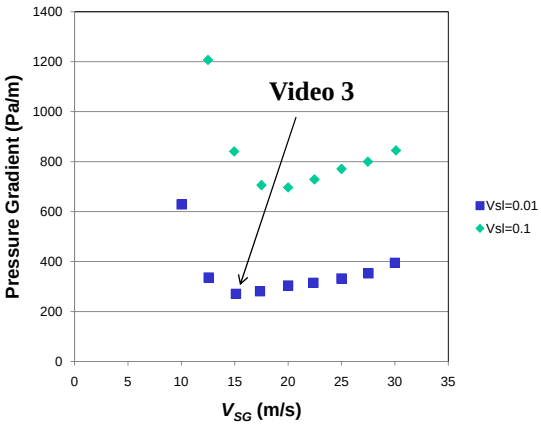
Video 2



Flow Pattern …

High Speed Videos (Vertical)

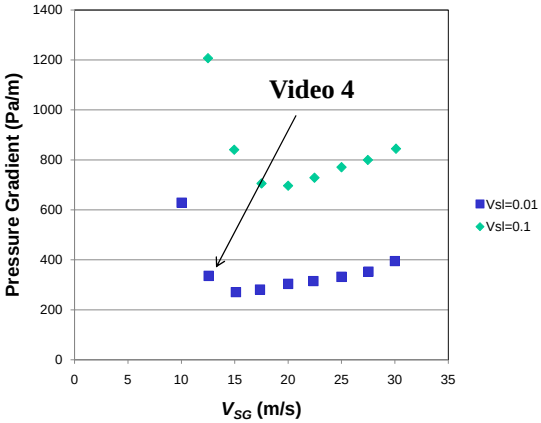
Video 3



Flow Pattern …

High Speed Videos (Vertical)

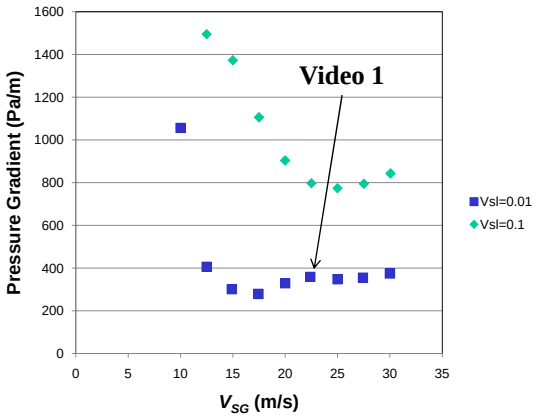
Video 4



Flow Pattern …

High Speed Videos (15° Well Deviation)

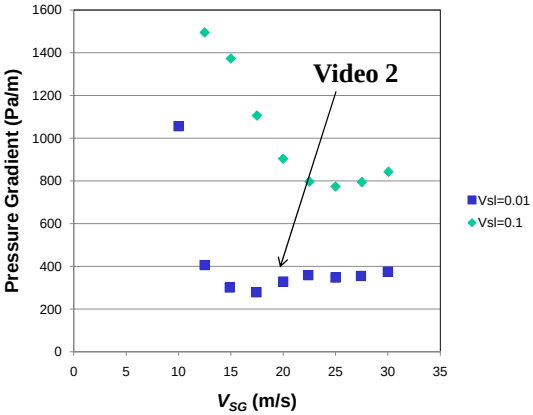
Video 1



Flow Pattern …

High Speed Videos (15° Well Deviation)

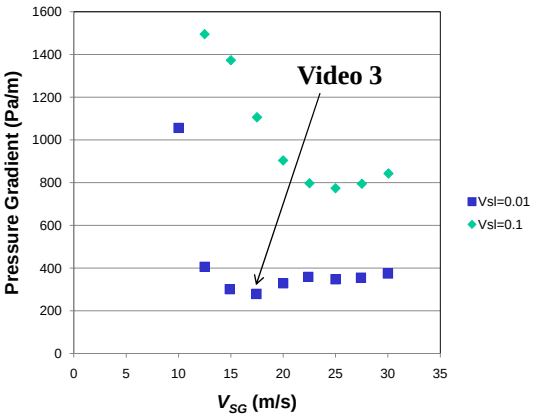
Video 2



Flow Pattern …

High Speed Videos (15° Well Deviation)

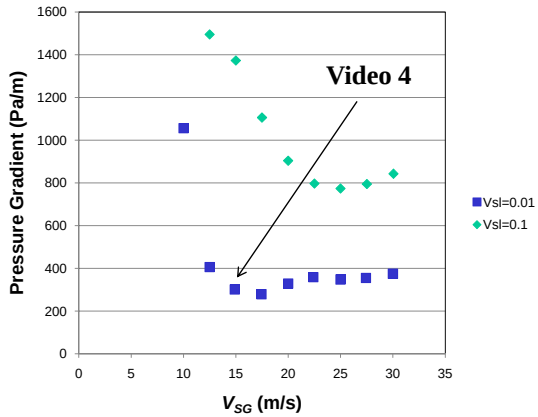
Video 3



Flow Pattern …

- High Speed Videos (15° Well Deviation)

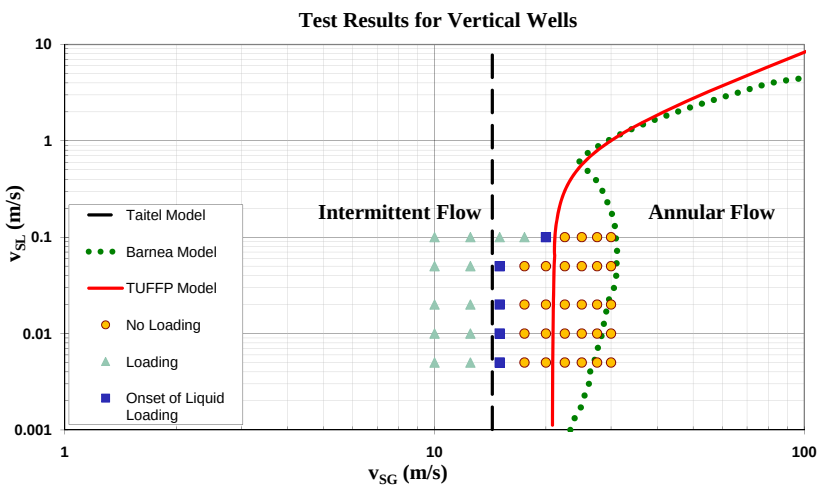
Video 4



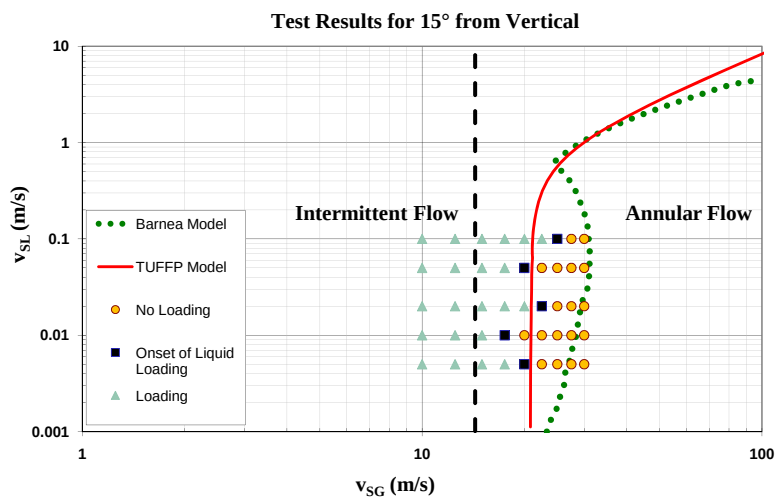
Criteria of Liquid Loading

- Vertical Wells
  - Film Flow Reversal
  - Flow Pattern Changes to Churn Flow
- Deviated Wells
  - Film at the Bottom Flows Downward
  - Flow Pattern Changes to Intermittent Flow

Experimental Results …



Experimental Results …



Transient Phenomena

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

HD VIDEO

Conclusion

- For Vertical Wells
  - Droplets Flowing Upward with Gas Core Even Though Liquid Loading Occurs
  - Controlled by Film Flow Reversal and Droplet Deposition
- For Deviated Wells
  - Wave Growth at Gas-Liquid Interphase is Main Mechanism

Near Future Tasks

Data Analysis	November 2011
Model Comparison	November 2011
Final Report	December 2011

Questions/Comments

Liquid Loading of Gas Wells (Part 1)

Ge (Max) Yuan

Project Completion Dates

Literature Review	Ongoing
Experimental Testing	October 2011
Data Analysis	November 2011
Model Comparison	November 2011
Final Report	December 2011

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 in the form of mist. The reservoir pressure is sufficient for the gas wells 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 and further reduces gas production rate. Then, the flow pattern may change to bubbly flow. 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 elevational losses. Although a lot of 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.

Turner *et al.* (1969) derived a method of predicting the critical gas rate by equating the upward drag and downward gravity forces on the largest possible liquid droplet. The maximum Weber number determines the largest possible droplet size. The 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 readily measurable wellhead parameters.

There is no satisfactory model to predict the critical velocity for inclined wells. Grija's (2006) observed a transitional annular flow. In this flow regime, gas flows upward in the central core of the conduit, and a liquid film is on 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 have been used in this study.

Instrumentation and Data Acquisition

The test section of the facility has been modified to accommodate the needs of this study. Capacitance sensors are used for qualitative analysis of the liquid film thickness variation and wave structure. The sensor is a two parallel wire sensor with a capacity of measuring film thickness from 5 to 20 mm. The two probes are placed at the bottom of the pipe. High

speed camera is used to observe and analyze the liquid loading phenomena. Wave propagation and liquid film flow direction were also observed from the video.

Experimental Program

In this study, experiments have been conducted at different flow rates and inclination angles. Superficial water velocities range from 0.005 to 0.1 m/s. Superficial gas velocities vary from 10 to 30 m/s. The test range should cover the onset of liquid loading in order to get the critical gas velocity. Experiments will be conducted at well deviation of 0°, 25°, 30°, 45° and 60° from vertical. . During one test run, liquid flow rate is constant and gas flow rates are decreased step by step until the occurrence of the liquid loading. The experimental program has been designed as two stages. In the first stage, gas flow rates vary from 10 to 30 m/s, with increments of 5 m/s. Once the loading is bracketed into two gas velocity, the interval is narrowed down looking for the critical gas velocity. The onset of liquid loading is defined as the liquid film flowing downward while the gas core is still flowing upward.

Activities Summary

During this time period, preliminary testing and main testing have been completed. Data analysis and model comparison are underway.

The two-phase flow characteristics being studied are flow patterns, differential pressure gradient and entrainment for annular flow. A summary of experimental results are given below.

Flow Pattern

Annular flow and intermittent flow (slug flow and churn flow) are the flow patterns observed.

Pressure Gradient

Differential pressure gradient was measured with Rosemount DP transducer. Generally, when gas velocity was decreased, the DP decreased reaching a minimum value at the onset of liquid loading. Further gas velocity reduction results in a DP increase.

Film Removal Device

Film removal was utilized in this study to measure entrainment data in annular flow. Data was collected but has not yet been analyzed.

Liquid Holdup

Liquid holdup was measured from the quick closing valves section. When the gas velocity was decreased, the liquid holdup increased step by step. When the gas velocity was approaching the critical value, a larger increase of the liquid holdup was observed. Then, the flow pattern changed to intermittent flow which is hard to get a representative holdup using this method.

Conclusions

The mechanism of liquid loading phenomena is different for vertical wells and deviated wells. For vertical wells, the droplets were still flowing upward with the gas core even though liquid loading occurred. The liquid loading is controlled by the film flow reversal and droplet deposition. While for deviated wells, the wave growth at the liquid-gas interphase is the main mechanism.

Near Future Tasks

Thesis defense will be made in November and final report will be submitted by December.

References

Coleman, S.B., Clay, H.B., McCurdy, D.G., and Lee Norris, H. III (1991): "A New Look at Predicting Gas-Well Load Up," J. Pet. Tech., 329-333. March (1991)

Girija, E.G: "Experimental Study of Gas-Liquid Flow through a Tubing-Casing Annulus with Application to Natural Gas Wells," M.S. Thesis, Colorado School of Mines (2006)

Turner, R.G., Hubbard, M.G., and Dukler, A.E. (1969): "Analysis and Prediction of Minimum Flow Rate for the Continuous Removal of Liquids from Gas Wells," J. Pet. Tech., 1475-1482., Nov. (1969)

Veeken K., Hu B. and Schiferli W., (2009): "Transient Multiphase Flow Modeling of Gas Well Liquid Loading," SPE paper 123657 presented at SPE Offshore Europe Oil & Gas Conference & Exhibition held in Aberdeen, UK, 8–11 September (2009).

Fluid Flow Projects

Liquid Loading of Gas Wells (Part 2)

Mujgan Guner

Advisory Board Meeting, Oct. 26, 2011

Outline

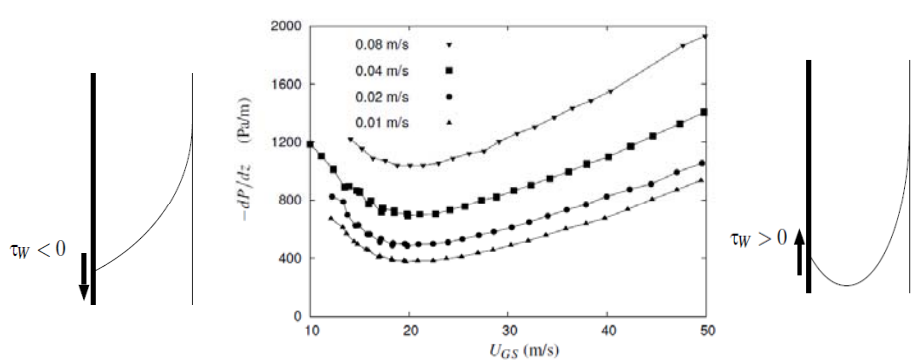
- Objective
- Literature Review
- Proposed Study
- Instrumentation
- Near Future Tasks

Objective

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

Literature Review

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



Literature Review

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

Literature Review …

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

Proposed Study

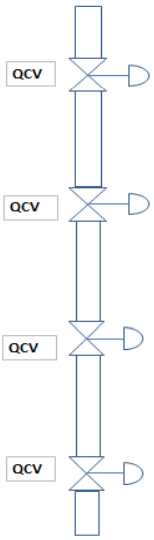
- Experimental Study of Film Reversal Mechanisms in Annular Flow
  - Effects of Inclination
  - Entrance Effects
- Exploratory Experiments from Ge (Max)Yuan Will be Utilized to Generate the Test Matrix
- Improved Instrumentation Will be Implemented

Proposed Study …

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

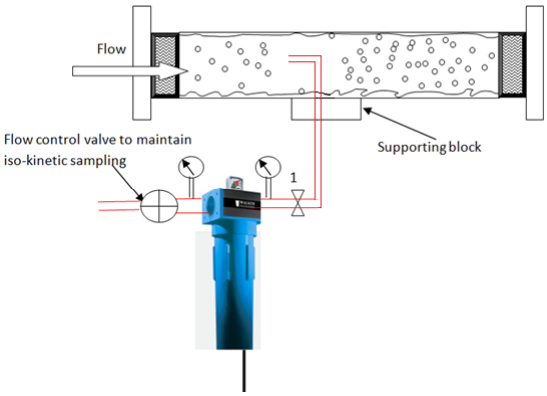
Instrumentation

- Liquid Holdup
  - Quick Closing Valves
    - Multiple QCVs
    - Three Trapping Sections



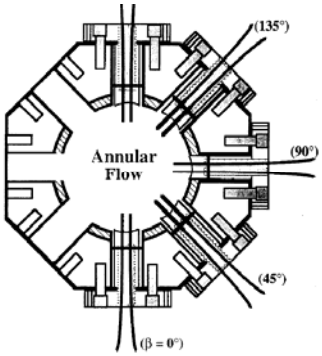
Instrumentation …

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



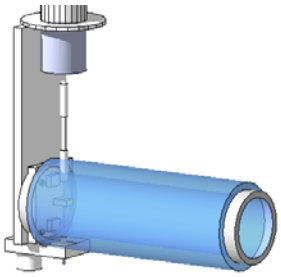
Instrumentation …

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



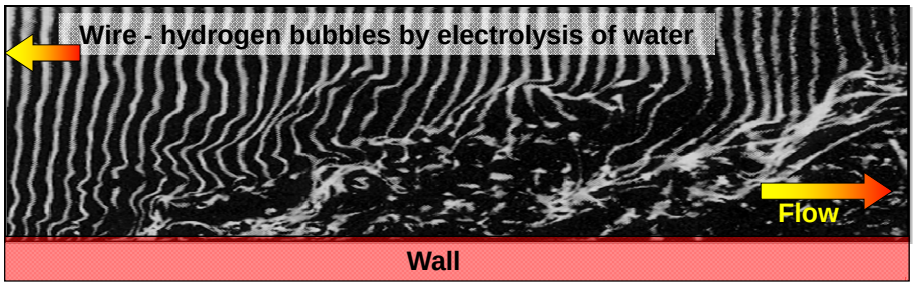
Instrumentation …

- Wave Characteristics
  - Capacitance Probes Calibration Device
    - Motorized Linear Slide



Instrumentation …

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

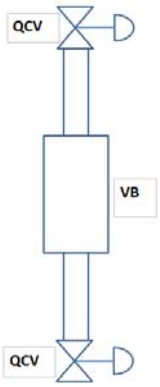


Instrumentation …

- Boundary Layer Study
  - Bussman *et al.*

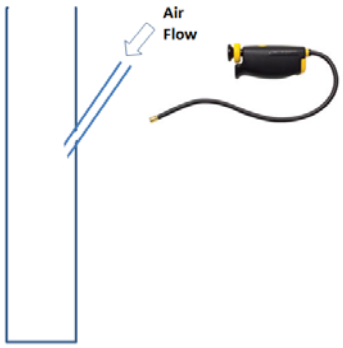
Instrumentation …

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



Instrumentation …

- Visual Observation
  - Boroscope
    - Boroscope Will be Utilized to Observe the Film Flow Mechanism



Near Future Tasks

Literature Review	Ongoing
Instrumentation	March 2012
Experimentation	October 2012
Data Analysis	October 2012
Final Report	December 2012

Questions & Comments

Liquid Loading of Gas Wells (Part 2)

Mujgan Guner

Project Completion Dates

Literature Review	Ongoing
Instrumentation	March 2012
Experimentation	August 2012
Data Analysis and Model Comparison	August 2012
Final Report	December 2012

Objectives

The main objectives of this study are:

- Explore mechanisms controlling onset of liquid loading in vertical and inclined pipe configurations
- Investigate entrance effect on liquid loading onset for vertical and inclined pipes

Introduction

Liquid loading in gas wells have been recognized one of the most important problems in gas production. For normally operated gas wells, gas flow rate is enough 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 flow back to the well and the liquid loading may eventually block further production of gas. Therefore, it is very essential to investigate the mechanisms of liquid loading, in order to avoid its occurrence.

Several studies address the liquid loading in gas wells depending on two mechanisms. The first one considers that loading occurs owing to accumulation of droplets, which are unable to be effectively carried by gas phase. The second mechanism is associated with a reversal on the film velocity profile. In this study, mainly, reversal effect will be investigated.

Activities Summary

Two main activities have been carried out during this period, namely, literature review and instrumentation design.

Literature Review

Two main criteria have been used to determine the initiation of the liquid loading. The first criterion considers that the loading occurs when the droplets are large enough that cannot be lifted by the gas and falls back to the well. The second criterion considers the stability of the liquid film. Turner *et al.* (1969) analyzed both criteria concluding that the first one presents better fit with the experimental data.

Later, Westenende (2008) measured the droplet size at the initiation of the liquid loading. He found that the droplet size was one order of magnitude smaller than the required diameter to achieve neutral settling velocity. The author concluded that the liquid loading should be characterized by film instability instead of a force balance over the droplet.

Belt (2007) studied the film reversal in 2-in ID inclined and vertical pipes using air and water as working fluids. Belt (2007) investigated film distribution mechanisms by observing interfacial friction, wave characteristic on the film and the effect of secondary flow. The film thickness is measured by using conductance sensor. Secondary flow effects, which are caused by non-uniform gas core, are investigated. Belt (2007) showed that the interfacial friction can be well predicted using the height and spatial distribution of the roll waves. Roll waves distribution plays important role on the redistribution mechanism of the liquid film and mean film thickness depends mainly on roll waves.

Instrumentation

Current instrumentation will be updated according to the parameters to be investigated introducing new sensors to the existing facility.

Average liquid holdup will be measured by using quick closing valves (QCV). A multiple QCV configuration will be applied. There will be three successive trapping sections, namely, entrance, developing and test sections. This arrangement allows the evolution of the liquid holdup along the system.

Liquid entrainment will be measured by isokinetic sampling device, which will be fixed in the center of the pipe cross sectional area. This measurement will be utilized to collaborate with previous observations, which indicates that at the initiation of the liquid loading large lumps of liquids falls back in the center of the pipe.

Wave characteristics will be investigated. A special design of capacitance probes will be utilized, which will provide wave information not only in vertical but also inclined configurations. The design is, basically, a distribution of the probes with 45° angles on the pipe periphery. The probes will be calibrated by using motorized linear slide. The slide

will accurately measure small increments in water height and the corresponding voltage values will be obtained in order to construct the calibration curve. A calibration bank is under development allowing proper sensor calibration for given temperatures.

Onset of the film reversal and the film reversal mechanisms are critical parameters for this study. Velocity distribution on the pipe wall may help to understand the mechanism indicating the onset. Therefore, hydrogen bubble wire is considered to identify the cross location of the film reversal. Additionally, this technique can be utilized to study liquid film wall velocity along the pipe perimeter.

Lighting and location of the actual high speed video system will be improved, allowing better description of the mechanism involve. Additionally, six low speed video cameras will be added to record lateral and bottom videos at the entrance, developing and test section. This will be utilized for the flow evaluation in different sections of the pipe qualitatively. Additionally, a boroscope device is considered to investigate the film reversal mechanism. A temporary tubular insert to the periphery of the pipe is considered and the boroscope will be inserted into the tubular. The lens of the Boroscope will be cleaned with air purge.

Future Work

- Instrumentation design and construction (Fall 2011)
- Calibration and Verification of new instrumentation (Winter 2012)
- Facility modification (Spring 2012)
- Start preliminary tests (Summer 2012)

References

Belt, R.J.: “On the Liquid Film in Inclined Annular Flow,” PhD Dissertation, Technische Universiteit Delft, (2007).

Westenende, J,:" Droplets in Annular -Dispersed Gas-Liquid Pipe-Flows". PhD Thesis TU Delft (2008).

Turner, R.G., Hubbard, M.G., and Dukler, A.E. (1969): “Analysis and Prediction of Minimum Flow Rate for the Continuous Removal of Liquids from Gas Wells,” J. Pet. Tech., 1475-1482., Nov. (1969)

Fluid Flow Projects

Simplified Transient Two-Phase Flow Modeling

Jinho Choi

Outline

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

Objectives

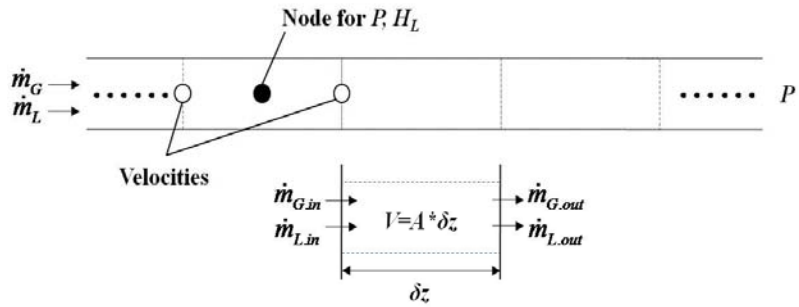
- Develop a Simplified Transient Model and Simulator for Gas-Liquid Two-Phase Flow in Pipelines
- Test Model and Simulator Against Available Experimental Data

Activities Summary

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

Preliminary Simplified Transient Model

- Control Volume and Boundary Conditions



Preliminary Simplified Transient Model

- Liquid Continuity
  - Assumption
    - Constant Liquid Density

$$\rightarrow \quad \frac{dH_L}{dt} = \frac{u_{SL.in} - u_{SL.out}}{\delta z}$$

- Gas Continuity
  - Assumptions
    - Isothermal Flow
    - Constant Gas density

$$\rightarrow \quad u_{SLin} - u_{SLout} + u_{SGin} - u_{SGout} = 0$$

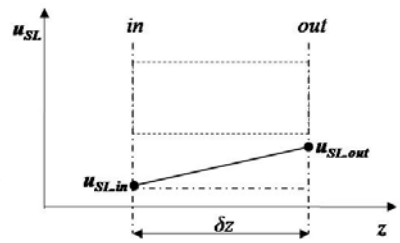
Preliminary Simplified Transient Model

- **Drift Flux Closure Relationship**

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

$$\overline{u_{SL}} = \frac{u_{SL.in} + u_{SL.out}}{2}$$

$$\overline{u_{SG}} = \frac{u_{SG.in} + u_{SG.out}}{2}$$



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

Preliminary Simplified Transient Model

- **Equation Summary**

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

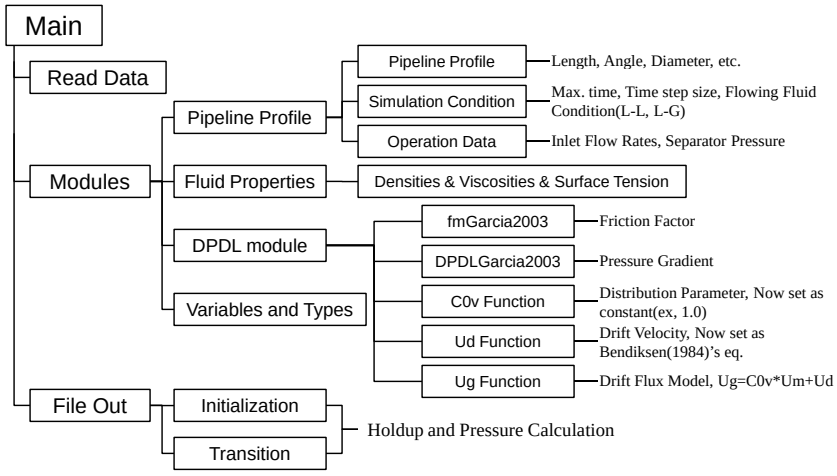
(1) $$\frac{dH_L}{dt} = \frac{u_{SL.in} - u_{SL.out}}{\delta z}$$

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

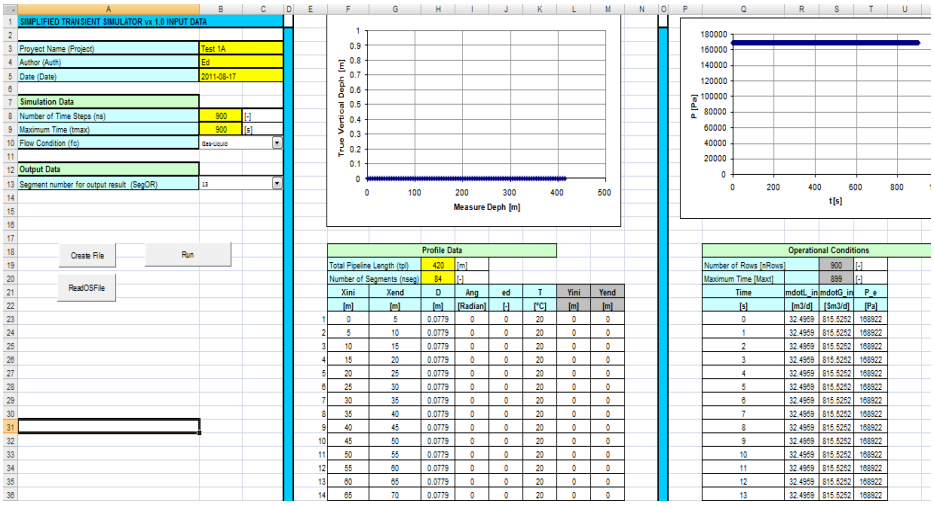
(3) $$u_{SL.out} = u_{SG.in} + u_{SL.in} - u_{SG.out}$$

(4) $$\frac{dp}{dz} = 2 f_M \frac{\rho_M u_M^2}{d} + \rho_M g \sin\theta$$

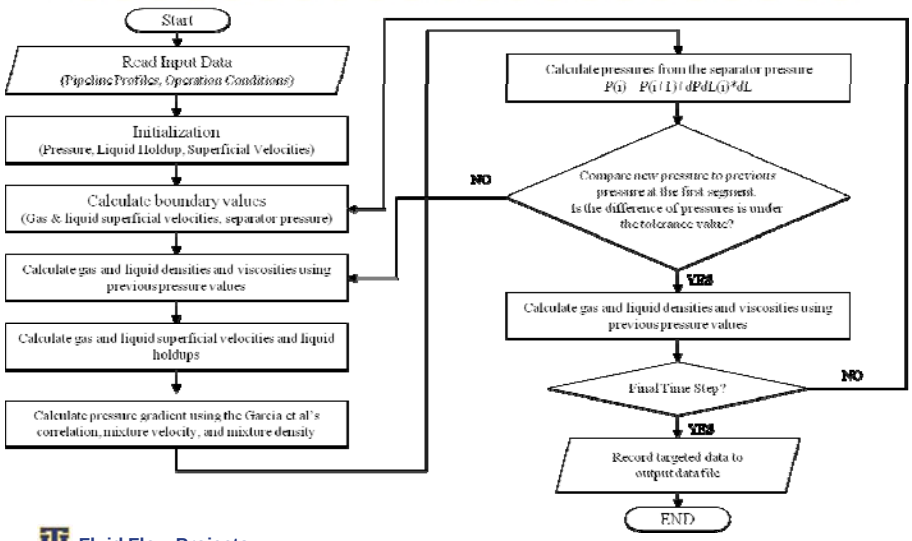
Simulator Composition



Excel UI



Simulator Flow Chart



Simulator Validation

- Experiments by Vigneron *et al.* (1995)
  - Air and Kerosene
  - Horizontal Pipe L=420 m, d=77.9 mm
  - Two Test Sections @ 61.4m, 395.7m
  - Transient Caused By:
    - Liquid flow rate change
    - Gas flow rate change
    - Liquid blow out
    - Start up

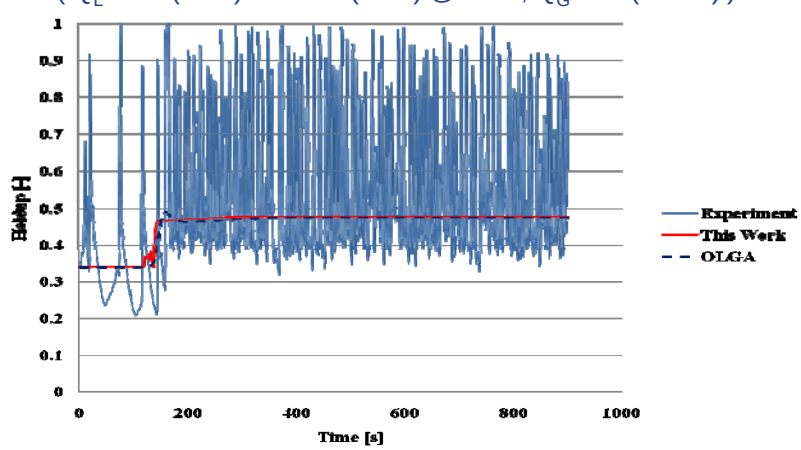
Simulator Validation

Experiments by Vigneron *et al.* (1995)

Test#	Initial(I) Final(F)	Flow Rate		Flow Patten	P_{sep} (Bar)
		Liquid (m3/d)	Gas (Sm3/d)		
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	8.0	850	SS	1.67
	F	8.0	4520	SW	
2B	I	20.2	340	SS	1.67
	F	20.2	2530	SW	
Liquid Blow Out					
3A	I	48.8	4825	SW	1.69
	F	0.0	4825	Single	
3B	I	204.0	5880	Slug	1.69
	F	0.0	5880	Single	

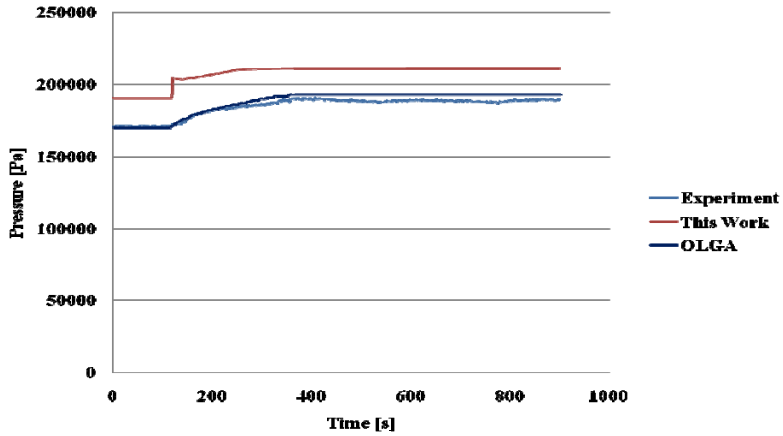
Simulator Validation

- **Test 1A** – Liquid Flow Rate Change
  (Q_L=32.5(m^3/d) → 168.4(m^3/d) @120s , Q_G=815(Sm^3/d))



Simulator Validation

- **Test 1A** – Liquid Flow Rate Change
  (Q_L=32.5(m^3/d) → 168.4(m^3/d) @120s , Q_G=815(Sm^3/d))

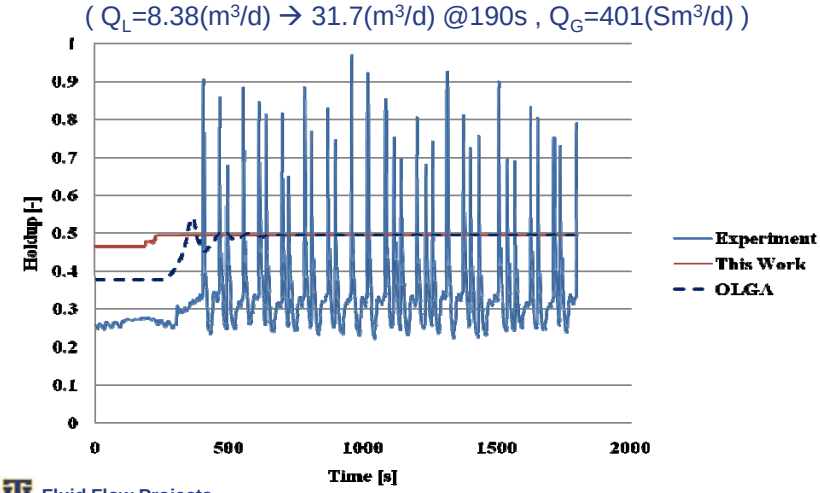


Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

Simulator Validation

- **Test 1B** – Liquid Flow Rate Change
  (Q_L=8.38(m^3/d) → 31.7(m^3/d) @190s , Q_G=401(Sm^3/d))

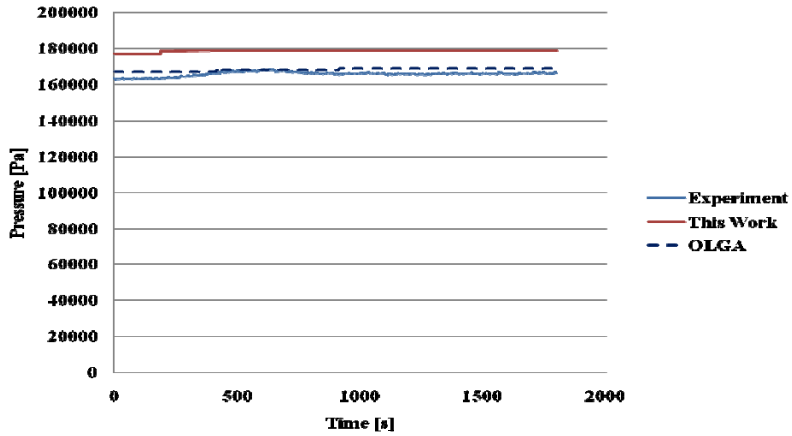


Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

Simulator Validation

- **Test 1B** – Liquid Flow Rate Change
  (Q_L=8.38(m^3/d) → 31.7(m^3/d) @190s , Q_G=401(Sm^3/d))

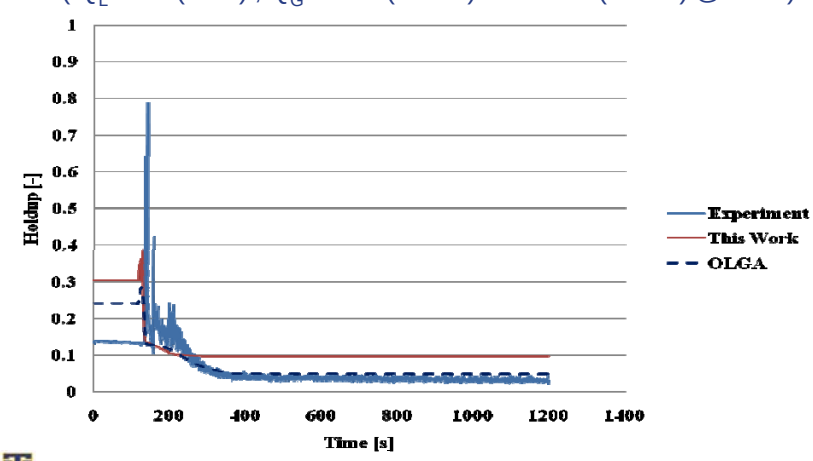


Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

Simulator Validation

- **Test 2A** – Gas Flow Rate Change
  (Q_L=8.00(m^3/d) , Q_G=852.9(Sm^3/d) → 4519.4(Sm^3/d) @120s)

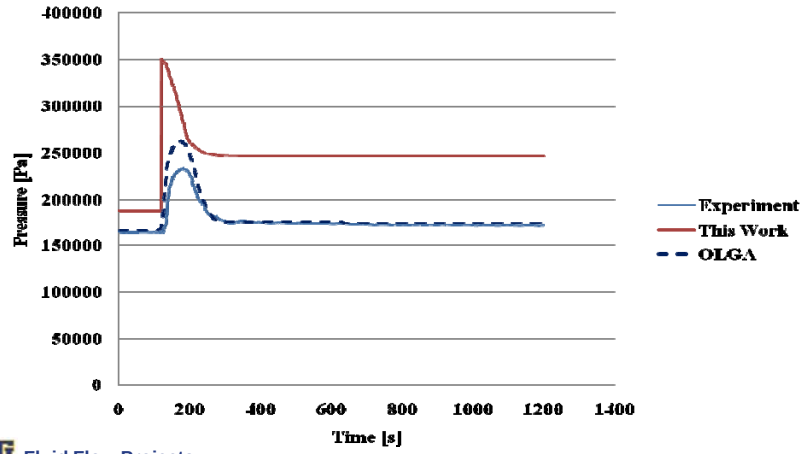


Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

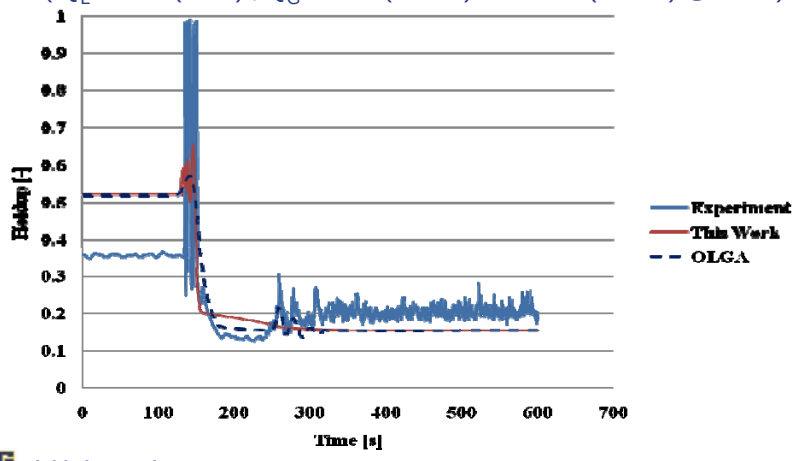
Simulator Validation

- **Test 2A** – Gas Flow Rate Change
  (Q_L=8.00(m^3/d) , Q_G=852.9(Sm^3/d) → 4519.4(Sm^3/d) @120s)



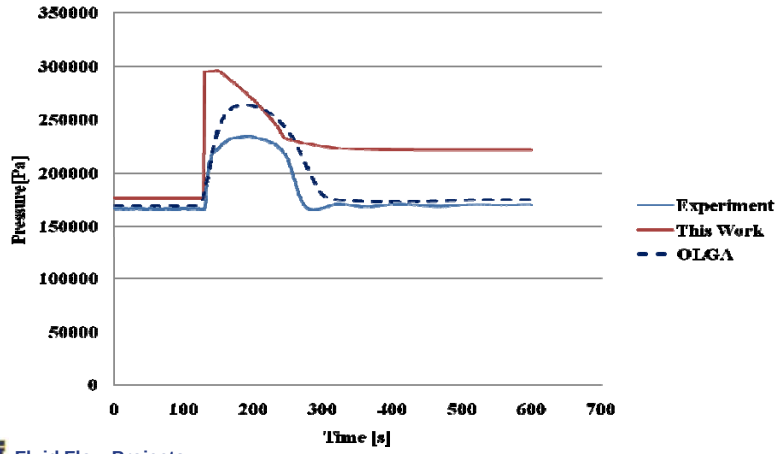
Simulator Validation

- **Test 2B** – Gas Flow Rate Change
  (Q_L=20.14(m^3/d) , Q_G=339.8(Sm^3/d) →2528.1(Sm^3/d) @130s)



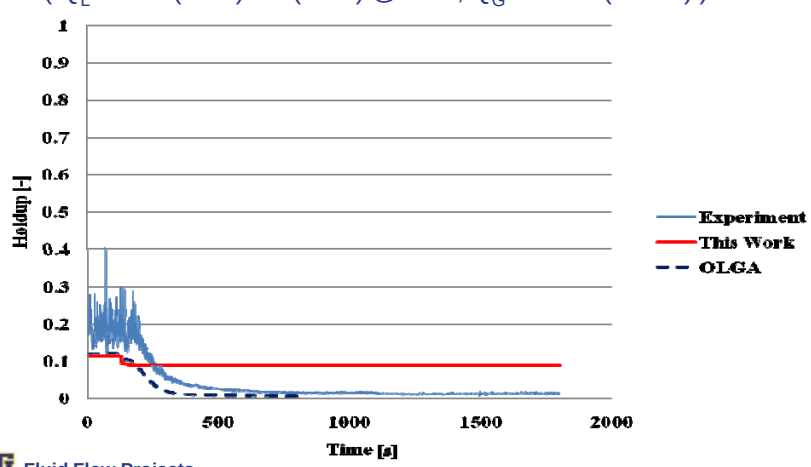
Simulator Validation

- **Test 2B** – Gas Flow Rate Change
  (Q_L=20.14(m^3/d) , Q_G=339.8(Sm^3/d) →2528.1(Sm^3/d) @130s)



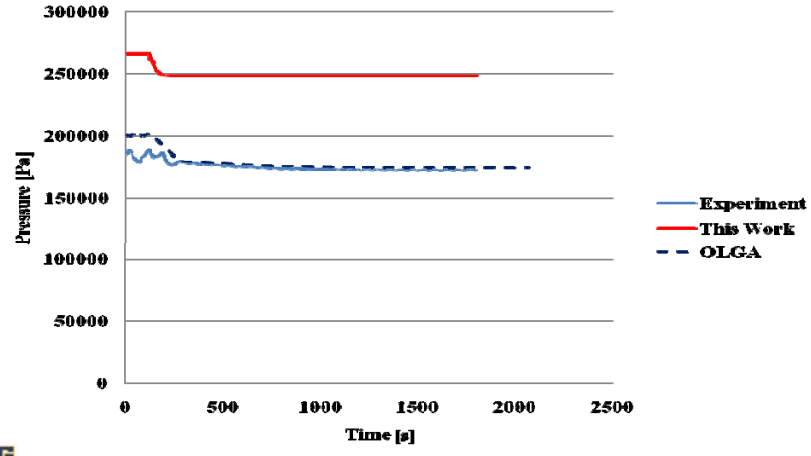
Simulator Validation

- **Test 3A** – Liquid Blow Out
  (Q_L=48.77(m^3/d) →0(m^3/d) @120s, Q_G=4528.2(Sm^3/d))



Simulator Validation

- **Test 3A** – Liquid Blow Out
  (Q_L=48.77(m^3/d) →0(m^3/d) @120s, Q_G=4528.2(Sm^3/d))

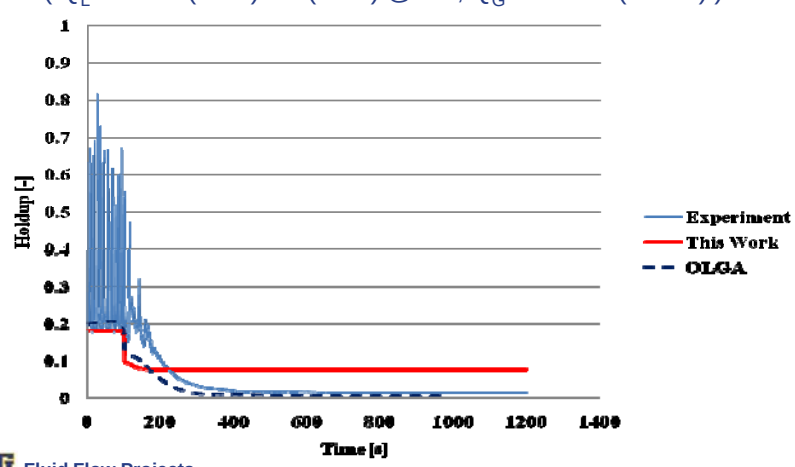


Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

Simulator Validation

- **Test 3B** – Liquid Blow Out
  (Q_L=204.12(m^3/d) →0(m^3/d) @95s, Q_G=5929.55(Sm^3/d))

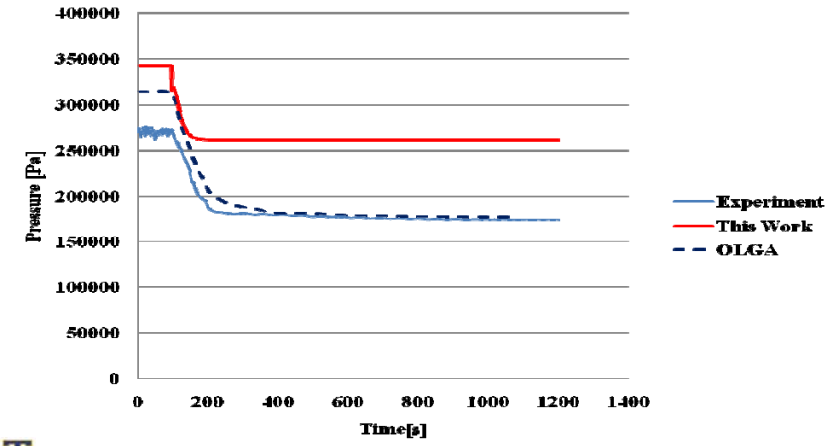


Fluid Flow Projects

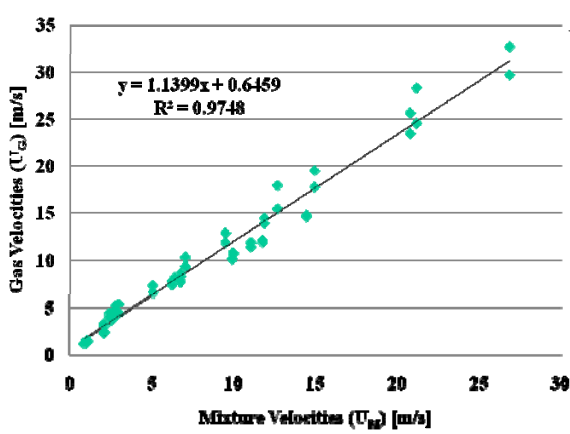
Advisory Board Meeting, October 26, 2011

Simulator Validation

- **Test 3B** – Liquid Blow Out
  (Q_L=204.12(m^3/d) →0(m^3/d) @95s, Q_G=5929.55(Sm^3/d))



Improvement of the Model



Vigneron *et al.* (1995)

$U_M = U_{sl} + U_{sg}$

$U_G = CU_M + U_D$

- U_M : Mixture Velocity
- U_{sl} : Liquid Supeficial Velocity
- U_{sg} : Gas Superficial Velocity
- U_G : Gas Velocity
- C : Distribution Parameter
- U_D : Drift Velocity

Near Future Work

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

    $f(u_{sl}, u_{sg}, \rho_{liquid}, \rho_{gas})$, or $f(Fr_M, Re_s, \beta)$, etc.
  - Drift Velocity (Ud)

    $f(u_{sg}, \rho_{liquid}, \rho_{gas}, \sigma)$, or $f(N_f, Eo, \beta)$, etc.
  - Liquid – Liquid (Oil-Water) Extension

Near Future Work …

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

Questions and Comments

?

Simplified Transient Gas-Liquid Two-Phase Flow Modeling

Jinho Choi

Project Completion Dates

Literature Review October.2011
Preliminary Simulator Validation and Debugging October.2011
Extension and Modification of Model and Code December.2011
Simulator Test January.2012
Final Report March.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, two-fluid model and drift flux model. Each model gave good predictions for different flow patterns. Two-fluid model is suitable for stratified flow, while drift flux model is appropriated 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 drift flux model for all flow patterns based on Danielson and Fan (2010).

Activities Summary

During this period, simulator design, coding and validation are completed based on the developed preliminary model.

Simulator Structure and Preliminary Coding

The simulator consists of three components. The first is the input data module, followed by the numerical simulation module, and finally the output or post-processing module. Data input component reads the input parameters such as pipeline profiles, inflow gas and liquid flow rates, and separator pressures. This information is located in an ASCII file. Data output component reports pressures and liquid holdup profile for each time steps. Numerical simulation component consists of initialization and numerical solver parts with four modules; variables and types, pipeline profile, fluid properties, and DPDL modules. Based on the input data, the initialization part makes initial conditions for whole pipelines assuming steady state. Numerical solver calculates changes of variables like flow rates, pressures, and liquid holdups over time.

Fortran is selected as a programming language. Data input component, numerical simulation component, and output component are completed for preliminary code. Input and output user interface (UI) is made with Microsoft EXCEL, facilitating the simulator execution and data interpretation.

Simulator Validation

The 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 consists on 420m horizontal pipeline with 77.9mm diameter pipes. There were two test sections, one is placed at 61.4m from inlet, and the other is placed at 395.7m from inlet. This study analyzes the simulator performance for the front test 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.

Experimental data sets used in this work correspond to three cases, namely, liquid flow rate changes, gas flow rate changes and liquid blow out.

Liquid Flow Rate Changes

Two data sets of liquid flow rate change experiments were tested. The result was compared with experimental data and OLGA.

Developed simulator matches well the liquid holdup of TEST1A. However, pressure values are higher than the true values and OLGA. In the case of TEST1B, a shift of the initial holdup is observed but at late time fair agreement is reported. Pressure value is still higher.

Gas Flow Rate Changes

Two data sets of gas flow rate change were tested. In the case of TEST2A, a liquid flow rate changes to a low liquid loading condition, showing a systematic discrepancy with the data. These results suggest that the actual model and simulator need to be improve for low liquid loading conditions. Simulator holdup presents a good match with OLGA in the case of TEST2B. But initial values of holdup do not fit the experimental data. Predicted pressures are higher than the experiments and OLGA simulation in both cases.

Liquid Blow Out

Two data sets of liquid blow out experiment cases were tested. In the both cases, simulator could not show the good matches with the experimental data and OLGA. Smooth transition from dilute system to single phase flow need to be implemented, adding to solve for this conditions. For this case, the initial holdup values match the experimental data and OLGA simulations. Pressure values from simulator are higher as the previous cases.

Future Work

The simulator will be tested with OLGA, and more TUFFP experimental data including Vigneron *et al.* (1995).

The inclusion of look-up table for fluid properties will be implemented. PVTSim file format as used by OLGA is suggested as fluid properties table format.

A better drift flux closure relationship for all flow patterns is required, in order to improve the accuracy of the simulator. Proper distribution parameter and drift velocity model will be applied from the previous literatures. New parameters will be proposed based on experimental data available in TUFFP. A heat transfer model will be included to relax the isothermal flow assumption.

The final drift flux model will be tested against available experimental data.

References

Danielson, T.J., Fan, Y.: "Hydrodynamic Slug Flow Modeling," (2010)

Danielson, T.J., Fan, Y.: "Relationship between Mixture and Two-Fluid Models," BHR Group Multiphase Production Technology 14, 479-490 (2010)

Garcia, F., Garcia, R., Padrino, J.C., Mata, C., Trallero, J.L., Joseph, D.D.: "Power Law and Composite Power Law Friction Factor Correlations for Laminar and Turbulent Gas-Liquid Flow in Horizontal Pipelines," International Journal of Multiphase Flow, 29, 1605-1624 (2003)

Michelle Li: "Transient Gas-Liquid Two-Phase Flow Simulation," TUFFP Seventy Fifth Semi-Annual Advisory Board Meeting (2010)

Vigneron, F., Sarica, C., and Brill, J.P.: "Experimental Analysis of Imposed Two-Phase Flow Transients in Horizontal Pipelines," Proceedings of the BHR Group 7th International Conference, 199-217 (1995)

Kazuioshi Minami: "Transient Flow and Pigging Dynamics in Two-Phase Pipelines," Ph.D Dissertation, University of Tulsa (1991)

Mamoru Ishii, Takashi Hibiki:"Thermo-fluid Dynamics of Two-Phase Flow," Springer (2005)

Mauricio Gargaglione Prado:"A Block Implicit Numerical Solution Technique For Two-Phase Multidimensional Steady State Flow," Ph.D Dissertation, University of Tulsa (1995)

Zhang, H.Q., Wang, Q., Sarica, C., and Brill, J.P.:"Unified Model for Gas-Liquid Pipe Flow via Slug Dynamics – Part 1: Model Development," ASME J. Energy Res. Tech., 125, 266-273 (2003)

Fluid Flow Projects

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

Wei Zheng

Outline

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

Comments from May ABM 2011

- Mr. Mack Shippen, Schlumberger
  - Suggested Kaminsky Model
- Mr. Thomas Danielson, ConocoPhillips
  - Suggested to Consider Pressure Effects Over the Pipe Temperature

Comments from May ABM 2011

- Mr. John Friedemann, GE
  - Suggest to Study J-Factor in Boiling Water
- Dr. Brill, University of Tulsa
  - Recommend Paper "Comparison of 20 Two-Phase Heat Transfer Correlations with Seven Sets of Experimental Data, Including Flow Pattern and Tube Inclination Effects" from OSU

Objective

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

Introduction

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

Model Approaches

- First Approach
  - Pseudo-Gas/Liquid Phase
- Second Approach
  - Gas/Liquid Flow Pattern
  - Oil/Water Flow Pattern

First Approach

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

First Approach …

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

First Approach …

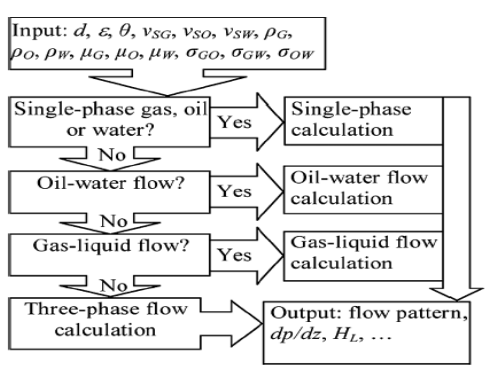
- Zhang *et al*. (2005)
  - Bubble Flow
  - Stratified/Annular Flow
  - Slug Flow

Second Approach

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

Second Approach …

- Hydrodynamic Model



Second Approach …

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

Second Approach …

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

Bubble and Dispersed Bubble Flow

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

$$\frac{\partial T_M}{\partial l} = -\frac{4U_M(T_M - T_O)}{d_I(\rho_L C_{PL} v_{SL} + \rho_L C_{PG} v_{SG})}$$

Annular Flow

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

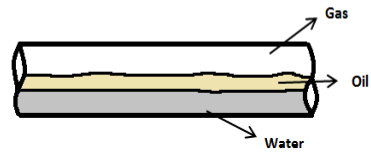
$$\frac{\partial T}{\partial l} = -\frac{U_F S_F (T_F - T_O) + U_C S_C (T_C - T_O)}{A(\rho_L C_{PL} v_{SL} + \rho_G C_{PG} v_{SG})}$$

Stratified Flow

- Stratified Flow with Stratified Oil and Water
  - Assume

$$\frac{\partial T_C}{\partial l} = \frac{\partial T_O}{\partial l} = \frac{\partial T_W}{\partial l}$$

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



Stratified Flow …

- Heat Loss between Layers Neglected
- Heat Balance Equation

$$(T_{C1} - T_{C2})\rho_C A \upsilon_{SC} C_{PC} = q_C S_C dl$$

$$(T_{O1} - T_{O2})\rho_O A \upsilon_{SO} C_{PO} = q_O S_O dl$$

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

$$\frac{\partial T}{\partial l} = \frac{U \pi d_I (T_M - T_O)}{\rho_C A \upsilon_{SC} C_{PC} + \rho_O A \upsilon_{SO} C_{PO} + \rho_W A \upsilon_{SW} C_{PW}}$$

Stratified Flow …

- **Overall Heat Transfer Coefficient**

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

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

Stratified Flow …

- **Overall Heat Transfer Coefficient**

$$T_C - T_O = \frac{\rho_C \upsilon_{SC} C_{PC}}{\rho_O \upsilon_{SO} C_{PO}} \frac{U_O S_O}{U_C S_C} (T_{Oil} - T_O) \qquad B_1 = \frac{\rho_C \upsilon_{SC} C_{PC}}{\rho_O \upsilon_{SO} C_{PO}} \frac{U_O S_O}{U_C S_C}$$

$$T_C - T_O = \frac{\rho_C \upsilon_{SC} C_{PC}}{\rho_W \upsilon_{SW} C_{PW}} \frac{U_W S_W}{U_C S_C} (T_W - T_O) \qquad B_2 = \frac{\rho_C \upsilon_{SC} C_{PC}}{\rho_W \upsilon_{SW} C_{PW}} \frac{U_W S_W}{U_C S_C}$$

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

Stratified Flow …

Overall Heat Transfer Coefficient

$$\frac{T_M - T_O}{T_C - T_O} = \frac{1}{3B_1} + \frac{1}{3B_2} + \frac{1}{3} \qquad \frac{T_M - T_O}{T_W - T_O} = \frac{B_2}{3B_1} + \frac{1}{3} + \frac{B_2}{3}$$

$$\frac{T_M - T_O}{T_{Oil} - T_O} = \frac{B_1}{3B_2} + \frac{1}{3} + \frac{B_1}{3}$$

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

Slug Flow

General Calculation

$$T_{UA} = \frac{\int_0^{t_F} T_F \, dt + \int_0^{t_S} T_S \, dt}{l_U / \upsilon_T}$$

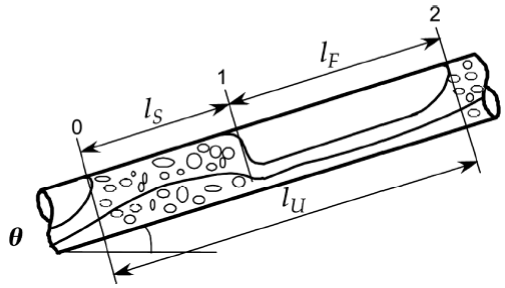
$$\frac{\partial \overline{T}}{\partial l} = -\frac{(T_{UA} - T_O)}{\left(\frac{b}{a} l_F - \frac{f}{e} l_s \right) + \left(\frac{b}{a} - \frac{f}{e} \right) \left(\frac{1}{e} - \frac{1}{a} \right) \frac{\left(1 - e^{-a l_F}\right)\left(1 - e^{-e l_S}\right)}{\left(1 - e^{-a l_F - e l_S}\right)}}$$

Slug Flow …

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

Slug Flow …

- Slug Flow with Stratified Oil and Water



Slug Flow with Stratified Oil and Water

- **Film Region**

$$\frac{1}{\upsilon_T}\frac{\partial T_W}{\partial t}A(\upsilon_T-\upsilon_{WF})H_{WF}\rho_W C_{PW}=\frac{\Delta T_U}{l_U}\upsilon_{WF}H_{WF}A\rho_W C_{PW}-U_{WF}(T_{WF}-T_O)S_{WF}$$

$$\frac{1}{\upsilon_T}\frac{\partial T_{Oil}}{\partial t}A(\upsilon_T-\upsilon_{OF})H_{OF}\rho_O C_{PO}=\frac{\Delta T_U}{l_U}\upsilon_{OF}H_{OF}A\rho_O C_{PO}-U_{OF}(T_{OF}-T_O)S_{WF}$$

$$\frac{1}{\upsilon_T}\frac{\partial T_C}{\partial t}A(\upsilon_T-\upsilon_{CF})(1-H_{WF}-H_{OF})\rho_C C_{PC}=\frac{\Delta T_U}{l_U}\upsilon_{CF}(1-H_{WF}-H_{OF})A\rho_C C_{PC}-U_{CF}(T_{CF}-T_O)S_{CF}$$

Slug Flow with Stratified Oil and Water …

- **Film Region**
  - **Assume** $\frac{\partial T_W}{\partial t}=\frac{\partial T_{Oil}}{\partial t}=\frac{\partial T_C}{\partial t}=\frac{\partial T_F}{\partial t}$

$$\frac{1}{\upsilon_T}\frac{\partial T_F}{\partial t}=b\Delta T_U-a(T_F-T_O)$$

$$b=\frac{\upsilon_{WF}H_{WF}\rho_W C_{PW}+\upsilon_{OF}H_{OF}\rho_O C_{PO}+\upsilon_{CF}(1-H_{WF}-H_{OF})\rho_C C_{PC}}{l_U[(\upsilon_T-\upsilon_{WF})H_{WF}\rho_W C_{PW}+(\upsilon_T-\upsilon_{OF})H_{OF}\rho_O C_{PO}+(\upsilon_T-\upsilon_{CF})(1-H_{WF}-H_{OF})\rho_C C_{PC}]}$$

$$a=\frac{U_{WF}S_{WF}+U_{OF}S_{OF}+U_{CF}S_{CF}}{A[(\upsilon_T-\upsilon_{WF})H_{WF}\rho_W C_{PW}+(\upsilon_T-\upsilon_{OF})H_{OF}\rho_O C_{PO}+(\upsilon_T-\upsilon_{CF})(1-H_{WF}-H_{OF})\rho_C C_{PC}]}$$

Slug Flow with Stratified Oil and Water …

- **Slug Body**

$$\frac{1}{\upsilon_T}\frac{\partial T_{OS}}{\partial t}A(\upsilon_T-\upsilon_{OS})(1-H_{WS})(1-\alpha_{OS})\rho_O C_{PO}=\frac{\Delta T_U}{l_U}\upsilon_{OS}(1-H_{WS})(1-\alpha_{OS})A\rho_O C_{PO}-U_{OS}(T_{OS}-T_O)S_{OS}$$

$$\frac{1}{\upsilon_T}\frac{\partial T_{WS}}{\partial t}A(\upsilon_T-\upsilon_{WS})H_{WS}(1-\alpha_{WS})\rho_W C_{PW}=\frac{\Delta T_U}{l_U}\upsilon_{WS}H_{WS}(1-\alpha_{WS})A\rho_W C_{PW}-U_{WS}(T_{WS}-T_O)S_{WS}$$

Slug Flow with Stratified Oil and Water …

- **Slug Body**
  - **Assume** $\frac{\partial T_{WS}}{\partial t}=\frac{\partial T_{OS}}{\partial t}=\frac{\partial T_S}{\partial t}$

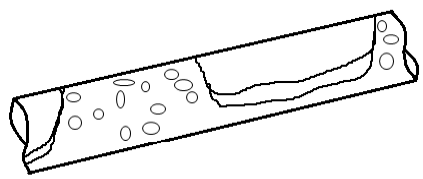
$$\frac{1}{\upsilon_T}\frac{\partial T_S}{\partial t}=f\Delta T_U-e(T_S-T_O)$$

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

$$e=\frac{U_{OS}S_{OS}+U_{WS}S_{WS}}{A[(\upsilon_T-\upsilon_{OS})(1-H_{WS})(1-\alpha_{OS})\rho_O C_{PO}+(\upsilon_T-\upsilon_{WS})H_{WS}(1-\alpha_{WS})\rho_W C_{PW}]}$$

Slug Flow

- Slug Flow with Stratified Oil and Water in Film Region



Slug Flow with Stratified Oil and Water in Film Region

- Film Region

$$\frac{1}{\upsilon_T}\frac{\partial T_F}{\partial t} = b\Delta T_U - a\left(T_F - T_O\right)$$

$$a = \frac{U_{WF}S_{WF} + U_{OF}S_{OF} + U_{CF}S_{CF}}{A\left[\left(\upsilon_T - \upsilon_{WF}\right)H_{WF}\rho_W C_{PW} + \left(\upsilon_T - \upsilon_{OF}\right)H_{OF}\rho_O C_{PO} + \left(\upsilon_T - \upsilon_{CF}\right)\left(1 - H_{WF} - H_{OF}\right)\rho_C C_{PC}\right]}$$

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

Slug Flow with Stratified Oil and Water in Film Region …

- **Slug Body**

$$\frac{1}{\upsilon_T}\frac{\partial T_S}{\partial t} = f\Delta T_U - e\left(T_S - T_O\right)$$

$$e = \frac{U_S \pi d_I}{\rho_L C_{PL} H_{LS} A\left(\upsilon_T - \upsilon_M\right)} \qquad f = \frac{\upsilon_M}{l_U\left(\upsilon_T - \upsilon_M\right)}$$

Preliminary Result

- **First Approach (Software Inputs)**

Fluid Properties		
Superficial Oil Velocity	m/s	0.5
Superficial Water Velocity	m/s	0.5
Superficial Gas Velocity	m/s	4
Oil Density	kg/m³	1200
Water Density	kg/m³	1200
Gas Density	kg/m³	1.2047
Oil Viscosity	Pa.s	0.001
Water Viscosity	Pa.s	0.001
Gas Viscosity	Pa.s	0.0000181
Liquid Viscosity at Wall	cp	254
OW Surface Tension	N/m	0.076
OG Surface Tension	N/m	0.076
GW Surface Tension	N/m	0.076
Inlet Pressure	psia	1001
Inlet Temperature	F°	69

Preliminary Result …

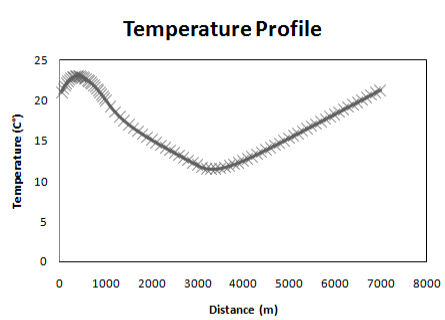
First Approach (Software Inputs)

Pipe Profile				
Total Pipe Number	-	1	2	3
Inner Diameter	in	6	6	6
Outer Diameter	in	6.4	6.7	6.7
Length	m	1000	2000	4000
Number of Section	-	30	20	40
Elevation	m	500	800	200
Absolute Roughness	mm	0.004	0.004	0.04

Heat Transfer Input		
Oil Heat Capacity	J/(Kg.C°)	1980
Water Heat Capacity	J/(Kg.C°)	2210
Gas Heat Capacity	J/(Kg.C°)	2344.6
Oil Thermal Conductivity	W/(m.C°)	0.2
Water Thermal Conductivity	W/(m.C°)	0.1609
Gas Thermal Conductivity	W/(m.C°)	0.0403
Pipe Thermal Conductivity	W/(m.C°)	16.29
Initial Ambient Temperature	F°	80
Geothermal Temperature Gradient	-	-0.02
Outside Heat Transfer Coefficient	W/(m².C°)	2396.28

Preliminary Result …

First Approach (Software Outputs)



Verification

Gas/Liquid Heat Transfer Model

Fluid Properties		
Superficial Liquid Velocity	m/s	1
Superficial Gas Velocity	m/s	4
Liquid Density	kg/m³	1200
Gas Density	kg/m³	1.2047
Liquid Viscosity	Pa.s	0.001
Gas Viscosity	Pa.s	0.0000181
Liquid Viscosity at Wall	cp	254
Surface Tension	N/m	0.076
Inlet Pressure	psia	1001
Inlet Temperature	F°	69

Fluid Properties		
Superficial Oil Velocity	m/s	0.5
Superficial Water Velocity	m/s	0.5
Superficial Gas Velocity	m/s	4
Oil Density	kg/m³	1200
Water Density	kg/m³	1200
Gas Density	kg/m³	1.2047
Oil Viscosity	Pa.s	0.001
Water Viscosity	Pa.s	0.001
Gas Viscosity	Pa.s	0.0000181
Liquid Viscosity at Wall	cp	254
OW Surface Tension	N/m	0.076
OG Surface Tension	N/m	0.076
GW Surface Tension	N/m	0.076
Inlet Pressure	psia	1001
Inlet Temperature	F°	69

Verification

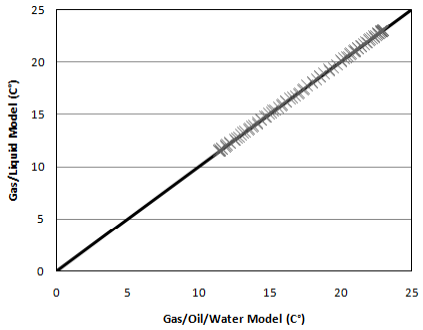
Gas/Liquid Heat Transfer Model

Pipe Profile				
Total Pipe Number	-	1	2	3
Inner Diameter	in	6	6	6
Outer Diameter	in	6.4	6.7	6.7
Length	m	1000	2000	4000
Number of Section	-	30	20	40
Elevation	m	500	800	200
Absolute Roughness	mm	0.004	0.004	0.04

Heat Transfer Input		
Oil Heat Capacity	J/(Kg.C°)	1980
Water Heat Capacity	J/(Kg.C°)	2210
Gas Heat Capacity	J/(Kg.C°)	2344.6
Oil Thermal Conductivity	W/(m.C°)	0.2
Water Thermal Conductivity	W/(m.C°)	0.1609
Gas Thermal Conductivity	W/(m.C°)	0.0403
Pipe Thermal Conductivity	W/(m.C°)	16.29
Initial Ambient Temperature	F°	80
Geothermal Temperature Gradient	-	-0.02
Outside Heat Transfer Coefficient	W/(m².C°)	2396.28

Verification

- Results Comparison



Research Plan

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

Project Schedule

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

Questions/Comments

?

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

Wei Zheng

Project Completion Dates

Gas/Oil/Water Pipe Flow Heat Transfer Modeling – Step 1	Complete
Model Verification	Complete
Software Update	Complete
Gas/Oil/Water Pipe Flow Heat Transfer Modeling – Step 2	Complete
Model Verification	February 2012
Software Implementation	April 2012

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 from -90° to +90°. The resultant model will be included in the TUFFP Excel VBA software package for wellbore and pipeline thermal calculations.

Introduction

Accurate prediction of pipeline temperature profile is crucial for flow assurance and production system design. It is important to accurately predict the fluid temperature to predict wax deposition and hydrate formation. For heavy oil, temperature has a significant effect on oil viscosity, which is a critical parameter to characterize the flow behavior.

Single phase heat transfer in pipe flow has been widely studied and well understood, while the multiphase pipe flow heat transfer is still under development. Comparing to single phase, multiphase flow presents different flow patterns and requires more complicated fluid flow description for heat transfer characterization.

Activities Summary

After reviewing single-phase and two-phase heat transfer models, two approaches of gas/oil/water heat transfer model have been proposed.

Approach 1

The TUFFP unified model of heat transfer for gas/liquid pipe flow is utilized by combining oil and water phases into a pseudo single phase based on the hydrodynamic outputs from the TUFFP unified hydrodynamic model for gas/oil/water pipe flow.

Approach 2

Three phase hydrodynamic model is used for the hydrodynamic calculation. Then, different heat transfer models are developed corresponding to different gas/oil/water flow patterns. The flow patterns are classified based on gas/liquid flow pattern and oil/water flow mixing status. In terms of gas/liquid flow, the flow patterns include bubble and dispersed bubble flow, annular flow, stratified flow and slug flow. Oil and water are assumed to be fully mixed in dispersed bubble and annular flows. They may be stratified or mixed in stratified gas-liquid flow. For slug flow three cases are considered, namely, fully mixed oil and water in film region and slug body, stratified oil and water in film region and slug body and, stratified oil and water in film region and mixed oil and water in slug body.

Bubble and Dispersed Bubble Flow

For bubble and dispersed bubble flow, oil and water is treated as pseudo single liquid phase and the liquid properties are adjusted with water fraction. The gas/liquid unified heat transfer model for bubble and dispersed bubble flow is then applied to calculate the temperature gradient.

Annular Flow

For annular flow, the film layer which contains both oil and water is considered as a pseudo single liquid phase. After calculating the fluid properties with water fraction, the unified model of heat transfer for gas/liquid pipe flow is used for the annular flow calculation.

Stratified Flow

For gas/oil/water stratified flow, oil and water is considered to be stratified. Assuming that the heat loss between the layers is negligible and the temperature gradient for gas, oil and water over the same segment is the same, heat balance equation can be derived. Then, the temperature gradient can be calculated through over-all heat transfer coefficient.

Slug Flow

Three possible scenarios are considered for this flow pattern.

Fully Mixed Oil and Water

For slug flow with fully mixed oil and water in both slug body region and film region, the slug flow approach from unified heat transfer model for gas/liquid pipe flow can be used with the effective

liquid properties obtained based on water fraction and water and oil properties.

Stratified Oil and Water

Oil and water are stratified in both slug body and film region. Average slug unit temperature is obtained based on heat capacities of the three phases across slug body and film region. In the film region, heat balance equations are derived for gas layer, oil layer and water layer. Assuming that the temperature gradients are the same for gas, oil and water layers, and an equation is reached which can describe film temperature. For slug body region, similar equations are developed. Then, the average temperature gradient across the liquid film and slug body of a slug unit can be predicted.

Mixed Oil and Water in Slug Body and Stratified Oil and Water in Film Region

The slug unit temperature gradient can be calculated using the method of the first scenario for the slug body and the method of the second scenario for film region.

Preliminary Result

After the first approach of modeling is proposed, the TUFFP software package is updated accordingly, and the preliminary simulation is conducted.

Future Work

The TUFFP software package will be updated with the second approach of gas/oil/water heat transfer model to generate the temperature profile of multiphase pipe flow. Model evaluation will be carried out after code debugging. Final report will be submitted May 2012.

References

Zhang, H.-Q. *et al*.: "Unified Model for Gas-Liquid Pipe Flow via Slug Dynamics-Part1: Model Development," J. Energy Res. Technol. (2003a) 125, No. 4, 266.

Zhang, H.-Q. *et al*.: "Unified Model for Gas-Liquid Pipe Flow via Slug Dynamics-Part 2: Model Validation," J. Energy Res. Technology. (2003b) 125, No. 4, 274.

Zhang, H.-Q., Sarica, C., "Unified Modeling of Gas/Oil/Water-Pipe Flow-Basic Approaches and Preliminary Validation," SPE Projects, June 2006.

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

Yang, S.-M., "Heat Transfer Theory," China Higher Education Press, 1980.

Christian, C., "Solution Techniques for Elementary Partial Differential Equations," CRC Press, 2010.

Goldstein, R.J., Ibele, W.E., Patankar, S.V., Simon, T.W., Kuehn, T.H., Strykowski, P.J., Tamma, K.K., Heberlein, J.V.R., Davidson, J.H., Bischof, J., Kulacki, F.A., Kortshagen, U., Garrick, S., Srinivasan, V., Ghosh, K., Mittal, R. "Heat Transfer-A Review of 2005 Literature," International Journal of Heat and Mass Transfer 53 (2010).

Fluid Flow Projects

Business Report

Cem Sarica

Advisory Board Meeting, October 26, 2011

Membership and Collaboration Status

- Current Membership Status
  - Membership Steady at 16
    - 15 Industrial and MMS
- Efforts Continue to Increase TUFFP Membership
  - Saudi Aramco and Statoil are Expected to Rejoin for 2012
- Collaboration with Seoul National University Continues
  - Visiting Research Scholars and Financial Contribution

Publications and Papers

- Alsarkhi, A. and Sarica, C.: Comment on: "Correlation of Entrainment for Annular Flow in Horizontal Pipes", by Pan, L., and Hanratty, T.J., Int. J. Multiphase Flow, 28(3), pp. 385-408. (2002)" *International Journal of Multiphase Flow,* pp.535-536, 37/5, June 2011.
- Alsarkhi, A. and Sarica, C.: Comment on: "Droplet entrainment correlation in vertical upward co-current annular two-phase flow", by Sawant, P., Ishii, M., Mori, M., Nuclear Engineering and Design 238 1342–1352 (2008) *Nuclear Engineering and Design.* pp. 3357-3358, 241/8, August 2011.
- Zhang, H. Q., and Sarica, C.: "A Model for Wetted Wall Fraction and Gravity Center of Liquid Film in Gas-Liquid Pipe Flow," *Society of Petroleum Engineers Journal* September 2011.
- Al-Safran, E., Gokcal, B., and Sarica, C.: "High Viscosity Liquid Effect on Two-Phase Slug Length in Horizontal Pipes," Presented at 15th International Conference Multiphase Production 11, Cannes, France, June 15-17, 2011.

Next Advisory Board Meetings

- Tentative Schedule
  - April 25, 2012
    - TUHOP Meeting
    - TUFFP Workshop
    - Facility Tour
    - TUHOP/TUHFP/TUFFP Reception
  - April 26, 2012
    - TUFFP Meeting
    - TUFFP/TUPDP Dinner
  - April 27, 2012
    - TUPDP Meeting
- Venue is The University of Tulsa

Financial Report

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

Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

2011 Industrial Account Summary

(Prepared October 10, 2011)

Anticipated Reserve Fund Balance on January 1, 2011					**($29,760)**
Income for 2011					
	2011 Anticipated Membership Fees (15 @ $55,000 - excludes MMS)				**825,000**
	Facility Utilization Fee (SNU)				**55,000**
	Facility Utilization Fee (Foam Project)				**60,000**
Total Budget					**$ 910,240**
Projected Budget/Expenditures for 2011					
		Projected Budget 11/3/10	**Revised Budget April 2011**	**2011 Expenditures 10/10/11**	**Revised Budget 10/10/11**
90101 - 90103	Faculty Salaries	38,481.88	38,481.88	13,896.26	27,918.00
90600 - 90609	Professional Salaries	71,906.23	51,656.23	32,193.70	44,588.00
90700 - 90703	Staff Salaries	28,306.09	31,289.67	20,310.56	30,858.00
90800	Part-time/Temporary		24,000.00	19,272.67	20,339.35
91000	Student Salaries - Monthly	43,950.00	43,950.00	34,000.00	43,950.00
91100	Student Salaries - Hourly	15,000.00	15,000.00	7,195.78	10,000.00
91800	Fringe Benefits (35 %)	48,542.97	42,500.00	23,487.31	36,177.00
92102	Fringe Benefits (Students)		3,516.00	2,460.00	3,516.00
81801	Tuition & Student Fees		-	10,492.00	19,223.00
81806	Fellowship			1,125.00	1,125.00
93100	General Supplies	3,000.00	3,000.00	2,786.50	3,500.00
93101	Research Supplies	100,000.00	100,000.00	92,236.98	120,000.00
93102	Copier/Printer Supplies	500.00	500.00	75.08	300.00
93104	Computer Software	4,000.00	4,000.00	2,623.50	3,000.00
93106	Office Supplies	2,000.00	2,000.00	656.91	1,200.00
93150	Computers ($1000 - $4999)			1,423.23	1,423.23
93200	Postage and Shipping	500.00	500.00	326.28	500.00
93300	Printing and Duplicating	2,000.00	2,000.00	2,202.74	3,000.00
93400	Telecommunications	3,000.00	3,000.00	1,500.00	2,500.00
93500	Membership	1,000.00	1,000.00	133.67	500.00
93601	Travel - Domestic	10,000.00	10,000.00	3,030.52	9,000.00
93602	Travel - Foreign	10,000.00	10,000.00	8,609.55	9,000.00
93700	Entertainment	10,000.00	16,000.00	11,714.95	16,000.00
94813	Outside Services	20,000.00	40,000.00	17,977.22	30,000.00
95103	Equipment Rental			11,518.05	15,000.00
95200	F&A (52.4%)	103,565.56	107,094.00	57,826.90	95,710.00
98901	Employee Recruiting	3,000.00	3,000.00	201.52	250.00
99001	Equipment	250,000.00	250,000.00	112,773.20	150,000.00
99002	Computers	8,000.00	8,000.00	6,155.51	6,155.51
99300	Bank Charges	40.00	40.00	32.00	40.00
Total Anticipated Expenditures		**776,792.73**	**810,527.78**	**498,237.59**	**704,773.09**
Anticipated Reserve as of 12/31/11					**205,466.65**

2011 BSEE Account Summary

(Prepared October 11, 2011)

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**

Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

2012 Proposed Industrial Account Budget

(Prepared October 11, 2011)

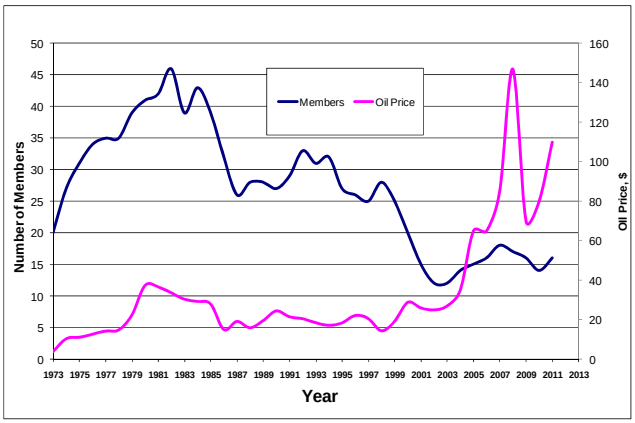
Anticipated Reserve Fund Balance on January 1, 2012		**$205,466.65**
Income for 2012		
	2012 Anticipated Membership Fees (15 @ $55,000 - excludes MMS)	**$825,000.00**
	Facility Utilization Fee (SNU)	**$55,000.00**
Total Income		**$1,085,466.65**
2009 Anticipated Expenditures		
90101-90103	Faculty Salaries	30,712.47
90600-90609	Professional Salaries	117,198.22
90700-90703	Staff Salaries	34,597.60
91000	Graduate Students	54,050.00
91100	Undergraduate Students	15,000.00
91800	Fringe Benefits (35%)	63,877.90
93100	General Supplies	3,000.00
93101	Research Supplies	120,000.00
93102	Copier/Printer Supplies	750.00
93104	Computer Software	4,000.00
93106	Office Supplies	2,000.00
93200	Postage/Shipping	500.00
93300	Printing/Duplicating	3,000.00
93400	Telecommunications	2,500.00
93500	Memberships/Subscriptions	1,000.00
93601	Travel - Domestic	10,000.00
93602	Travel - Foreign	10,000.00
93700	Entertainment (Advisory Board Meetings)	16,000.00
81801	Tuition/Student Fees	18,686.10
94803	Consultants	0.00
94813	Outside Services	20,000.00
95200	Indirect Costs (52.4%)	144,392.55
98901	Employee Recruiting	3,000.00
99001	Equipment	300,000.00
99002	Computers	8,000.00
99300	Bank Charges	40.00
	Total Expenditures	**$982,304.84**
Anticipated Reserve Fund Balance on December 31, 2012		**$103,161.81**

2012 Proposed BSEE Account Budget

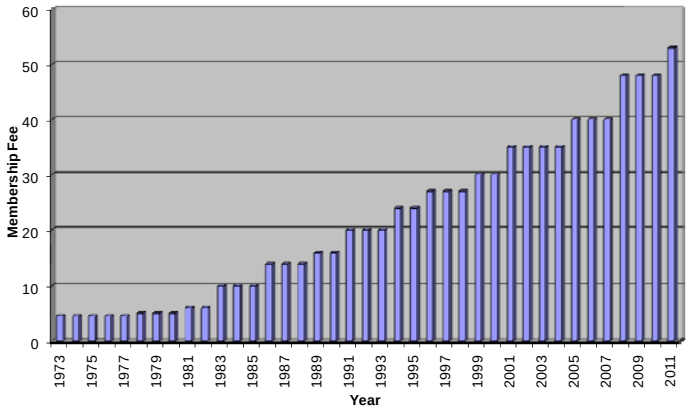
(Prepared October 11, 2011)

Account Balance - January 1, 2011		**$2,376.35**
Income for 2012		
	2012 Membership Fee	**$48,000.00**
Remaining Balance		**$50,376.35**
2009 Anticipated Expenditures		**Projected Budget**
90101-90103	Faculty Salaries	-
90600-90609	Professional Salaries	-
90700-90703	Staff Salaries	-
91000	Graduate Students	28,700.00
92102	Student Fringe Benefits (8%)	2,296.00
95200	Indirect Costs (55.6%)	15,957.20
	Total Expenditures	**$46,953.20**
Anticipated Reserve Fund Balance on December 31, 2012		**$3,423.15**

History – Membership



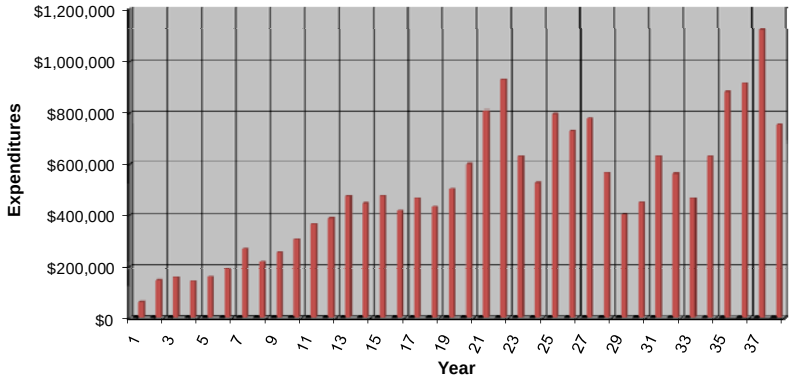
History – Membership Fees



Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

History - Expenditures



Fluid Flow Projects

Advisory Board Meeting, October 26, 2011

Membership Fees

- 2011 Membership Dues
  - All Paid
  - Thank You

Introduction

This semi-annual report is submitted to Tulsa University Fluid Flow Projects (TUFFP) members to summarize activities since the May 12, 2011 Advisory Board meeting and to assist in planning for the next six months. It also serves as a basis for reporting progress and generating discussion at the 77th semi-annual Advisory Board meeting to be held in Gallery Room of Allen Chapman Activity Center (ACAC) of the University of Tulsa Main Campus, ACAC 440 South Gary, Tulsa, Oklahoma on Wednesday on Wednesday, October 26, 2011.

The activities will start with Tulsa University High Viscosity Projects (TUHOP) Advisory Board meeting on October 25, 2011 between 8:15 a.m. and noon in Gallery. Between 1:00 and 3:30 p.m. on October 25, 2011, there will be TUFFP workshop in the same room. There will be presentations made by TUFFP member companies. A facility tour will be held on October 25, 2011 between 4:00 and 5:30 p.m. Several TUFFP/TUPDP/TUHOP facilities will be operating during the tour. Following the tour, there will be a TUHOP/TUFFP reception between 6:00 p.m. and 9:30 p.m. in Great Hall-B of ACAC.

TUFFP Advisory Board meeting will convene at 8:00 a.m. on October 26 and will adjourn at approximately 5:00 p.m. Following the meeting, there will be a joint TUFFP/TUPDP dinner between 6:00 and 9:00 p.m. in Atrium of ACAC.

The Tulsa University Paraffin Deposition Projects (TUPDP) Advisory Board meeting will be held on October 27 in Gallery of ACAC, between 8:00 a.m. and 1:15 p.m.

The following dates have tentatively been established for Spring 2012 Advisory Board meetings. The venue for Spring 2012 Advisory Board meetings is tentatively set to be the University of Tulsa Main Campus.

2012 Spring Meetings

April 24, 2012	Tulsa University High Viscosity Oil Projects (TUHOP) JIP Meeting
	Tulsa University Fluid Flow Projects (TUFFP) Workshop
	Facility Tour
	TUHOP/TUFFP Reception
April 25, 2012	Tulsa University Fluid Flow Projects (TUFFP) Advisory Board Meeting
	TUFFP/TUPDP Reception
April 26, 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 TUHFP and 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.

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. Benin (Ben) Chelinsky Jeyachandra, from India, has completed his MS degree in Petroleum Engineering studying the high oil viscosity multiphase flow in inclined pipes. He is currently working for Schlumberger Information Solutions.

Mr. Ge (Max) Yuan, from Peoples Republic of China (PRC), is pursuing his MS degree in Petroleum Engineering. Max has received a BS degree in Chemical Engineering and Technology from Dalian University of Technology in 2009. Max is studying Liquid Loading in Gas Wells.

Ms. Mujgan Guner has dual BS degrees in Petroleum and Mechanical Engineering from Middle East Technical University, Turkey. Mujgan has changed her degree program from Ph.D. to MS. in Petroleum Engineering. Therefore, she is assigned to the continuation project of Liquid Loading in Gas Wells.

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 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 assigned to unified mechanistic modeling project focusing on multiphase heat transfer.

Mr. Feras Alruhaimani, 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 assigned to High Viscosity Oil Multiphase Flow project.

Mr. Hamid Karami, from Iran, has successfully completed his MS degree requirements in petroleum engineering July 2011 studying shear effect on single-phase flow paraffin deposition in TUPDP. Hamid decided to pursue

his Ph.D. degree in petroleum engineering conducting research in TUFFP. Moreover, he has successfully passed his Ph.D. qualifying exams. He has already been assigned to the project titled "Effects of MEG on Multiphase Flow".

Mr. Yasser Alsaadi, from Saudi Arabia, has recently joined TUFFP team 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 will be assigned a research project after the Fall 2011 Advisory Board meeting.

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"

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*
Alruhaimani, Feras	Kuwait	Kuwait University	Kuwait University	Ph.D. PE	High Viscosity Oil Multiphase Flow	Spring 2014
Alsaadi, 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
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
Yuan, Ge (Max)	PRC	Yes – TUFFP	Waived – (BSEE)	MS – PE	Liquid Loading of Gas Wells	Fall 2011
Zheng, Wei	PRC	Partial – TU	Waived – (TU)	MS – PE	Unified Heat Transfer Modeling of Gas/Oil/Water Pipe Flow	Spring 2012

Membership

The current membership of TUFFP stays at 16: 15 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. Saudi Aramco and Statoil consider becoming TUFFP members in 2012.

Table 2 lists all the current 2011 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

2011 Fluid Flow Projects Membership

Aspen Tech

Baker Atlas

BP Exploration

BSEE (Bureau of Safety and Environmental Enforcement)

Chevron

ConocoPhillips

Exxon Mobil

General Electric

JOGMEG

KOC

Marathon Oil Company

Petrobras

Schlumberger

Shell Global Solutions

SPT

Total

Equipment and Facilities Status

Test Facilities

The 6 in. ID High Pressure Facility construction is near completion. Remaining tasks are commissioning of gas compressor, HAZOP review and instrumentation.

Three-phase 3 in. ID facility has been modified for the liquid unloading project from gas wells. The modifications involve incorporation of proper instruments on the test section.

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.

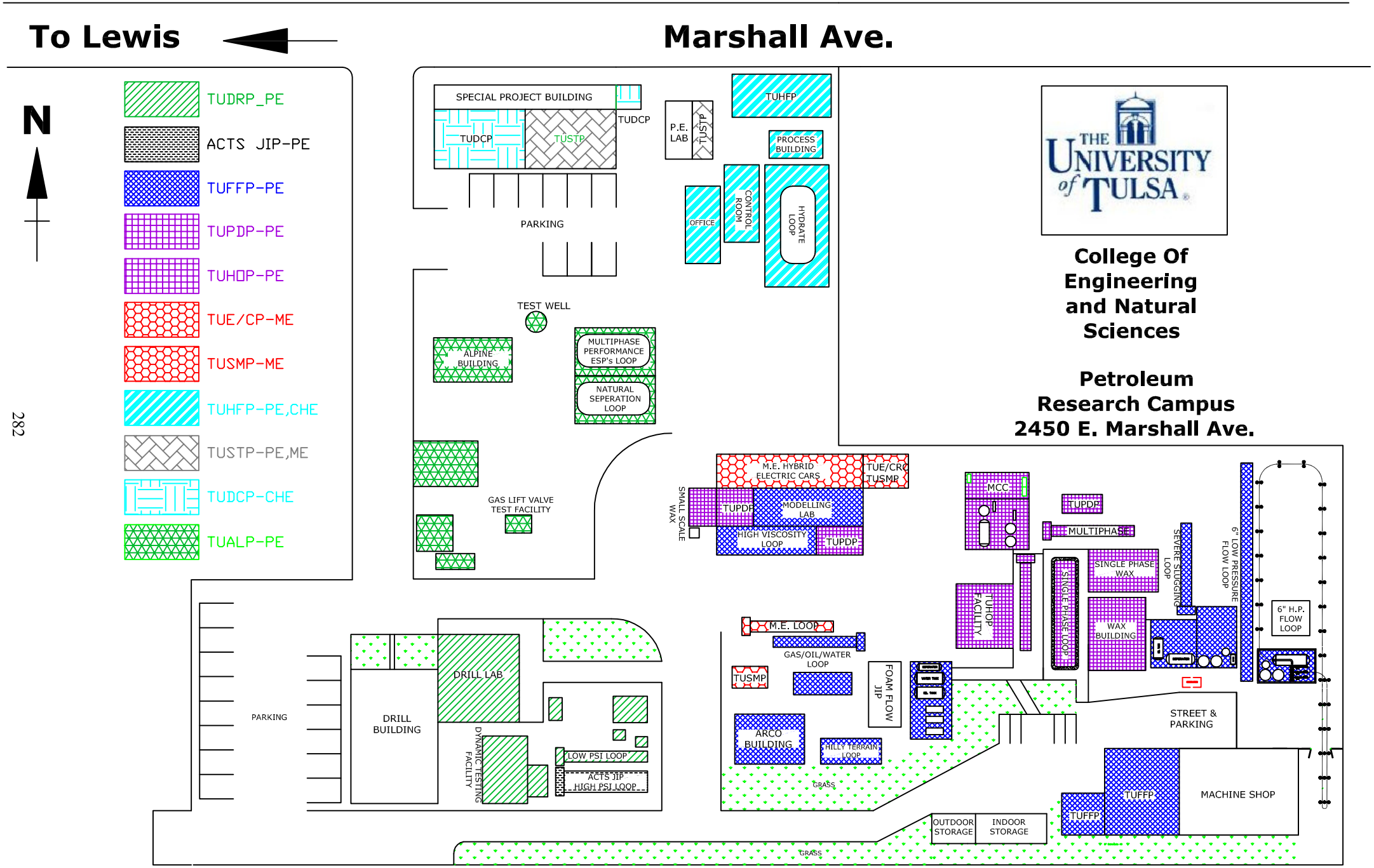


Figure 1: Site Plan for the North Campus Research Facilities

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 October 10, 2011. Also shown are previous 2011 budgets that have been reported to the members. The total industry expenditures for 2011 are estimated to be $704,773. This results in an estimated carryover of $205,467 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 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 15 members. This provides $825,000.00 of industrial membership income for 2012. In addition TUFFP will receive facility utilization fee from SNU totaling $55,000.00. The total of the 2012 income and the reserve account is projected to be $1,085,467. The expenses for the industrial member account are proposed to be $982,305 leaving a carryover balance of $103,162 to 2013. The BSEE account is expected to have a carryover of $3,423 to 2013.

Table 3: 2011 Industrial Budget Summary

(Prepared October 10, 2011)

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

Projected Budget/Expenditures for 2011

		Projected Budget 11/3/10	Revised Budget April 2011	2011 Expenditures 10/10/11	Revised Budget 10/10/11
90101 - 90103	Faculty Salaries	38,481.88	38,481.88	13,896.26	27,918.00
90600 - 90609	Professional Salaries	71,906.23	51,656.23	32,193.70	44,588.00
90700 - 90703	Staff Salaries	28,306.09	31,289.67	20,310.56	30,858.00
90800	Part-time/Temporary		24,000.00	19,272.67	20,339.35
91000	Student Salaries - Monthly	43,950.00	43,950.00	34,000.00	43,950.00
91100	Student Salaries - Hourly	15,000.00	15,000.00	7,195.78	10,000.00
91800	Fringe Benefits (35 %)	48,542.97	42,500.00	23,487.31	36,177.00
92102	Fringe Benefits (Students)		3,516.00	2,460.00	3,516.00
81801	Tuition & Student Fees		-	10,492.00	19,223.00
81806	Fellowship			1,125.00	1,125.00
93100	General Supplies	3,000.00	3,000.00	2,786.50	3,500.00
93101	Research Supplies	100,000.00	100,000.00	92,236.98	120,000.00
93102	Copier/Printer Supplies	500.00	500.00	75.08	300.00
93104	Computer Software	4,000.00	4,000.00	2,623.50	3,000.00
93106	Office Supplies	2,000.00	2,000.00	656.91	1,200.00
93150	Computers ($1000 - $4999)			1,423.23	1,423.23
93200	Postage and Shipping	500.00	500.00	326.28	500.00
93300	Printing and Duplicating	2,000.00	2,000.00	2,202.74	3,000.00
93400	Telecommunications	3,000.00	3,000.00	1,500.00	2,500.00
93500	Membership	1,000.00	1,000.00	133.67	500.00
93601	Travel - Domestic	10,000.00	10,000.00	3,030.52	9,000.00
93602	Travel - Foreign	10,000.00	10,000.00	8,609.55	9,000.00
93700	Entertainment	10,000.00	16,000.00	11,714.95	16,000.00
94813	Outside Services	20,000.00	40,000.00	17,977.22	30,000.00
95103	Equipment Rental			11,518.05	15,000.00
95200	F&A (52.4%)	103,565.56	107,094.00	57,826.90	95,710.00
98901	Employee Recruiting	3,000.00	3,000.00	201.52	250.00
99001	Equipment	250,000.00	250,000.00	112,773.20	150,000.00
99002	Computers	8,000.00	8,000.00	6,155.51	6,155.51
99300	Bank Charges	40.00	40.00	32.00	40.00
Total Anticipated Expenditures		**776,792.73**	**810,527.78**	**498,237.59**	**704,773.09**
Anticipated Reserve as of 12/31/11					**205,466.65**

Table 4: 2011 BSEE Budget Summary

(Prepared October 11, 2011)

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: Proposed 2012 Industrial Budget

(Prepared October 11, 2011)

Anticipated Reserve Fund Balance on January 1, 2012		**$205,466.65**
Income for 2012		
	2012 Anticipated Membership Fees (15 @ $55,000 - excludes MMS)	**$825,000.00**
	Facility Utilization Fee (SNU)	**$55,000.00**
Total Income		**$1,085,466.65**
2009 Anticipated Expenditures		
90101-90103	Faculty Salaries	30,712.47
90600-90609	Professional Salaries	117,198.22
90700-90703	Staff Salaries	34,597.60
91000	Graduate Students	54,050.00
91100	Undergraduate Students	15,000.00
91800	Fringe Benefits (35%)	63,877.90
93100	General Supplies	3,000.00
93101	Research Supplies	120,000.00
93102	Copier/Printer Supplies	750.00
93104	Computer Software	4,000.00
93106	Office Supplies	2,000.00
93200	Postage/Shipping	500.00
93300	Printing/Duplicating	3,000.00
93400	Telecommunications	2,500.00
93500	Memberships/Subscriptions	1,000.00
93601	Travel - Domestic	10,000.00
93602	Travel - Foreign	10,000.00
93700	Entertainment (Advisory Board Meetings)	16,000.00
81801	Tuition/Student Fees	18,686.10
94803	Consultants	0.00
94813	Outside Services	20,000.00
95200	Indirect Costs (52.4%)	144,392.55
98901	Employee Recruiting	3,000.00
99001	Equipment	300,000.00
99002	Computers	8,000.00
99300	Bank Charges	40.00
	Total Expenditures	**$982,304.84**
Anticipated Reserve Fund Balance on December 31, 2012		**$103,161.81**

Table 6: 2012 Proposed BSEE Budget

(Prepared October 11, 2011)

Account Balance - January 1, 2011		**$2,376.35**
Income for 2012		
	2012 Membership Fee	**$48,000.00**
Remaining Balance		**$50,376.35**
2009 Anticipated Expenditures		**Projected Budget**
90101-90103	Faculty Salaries	**-**
90600-90609	Professional Salaries	-
90700-90703	Staff Salaries	**-**
91000	Graduate Students	28,700.00
92102	Student Fringe Benefits (8%)	2,296.00
95200	Indirect Costs (55.6%)	15,957.20
	Total Expenditures	**$46,953.20**
Anticipated Reserve Fund Balance on December 31, 2012		**$3,423.15**

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 spend very productive 1 ½ months with TUFFP during summer of 2011. During his stay, he has helped TUFFP graduate students and worked on the droplet homo-phase project concentrating on entrainment fraction closure relationship development.

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.

15th International Conference on Multiphase Technology, supported by IFP, IFE, NEOTEC and TUFFP, held 15-17 of June 2011 in Cannes, France. There were two papers with TUFFP contributions to be presented

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) Alsarkhi, A. and Sarica, C.**:** Comment on: "Correlation of Entrainment for Annular Flow in Horizontal Pipes", by Pan, L., and Hanratty, T.J., Int. J. Multiphase Flow, 28(3), pp. 385-408. (2002)" *International Journal of Multiphase Flow*, pp.535-536, **37/5**, June 2011.
2) Alsarkhi, A. and Sarica, C.**:** Comment on: "Droplet entrainment correlation in vertical upward co-current annular two-phase flow", by Sawant, P., Ishii, M., Mori, M., Nuclear Engineering and Design 238 1342–1352 (2008) *Nuclear Engineering and Design.* pp. 3357-3358, **241/8**, August 2011.
3) Zhang, H. Q., and Sarica, C.: "A Model for Wetted Wall Fraction and Gravity Center of Liquid Film in Gas-Liquid Pipe Flow," *Society of Petroleum Engineers Journal* September 2011.
4) Al-Safran, E., Gokcal, B., and Sarica, C.: "High Viscosity Liquid Effect on Two-Phase Slug Length in Horizontal Pipes," Presented at 15th International Conference Multiphase Production 11, Cannes, France, June 15-17, 2011.

Tulsa University Paraffin Deposition Projects (TUPDP) Activities

The forth 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, 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)

A new JIP was recently formed to investigate 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 estimated to be $50,000.

TUHWALP will work cooperatively in the Petroleum Industry:

- 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
- 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 2011 and 2012. Table 9 lists meetings that would be of interest to TUFFP members.

Table 9

Meeting and Conference Calendar

2011

Oct. 25	TUHOP Spring Advisory Board Meeting, Tulsa, Oklahoma
	TUFFP Spring Workshop, Tulsa, Oklahoma
Oct. 26	TUFFP Spring Advisory Board Meeting, Tulsa, Oklahoma
Oct. 27	TUPDP Spring Advisory Board Meeting, Tulsa, Oklahoma
Oct. 30 – Nov. 2	SPE Annual Technical Conference and Exhibition, Denver, CO, USA
Nov. 15 – 17	CSUG/SPE Canadian Unconventional Resources Conference, Alberta, Canada.
Dec. 12 -14	2011 SPE Heavy Oil Conference and Exhibition (HOCE), Kuwait City, Kuwait

2012

Apr. 1-5	AIChE Spring Meeting - 1st International Conference on Upstream Engineering and Flow Assurance
Apr. 25	TUHOP Fall Advisory Board Meeting, Tulsa, Oklahoma
	TUFFP Fall Workshop, Tulsa, Oklahoma
Apr. 26	TUFFP Fall Advisory Board Meeting, Tulsa, Oklahoma
Apr. 27	TUPDP Fall 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

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).

---

[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).

Appendix B

2011 Fluid Flow Projects Advisory Board Representatives

Aspen Tech

Glenn Dissinger
Aspen Technology, Inc.
200 Wheeler Road
Burlington, MA 01803
Phone:
Fax:
Email Glenn.Dissinger@aspentech.com

Benjamin Fischer
Sr. Principal Engineer
Aspen Technology, Inc.
200 Wheeler Road
Burlington, MA 01803
Phone: (781) 221-4311
Email: Benjamin.Fischer@aspentech.com

Baker Atlas

Michael R. Wells
Director of Research
Baker Hughes
Phone: (281) 363-6769
Fax: (281) 363-6099
Email Mike.Wells@bakerhughes.com

Jeff Li
Senior Project Engineer
Coiled Tubing Research & Engineering
Baker Hughes
6620 36th Street, SE
Calgary, Canada T2C 2G4
Phone: 1 (403) 531-5481
Fax: 1 (403) 531-6751
Email: jli@bjservices.ca

Datong Sun
Baker Atlas
2001 Rankin Road
Houston, Texas 77073
Phone: (713) 625-5791
Fax: (713) 625-6795
Email: datong.sun@bakeratlas.com

Bureau of Safety and Environmental Enforcement (BSEE)

Timothy Steffek
BSEE
381 Elden Street, MS-4021
Herndon, VA 20170-4817
Phone: (703) 787-1562
Email: Timothy.Steffek@boemre.gov

Sharon Buffington
BSEE
381 Elden Street
Mail Stop 2500
Herndon, VA 20170-4817
Phone: (703) 787-1147
Fax: (703) 787-1555
Email: sharon.buffington@boemre.gov

BP

Official Representative & UK Contact
Tim Lockett
Flow Assurance Engineer
EPT Subsea and Floating Systems
BP Exploration Operating Co. Ltd.
Chertsey Road, Sunbury-on-Thames
Middlesex, TW16 7LN
United Kingdom
Phone: 44 1932 771885
Fax: 44 1932 760466
Email: tim.lockett@uk.bp.com

Alternate UK Contact
Andrew Hall
BP
Pipeline Transportation Team, EPT
1H-54 Dyce
Aberdeen, AB21 7PB
United Kingdom
Phone: (44 1224) 8335807
Fax:
Email: halla9@bp.com

Alternate UK Contact
Trevor Hill
BP
E&P Engineering Technical Authority – Flow Assurance
Chertsey Road
Sunbury on Thames, Middlesex TW16 7BP
United Kingdom
Phone: (44) 7879 486974
Fax:
Email: trevor.hill@uk.bp.com

US Contact
Taras Makogon
BP
501 Westlake Park Blvd.
Houston, Texas 77079
Phone: (281) 366-8638
Fax:
Email: taras.makogon@bp.com

US Contact
George Shoup
BP
501 Westlake Park Blvd.
Houston, Texas 77079
Phone: (281) 366-7238
Fax:
Email: shoupgj@bp.com

US Contact
Oris Hernandez
Flow Assurance Engineer
BP
501 Westlake Park Blvd.
Houston, Texas 77079
Phone: (281) 366-5649
Fax:
Email: oris.hernandez@bp.com

Chevron

Hariprasad Subramani
Chevron
Flow Assurance
1400 Smith Street, Room 23192
Houston, Texas 77002
Phone: (713) 372-2657
Fax: (713) 372-5991
Email: hjsubramani@chevron.com

Lee Rhyne
Chevron
Flow Assurance Team
1400 Smith Street, Room 23188
Houston, Texas 77002
Phone: (713) 372-2674
Fax: (713) 372-5991
Email: lee.rhyne@chevron.com

ConocoPhillips, Inc.

Tom Danielson
ConocoPhillips, Inc.
600 N. Dairy Ashford
1036 Offshore Building
Houston, Texas 77079
Phone: (281) 293-6120
Fax: (281) 293-6504
Email: tom.j.danielson@conocophillips.com

Kris Bansal
ConocoPhillips, Inc.
1034 Offshore Building
600 N. Dairy Ashford
Houston, Texas 77079
Phone: (281) 293-1223
Fax: (281) 293-3424
Email: kris.m.bansal@conocophillips.com

Yongqian Fan
ConocoPhillips, Inc.
600 N. Dairy Ashford
1052 Offshore Building
Houston, Texas 77079
Phone: (281) 293-4730
Fax: (281) 293-6504
Email: yongqian.fan@conocophillips.com

Steve Appleyard
ConocoPhillips, Inc.
238 GB Bartlesville Technology Center
Highway 60 & 123
Bartlesville, OK 74004
Phone: 918-661-7282
Fax: 918-661-1320
Email: Steve.Appleuard@conocophillips.com

ExxonMobil

Don Shatto
ExxonMobil
P. O. Box 2189
Houston, Texas 77252-2189
Phone: (713) 431-6911
Fax: (713) 431-6387
Email: don.p.shatto@exxonmobil.com

Jiyong Cai
ExxonMobil
P. O. Box 2189
Houston, Texas 77252-2189
Phone: (713) 431-7608
Fax: (713) 431-6387
Email: jiyong.cai@exxonmobil.com

Nader Berchane
ExxonMobil Upstream Research Company
Gas & Facilities Division
P. O. Box 2189
Houston, Texas 77252-2189
Phone: (713) 431-6059
Fax: (713) 431-6322
Email: nader.berchane@exxonmobil.com

General Electric

Nick Ellson
GE Oil & Gas
2 High Street, Nailsea
Bristol, BS48 1BS
United Kingdom
Phone: (44) 1275 811 645
Email: nick.ellson@ge.com

Rogier Blom
GE Global Research
Phone:
Fax:
Email: blom@ge.com

John "Dan" Friedemann
Chief Engineer Subsea Processing and Flow Assurance
GE Oil and Gas
Eyvind Lyches vei 10
1338 Sandvika
Norway
Phone: 4766985375
Email: john.friedemann@ge.com

JOGMEC

Arai Hirohisa
JOGMEC
1-2-2, Hamada, Mihama-ku
Chiba, 261-0025 Japan
Phone: (81 43) 2764464
Fax: (81 43) 2764063
Email: arai-hirohisa@jogmec.go.jp

Masaru Nakamizu
JOGMEC
One Riverway, Suite 450
Houston, Texas 77056
Phone: (713) 622-0204
Fax: (713) 622-1330
Email: nakamizu-masaru@jogmec.go.jp

Kuwait Oil Company

Eissa Alsafran
Kuwait University
College of Engineering and Petroleum
Petroleum Engineering Department
P. O. Box 5969
Safat – 13060 – Kuwait
Phone: (965) 4987699
Fax: (965) 4849558
Email: eisa@kuniv.edu.kw
dr_ealsafran@yahoo.com

Adel Al-Abbasi
Manager, Research and Technology
Kuwait Oil Company (K.S.C.)
P. O. Box 9758
Ahmadi – Kuwait 61008
Phone: (965) 398-8158
Fax: (965) 398-2557
Email: aabbasi@kockw.com

Ahmad K. Al-Jasmi
Team Leader R & T (Surface)
Research and Technology Group
Industrial Area
Kuwait Oil Company
P. O. Box 9758
Ahmadi – Kuwait 61008
Phone: (965) 3984126
(965) 3866771
Fax: (965) 3989414
Email: ajasmi@kockw.com

Bader S. Al-Matar
Snr. Reservoir Engineer
R & T Subsurface Team
Kuwait Oil Company
P. O. Box 9758
Ahmadi – Kuwait 61008
Phone: (965) 398-9111 ext. 67708
Email: bmatar@kockw.com

Marathon Oil Company

Rob Sutton
Marathon Oil Company
P. O. Box 3128
Room 3343
Houston, Texas 77253
Phone: (713) 296-3360
Fax: (713) 296-4259
Email: rpsutton@marathonoil.com

Petrobras

Rafael Mendes
Petrobras
Cidade Universitaria – Quadra 7 – Ilha do Fundao
CENPES/PDEP/TEEA
Rio de Janeiro 21949-900
Brazil
Phone: (5521) 38652008
Fax:
Email: rafael.mendes@petrobras.com.br

Kazuoishi Minami
Petrobras
Av. Republica do Chile
65 – 17° Andar – Sala 1703
Rio de Janerio 20035-900
Brazil
Phone: (55 21) 5346020
Fax: (55 21) 5341128
Email: minami@petrobras.com.br

Marcelo Goncalves
Petrobras
Cidade Universitaria – Quadra 7 – Ilha do Fundao
CENPES/PDEP/TEEA
Rio de Janeiro 21949-900
Brazil
Phone: (5521) 38656712
Fax: (5521) 38656796
Email: marcelog@petrobras.com.br

Ibere Alves
Petrobras
Phone: (55 21) 5343720
Email: ibere@petrobras.com.br

Schlumberger

Mack Shippen
Schlumberger
5599 San Felipe
Suite 1700
Houston, Texas 77056
Phone: (713) 513-2532
Fax: (713) 513-2042
Email: mshippen@slb.com

Sammy Haddad
GFM Reservoir Domain Champion & Res. Eng. Advisor
Schlumberger Middle East S.A.
Mussafah
P. O. Box 21
Abu Dhabi, UAE
Phone: (971 2) 5025212
Fax:
Email: shaddad@abu-dhabi.oilfield.slb.com

Maria Vielma
Production Engineer
Schlumberger Information Solutions
1625 Broadway, Suite 1300
Denver, Colorado 80202
Phone: (303) 389-4438
Fax: (303) 595-00667
Email: mvielma@denver.oilfield.slb.com

William Bailey
Principal
Schlumberger – Doll Research
1 Hampshire Street, MD-B213
Cambridge, MA 02139
Phone: (617) 768-2075
Fax:
Email: wbailey@slb.com

Shell Global Solutions

Rusty Lacy
Fluid Flow (OGUF)
Shell Global Solutions (US) Inc.
Westhollow Technology Center
3333 Hwy 6 South
Houston, Texas 77082-3101
Phone: (281) 544-7309
Fax: (281) 544-8427
Email: rusty.lacy@shell.com

Ulf Andresen
Fluid Flow Engineer
Shell Global Solutions (US) Inc.
Westhollow Technology Center
3333 Hwy 6 South
Houston, Texas 77082
Phone: (281) 544-6424
Fax:
Email: ulf.andresen@shell.com

SPT

Richard Shea
SPT
11490 Westheimer, Suite 720
Houston, Texas 77077
Phone: (281) 496-9898 ext. 11
Fax: (281) 496-9950
Email: richard.shea@sptgroup.com

Jeff Gillis
SPT
11490 Westheimer, Suite 720
Houston, Texas 77077
Phone: (281) 496-9898 ext. 112
Fax: (281) 496-9950
Email: jeff.gillis@sptgroup.com

Lee Norris
SPT
11490 Westheimer, Suite 720
Houston, Texas 77077
Phone: (281) 496-9898 ext. 14
Fax: (281) 496-9950
Email: hln@sptgroup.com

Gunnar Staff
SPT Group A/S
P. O. Boks 113, Instituttveien 10
N-2027 Kjeller, Norway
Phone: 47 63 89 04 94
Fax: 47 64 84 45 00
Email: gunnar.staff@sptgroup.com

TOTAL

Pravin Subramanian
Flow Assurance Research Engineer
Engineering and Technology
TOTAL E & P USA
1201 Louisiana Street, Suite 1800
Houston, Texas 77002
Phone: (713) 647-3411
Email: pravin.subramanian@total.com

Fabien Papot
TOTAL Exploration & Production
DGEP/SCR/ED/ECP
2, place Jean Millier – La Defense 6
92078 Paris la Defense Cedex - France
Phone: (33) 1 47 44 82 78
Email: fabien.papot@total.com

Thierry Palermo
TOTAL
Email: thierry.palermo@total.com

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
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

Appendix D

Contact Information

Director
Cem Sarica — (918) 631-5154, cem-sarica@utulsa.edu

Associate Director
Holden Zhang — (918) 631-5142, hong-quan-zhang@utulsa.edu

Research Associate
Eduardo Pereyra — (918) 631-5107, eduardo-pereyra@utulsa.edu

Visiting Research Associate
Abdel Al-Sarkhi — alsarkhi@kfupm.edu.sa

Director Emeritus
James P. Brill — (918) 631-5114, brill@utulsa.edu

Project Coordinator
Linda M. Jones — (918) 631-5110, jones@utulsa.edu

Project Engineer
Scott Graham — (918) 631-5147, sdgraham@utulsa.edu

Research Technicians
Norman Stegall — (918) 631-5133, norman-stegall@utulsa.edu

Craig Waldron — (918) 631-5131, craig-waldron@utulsa.edu

Research Assistants
Feras Alruhaimani — (918) 631-5119, feras-alruhaimani@utulsa.edu

Yasser Alsaaid — (918) 631-5115, yasser-alsaadi@utulsa.edu

Rosmer Brito — (918) 631-5119, rosmer-brito@utulsa.edu

Kiran Gawas — (918) 631-5138, kiran-gawas@utulsa.edu

Mujgan Guner — (918) 631-5117, mujgan-guner@utulsa.edu

Hamidreza Karami — (918) 631-5107, hk274@utulsa.edu

Ge Yuan — (918) 631-5124, ge-yuan@utulsa.edu

Wei Zheng	(918) 631-5124 wei-zheng@utulsa.edu

Visiting Research Assistants

Jinho Choi	(918) 631-5119 jinho-choi@utulsa.edu
Huyoung Lee	(918) 631-5115 huyoung-lee@utulsa.edu

Web Administrator

Lori Watts	(918) 631-2979 lori-watts@utulsa.edu

Fax Number:	**(918) 631-5112**
Web Sites:	**www.tuffp.utulsa.edu**